

Article

# Spatial Recognition of the Urban-Rural Fringe of Beijing Using DMSP/OLS Nighttime Light Data

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Received: 20 August 2017; Accepted: 31 October 2017; Published: 7 November 2017

**Abstract:** Spatial identification of the urban-rural fringes is very significant for deeply understanding the development processes and regulations of urban space and guiding urban spatial development in the future. Traditionally, urban-rural fringe areas are identified using statistical analysis methods that consider indexes from single or multiple factors, such as population densities, the ratio of building land, the proportion of the non-agricultural population, and economic levels. However, these methods have limitations, for example, the statistical data are not continuous, the statistical standards are not uniform, the data is seldom available in real time, and it is difficult to avoid issues on the statistical effects from edges of administrative regions or express the internal differences of these areas. This paper proposes a convenient approach to identify the urban-rural fringe using nighttime light data of DMSP/OLS images. First, a light characteristics-combined value model was built in ArcGIS 10.3, and the combined characteristics of light intensity and the degree of light intensity fluctuation are analyzed in the urban, urban-rural fringe, and rural areas. Then, the Python programming language was used to extract the breakpoints of the characteristic combination values of the nighttime light data in 360 directions taking Tian An Men as the center. Finally, the range of the urban-rural fringe area is identified. The results show that the urban-rural fringe of Beijing is mainly located in the annular band around Tian An Men. The average inner radius is 19 km, and the outer radius is 26 km. The urban-rural fringe includes the outer portions of the four city center districts, which are the Chaoyang District, Haidian District, Fengtai District, and Shijingshan District and the part area border with Daxing District, Tongzhou District, Changping District, Mentougou District, Shunyi District, and Fangshan District. The area of the urban-rural fringe is approximately 765 km<sup>2</sup>. This paper provides a convenient, feasible, and real-time approach for the identification of the urban-rural fringe areas. It is very significant to extract the urban-rural fringes.

**Keywords:** urban-rural fringe area; DMSP/OLS nighttime light data; breakpoint method; Beijing

## 1. Introduction

The urban-rural fringe is the transitional region between city and rural areas where various social and economic factors intensely transform [1]. It is transitional, gradual, and dynamic in numerous aspects, such as population, economy, land use, and ecology [2–4]. Many problems have arisen in urban-rural fringes during the process of the urbanization in China. e.g., the contradiction between urban expansion and agricultural land protection, conflicts of interest in land expropriation, instability in land use changes, over-accumulation of large floating population with complex identities leading to serious crime and social harmfulness, arbitrary and aimless development and construction, and backward public infrastructure [5,6]. Thus, these areas can be regarded as the ones with the

most land use problems and acute contradictions in the world [7,8]. Urban-rural fringes are also located at the intersection of sensitive zones of social contradiction and conflict in China. Spatial identification of the urban-rural fringes is very significant for solving social problems, optimizing urban land management, and promoting urban and rural integration.

Many approaches have been used to recognize the urban-rural fringe area, including quantitative methods such as measuring the distance to the built-up area and the population density standard [9,10]. Other methods include field surveys [7,8], statistical analysis methods using single or multiple factors [11–13], and mutation point analysis methods using remote sensing images [14]. The traditional methods mostly use the single or multiple comprehensive index factors: for example statistical analysis of parameters, population density, construction land ratio, proportion of the non-agricultural population, landscape disorder degree, and economic level [15–17]. In these studies, urban-rural fringes were identified using breakpoints analysis, information entropy, thresholds, and landscape disorder degree discrimination [18–21]. However, these methods have deficiencies: for example, the statistical data are not continuous, the statistical standards are not uniform, the data is seldom available in real time, and it is difficult to overcome problems caused by the fact that most data sets are available in the form of mean values for administrative regions, making it impossible to express the internal differences of the areas.

Nighttime light data is available in real time, which is not collected by administrative boundaries. Therefore, there are no statistical limits to overcome the data continuity problem [22]. DMSP/OLS nighttime light images can be used to characterize human activities and has become a data source for monitoring and researching human activities [23] and used in urban expansion [24–27], estimation of social and economic factors [28–30], and other research fields, including environmental, disasters, fisheries, and energy [31–34].

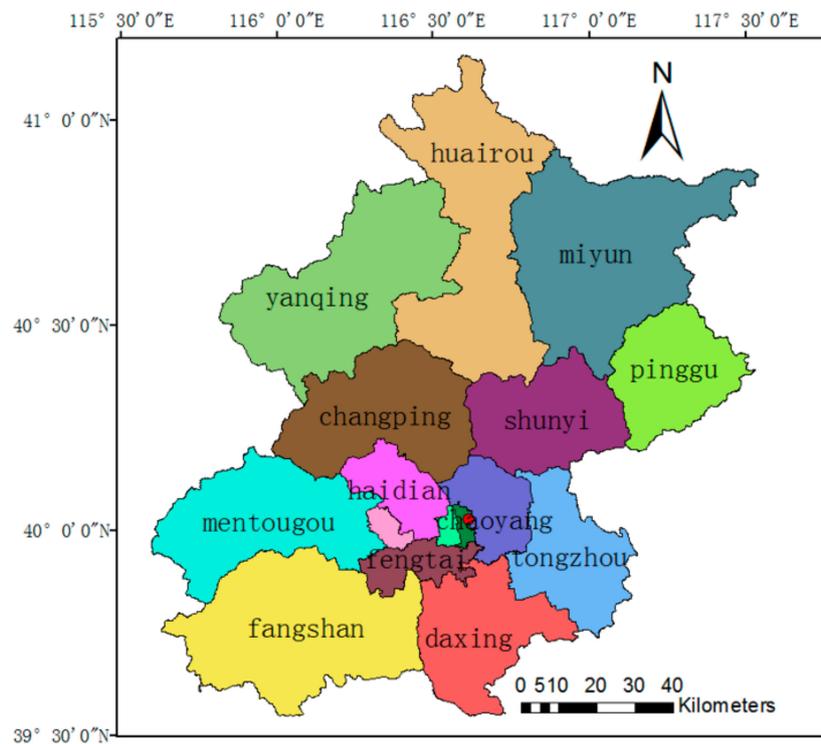
Currently, most research on urban spatial distributions using nighttime light data has mainly focused on urban expansion. There are few studies on the identification of urban-rural fringes. This paper proposes a convenient approach to identify the urban-rural fringe using the DMSP/OLS nighttime light data. We used light intensity and fluctuant degree to construct a model and extracted the breakpoints of the model in 360 directions in Beijing to recognize the urban-rural fringe.

## 2. Study Area and Materials

### 2.1. Introduction of the Study Area

As one of the world's largest cities, Beijing is the capital and the economic, political, cultural and international communication center of China. It has an important influence on the world and also has a large number of world cultural heritage sites. The center of Beijing is located at 39°54' north and 116°23' east, and it is on the northwest edge of the North China Plain. Beijing has a typical semi-humid continental climate of the northern hemisphere; the spring and autumn are short, the summer is hot and rainy, and the winter is cold and dry. The average elevation of the main city area is 43.5 m, the elevation of the plain in Beijing is 20–60 m, the mountain elevation is 1000–1500 m, and the area of the city is 16,411 km<sup>2</sup>. The plain area is 6339 km<sup>2</sup>, accounting for 38.6% of the total area, and the mountains area is 10,072 km<sup>2</sup>, accounting for 61.4%. The resident population of Beijing is 21,729,000 in 2016, and the population density is 1323 persons/ km<sup>2</sup> in 2015 [35].

There are 16 districts in Beijing, including two core capital function zones: the Dongcheng District and Xicheng District; four city function expansion areas: the Chaoyang District, the Haidian District, the Shijingshan District, the Fengtai District; five new city development districts: the Fangshan District, the Daxing District, the Tongzhou District, the Shunyi District, the Changping District; and five ecological conservation development zones in Figure 1: the Mentougou District, the Yanqing District, the Huairou District, the Pinggu District, and the Miyun District [36].



**Figure 1.** Administrative map of Beijing.

The urban-rural fringe of Beijing has become the frontier to promote the integration of urban and rural development under the influence of urban radiation, regional driving, and other factors during the new urbanization transformation of China [37]. The urban-rural fringe in Beijing has become a region that must be paid attention to during the current urbanization due to the strongest urban development vitality, the most obvious contradiction between population and environment, and the urgent demand of economic and social development in it [38].

## 2.2. Materials

The Defense Meteorological Satellite Program (DMSP) of the United States is equipped with an Operational Linescan System (OLS) sensor, which can work at night and detect light from cities or even low-intensity light from small-scale residential areas and vehicles. Lights make city areas obviously different from dark country backgrounds [39] and are more suitable for the dynamic monitoring of urbanization.

Version 4 DMSP-OLS nighttime light time data in 2013 were obtained from NOAA's National Centers for Environmental Information (NCEI, formerly NGDC) website [40]. There are three types of annually averaged data in the dataset: cloud free coverage, average visible light, and stable lights. Among the three types of data, the stable light data contain the lights derived from cities, towns, and other sites with persistent lighting, while fires, volcanoes, background noise, and other ephemeral events have been discarded [41]. The DMSP-OLS nighttime stable light (NSL) data have a spatial resolution of 30 arc-seconds, about 1 km at the equator, and a coverage spanning  $-180^{\circ}$  to  $180^{\circ}$  and  $-65^{\circ}$ S to  $75^{\circ}$ N. The digital number (DN) values of pixels range from 0 to 63. A value of 0 represents an unlit area and the greater the value, the higher the light level of the region.

In this paper, the data preprocessing and brightness correction between years have been executed to the DMSP-OLS data, so the DMSP-OLS NSL data in 2013 is used. The original data use the WGS84 reference coordinate system, which is changed to Chinese Lambert conformal conic projection in ArcGIS 10.3 (ESRI, Redland, CA, USA). The central meridian of the projection is at  $105^{\circ}$  E, and the two standard parallels are  $30^{\circ}$ N and  $62^{\circ}$ N. The administrative boundaries of Beijing, including all districts,

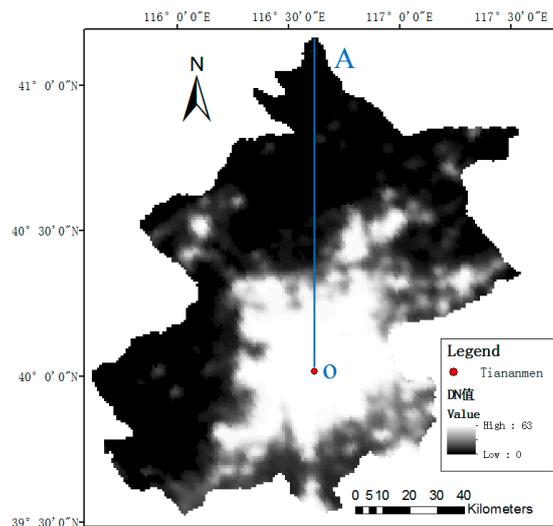
were obtained from the National Geomatics Center of China. The nighttime light data of Beijing in 2013 was extracted using the administrative boundary of Beijing.

### 3. Methods

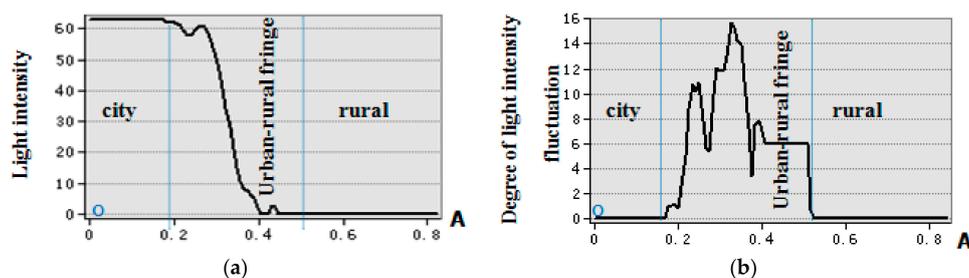
#### 3.1. Theory of the Analysis of Light Characteristics

The regional structure of the modern city can be divided into three parts: the urban core area, the urban and rural transition zone, and the rural area [42]. The urban and rural transition zone is also called the urban-rural fringe area. It usually includes the nearby suburbs of the periphery of the built-up area or the whole suburban district. It is the frontier of urban expansion [43]. The urban-rural fringes are different from the homogenous cities and countryside and shows characteristics of transition, diversity, and fluctuation [39]. Due to production and lifestyle differences, urban residents depend on the light at night much more than rural residents. Therefore, the light intensity and the degree of light intensity fluctuation in the urban-rural fringes show transitional characteristics from the city to the countryside.

Taking the main urban area of Beijing as an example, the profile line OA in the DMSP/OLS nighttime light data of Beijing in 2013 was used to obtain the DN intensity value of the profile line (Figure 2). Degree of light intensity fluctuation was calculated according to the light intensity (Figure 3). It shows that the light intensity gradually declined from the city center to the rural hinterland, and degree of light intensity fluctuation was lower in the urban and rural areas and higher in the middle of the urban-rural fringe area.



**Figure 2.** Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) nighttime light data of Beijing in 2013.



**Figure 3.** Characteristics of light intensity (a) and degree of light intensity fluctuation (b).

### 3.2. Construction of Model Used to Identify Urban-Rural Fringes

From the center of the cities to the rural hinterland, the overall light intensity decreases. The greater the light intensity value, the higher the possibility that the region is a city. Conversely, the lower the light intensity value, the higher the possibility that the region is countryside.

#### 3.2.1. Calculation of the Degree of Light Intensity Fluctuation

The degree of fluctuation of light intensity reflects the degree of variation of the light intensity in a certain range; the calculation is shown in Formula (1).

$$DN_w = DN_{nmax} - DN_{nmin} \quad (1)$$

where  $DN_w$  is the degree of light intensity fluctuation and  $DN_{nmax}$  and  $DN_{nmin}$  are the maximum and minimum values of light intensity value (DN) in the 3\*3 neighborhood.

The range of the light intensity value (DN) is 0–63, as shown in Figure 4a. In ArcGIS 10.3, the degree of light intensity fluctuation is calculated using Formula (1), as shown in Figure 4b. The range of the degree of light intensity fluctuation is 0–38.

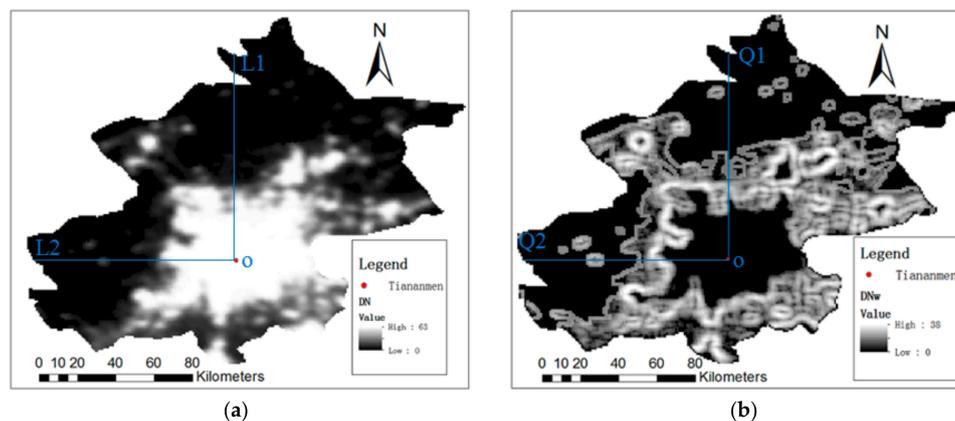


Figure 4. Light intensity (a) and degree of light intensity fluctuation (b).

#### 3.2.2. Extremum Normalization of Light Intensity and Degree of Light Intensity Fluctuation

Based on a related reference [44], an extremum normalization is performed on the light intensity DN and the degree of light intensity fluctuation ( $DN_w$ ) using Formulas (2) and (3). DN value is the digital number or the light intensity value of the pixels in the study area. The range of DN value of the pixels is from 0 to 63.  $DN_n$  is the light intensity normalization value,  $DN_{wn}$  is the degree of light intensity fluctuation normalization value, and the ranges of  $DN_n$  and  $DN_{wn}$  are (0, 1).  $DN_{max}$  and  $DN_{min}$  are the maximum and minimum values of light intensity in main urban areas, respectively.  $DN_{wmax}$  and  $DN_{wmin}$  are the maximum and minimum value of the degree of light intensity fluctuation in main urban areas, respectively.

$$DN_n = \frac{DN - DN_{min}}{DN_{max} - DN_{min}} \quad (2)$$

$$DN_{wn} = \frac{DN_w - DN_{wmin}}{DN_{wmax} - DN_{wmin}} \quad (3)$$

#### 3.2.3. Constructing the Formula of the Light Characteristic Combination Value

The coordination degree formula [44,45] was utilized to construct the light characteristic combination value formula that combines the light intensity and the degree of light intensity fluctuation.

The characteristic combination value formula is shown in Formula (4), where C is the characteristics combination value.

$$C = \begin{cases} 2 \times \sqrt{\frac{DN_n \times DN_{wn}}{(DN_n + DN_{wn})^2}} & , (DN_n \neq 0 \text{ or } DN_{wn} \neq 0) \\ 1, & (DN_n = 0 \text{ and } DN_{wn} = 0) \end{cases} \quad (4)$$

In ArcGIS 10.3, according to the Formulas (2)–(4), the light characteristic combination value (C) was computed, and the range of the C value is 0–1, as shown in Figure 5.

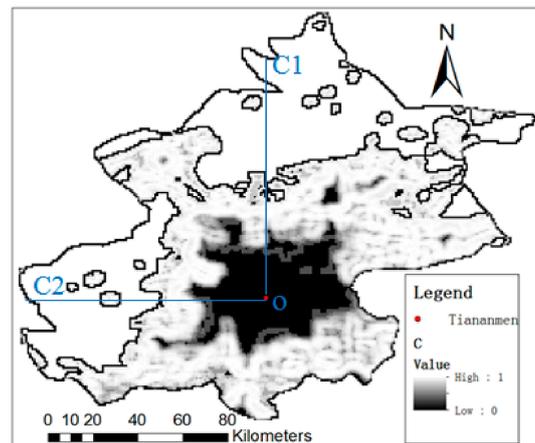


Figure 5. Light characteristic combination value.

### 3.2.4. Extraction of the Breakpoints of Light Characteristic Combination Value in 360 Directions of the Study Area

Taking Tian An Men, located in Beijing, as the center and starting in the east direction, 360 profile lines were created at intervals of one degree, which covered the entire research area. The longest distance from Tian An Men to the boundary of Beijing was used as radius. As shown in Figure 6, the profile lines covered the entire study area. After intersecting the light characteristic combination value data (C) with the 360 profile lines, the corresponding data in 360 directions of the study area were obtained. The light characteristic combination values ( $C_i$ ) of each pixel in 360 directions were obtained, as shown in Figure 6.



Figure 6. Schematic diagram of the data columns derived in 360 directions. (The center of the circle is blurred because the 360 lines are too dense.)

The maximum attenuation distance ( $D_i$ ) in each direction is extracted using Formula (5) to obtain breakpoints in each direction.

$$D_i = \max \frac{|C_{ij} - C_{i(j+1)}|}{\sum |C_{ij} - C_{i(j+1)}| / N} \quad (5)$$

where  $D_i$  is the maximum attenuation distance of  $i$ th profile line,  $C_{ij}$  is the  $j$ th sequence characteristic value of the  $i$ th profile line, and  $C_{i(j+1)}$  is the  $(j + 1)$ th sequence characteristic value of the  $i$ th profile line.

By looking up the FID\_ grid field in the attribute table, the value of  $D_i$  of each profile line can be obtained. After the attribute table of the above intersection result was exported, the Python programming language and the Formula (5) were used to extract the maximum distance attenuation value ( $D_i$ ) in each direction. The pixels with  $D_i$  value were the breakpoints.

Last, the breakpoints were displayed over the original night light data. The inner and outer boundary line of the urban-rural fringe areas were obtained by measuring the distance between the breakpoint points and the center of the study area, eliminating the abnormal mutation points, and finally connecting the breakpoints using curves and smoothing the curves.

#### 4. Results

##### 4.1. Analysis of Light Intensity, Degree of Light Intensity Fluctuation, and the Characteristic Combination Value of Beijing

Overall, the light intensity in Beijing gradually decreases from Tian An Men outward. The pattern of the light intensity fluctuation shows the tendency that both the inside and the outside areas have small fluctuations, and the middle area has large fluctuation. Overall, the light characteristic combination value  $C$  increases from the city center to the outward suburban areas. However, some directions from the urban to the rural hinterland have exceptional small bright spots where the value of  $C$  suddenly decreases and then increases within a short distance. These spots break up the general trend of the variation of the  $C$  value in very small areas, as shown in Figure 7.

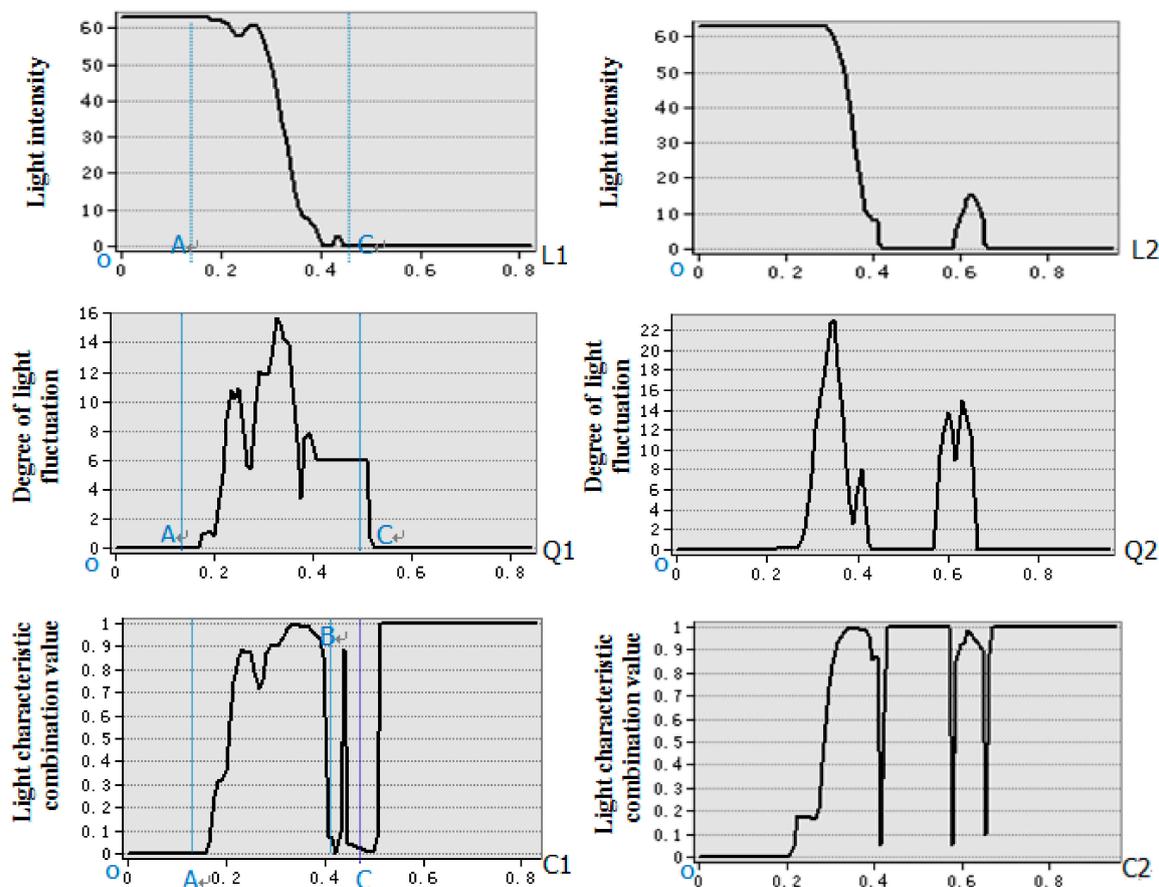


Figure 7. Graph of light intensity (L1,L2), degree of light intensity fluctuation (Q1,Q2), and light characteristic combination value (C1,C2).

The north and west directions of Beijing extending from the center of Beijing to the hinterland of the countryside have the most obvious changes in light characteristics. Using Tian An Men as the center, profiles of the light intensity (DN), degree of light fluctuation ( $DN_w$ ), and light characterization combination value (C) were created in the northward (direction 1) and westward (direction 2), as shown in Figures 4 and 5. The variation curves are shown in Figure 7, where point O is the center of the city. The curves in the northward (direction 1) direction are respectively L1, Q1, and C1 and the westward (direction 2) direction are L2, Q2, and C2.

Taking the northward (direction 1) direction as an example, the variations of light intensity DN, the degree of light intensity fluctuation  $DN_w$  and the light Characteristic combination value (C) were analyzed, as shown by the curves L1, Q1, and C1 in Figure 7.

The urban area is located from Tiananmen Center to point A. In this area, the value of the light intensity DN is 61, the value of the degree of light fluctuation  $DN_w$  is approximately 0, and the light characterization combination value C is also approximately 0. These values reflect the light characteristics of urban areas, which are high light intensities, low degree of light fluctuation, and low characterization combination value.

The urban-rural fringe is located between point A and point C. The value of the light intensity gradually decreases from 61 and reached approximately 0 near point C. The degree of light fluctuation  $DN_w$  is high, and it increases from point A to the first peak of approximately 11, decreases to 6, then increases to the highest value 16 again, decreases to 4, and finally drops to 0 at point C. The light characteristic combination value C gradually increases from 0 to 1. However, near point B, which is between points A and C, there is a small bright spot. On both sides of point B, the light characteristic combination values sharply decline and then rapidly increase. The light characteristics of the urban-rural fringe area are shown from point A to C. The light intensity DN gradually decreases from high to low, the light intensity fluctuation degree  $DN_w$  fluctuates greatly, and the light characteristic combination values show an overall increasing trend.

The rural area is from point C to the outer rural hinterland. In this area, the light intensity DN and the degree of light fluctuation  $DN_w$  are also closed to 0, and the light characterization combination value C is approximately 1. These results indicate that the light characteristics of the rural area are low light intensity, a low degree of light fluctuation, and high characteristic combination values.

#### 4.2. Urban Function Classification and the Range of Urban-Rural Fringe in Study Area

##### 4.2.1. Regional Function Classification of Beijing

The inner and outer boundaries of the urban-rural fringe are obtained by displaying the breakpoints that were extracted by the above model in ArcGIS 10.3, calculating the distance between the breakpoints to Tian An Men, excluding the abnormal mutation points, and connecting the breakpoints, as shown in Figure 8. According to the boundary lines, Beijing is divided into three types of areas: the urban area with high light intensity and a low degree of light intensity fluctuation, the urban-rural fringe with moderate light intensity and a high degree of light intensity fluctuation, and the countryside with low light intensity and a low degree of light intensity fluctuation, as shown in Table 1. The area covered by the inner boundary line is approximately 1358 km<sup>2</sup>, the area enclosed by the outer boundary is approximately 2123 km<sup>2</sup>, and the difference between the inner and outer boundary lines is the area of the urban-rural fringe, which is approximately 765 km<sup>2</sup>.

**Table 1.** Regional classification and light characteristics in Beijing.

Region Type	Light Intensity	Degree of Light Intensity Fluctuation	Combination Characteristic
Urban area	High	Low	High-low
Urban-rural fringe area	Middle	High	Middle-high
Rural	Low	Low	Low-low

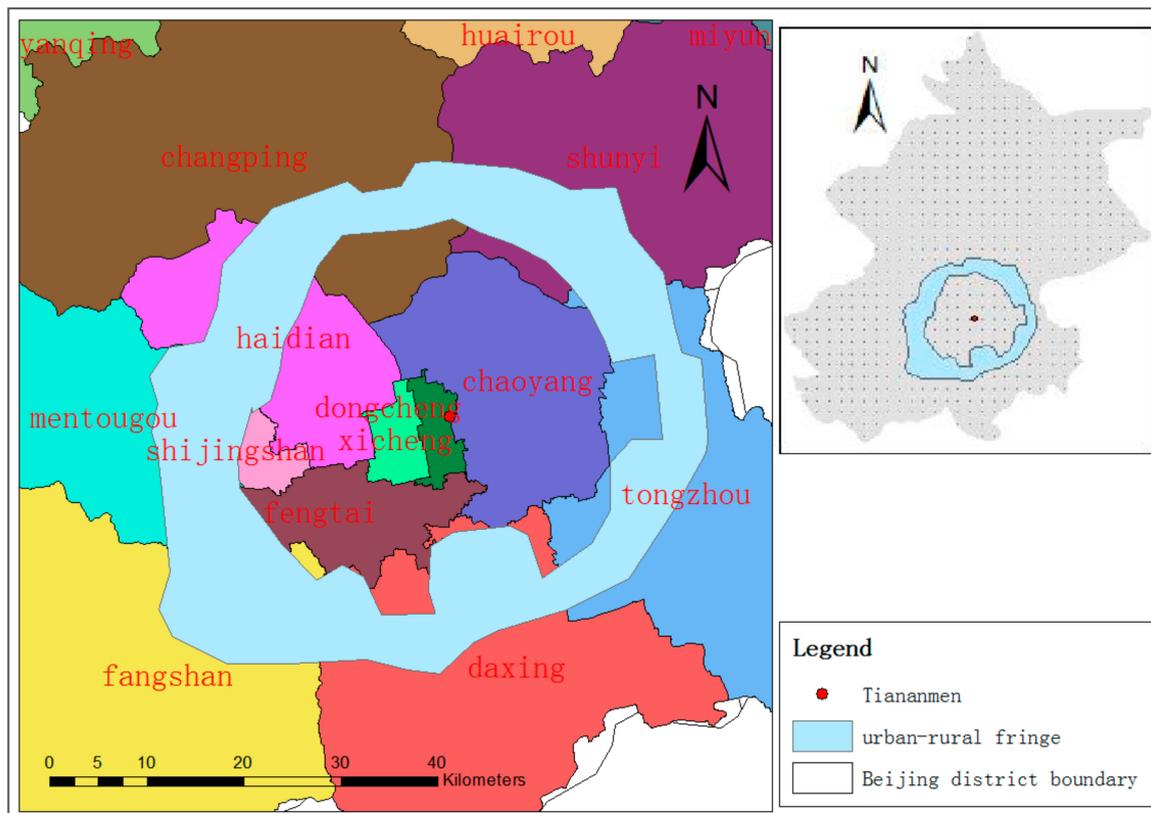


Figure 8. Territorial scope of the urban-rural fringe area in Beijing.

#### 4.2.2. Territorial Range of the Urban-Rural Fringe Area of Beijing

The urban-rural fringe area in Beijing is mainly located in the annular band with Tian An Men as the center. The average inner radius is 19 km, and the outer radius is 26 km. The area includes the outer edges of the four city center districts: Haidian District, Fengtai District, Chaoyang District, and Shijingshan District. Part of the urban-rural fringe area is located along the border of the Fangshan District, Daxing District, Changping District, Mentougou District, Shunyi District, Tongzhou District, and Fangshan District. The urban-rural fringe has an area of approximately 765 km<sup>2</sup>, as shown in Figure 8.

### 5. Discussion

DMSP/OLS night light images as a unique remote sensing data source that can detect the light of low intensity and provide a reliable and convenient way to research human activities associated with light use and their effects. The data can be widely used for the monitoring of urban expansion and the urbanization level, estimating of the population, GDP, energy consumption, and carbon emissions, and monitoring of light pollution and fire [46]. However, there are few studies on the identification of urban-rural fringes that have been based on nighttime light data.

In this study, DMSP-OLS nighttime light time data in 2013 was used to extract the urban-rural fringe of Beijing. Light intensity and fluctuation were used to define the transitional region between urban and rural. The model of light characteristics combination value was built to identify the urban-rural fringe. This paper provided a new rapid convenient and feasible approach for the identification of the urban-rural fringe areas. It is very meaningful for the application of nighttime light data.

In this research, the profile lines in 360 directions were selected, which can cover the entire research area, and the “breakpoint” method was used to improve the accuracy of the results. If only

four or eight directions were selected, it would be impossible to correctly identify the range of the urban-rural fringe area. However, there some subjective and empirical judgments were required when the abnormal mutation points were eliminated in this method. The light parameters generally change regularly from the urban center to the rural hinterland. Some abnormal small bright spots do in some directions. These small bright spots may be a specific light source and are much brighter than the surrounding background area. When we use this approach to extract the breakpoints, the small bright spots break the regular change of the light parameters in the minimal area, and abnormal breakpoints will appear. So, we need to combine other data and subjective experience to judge whether the abnormal breakpoints are in the edge of the urban-rural fringe or to eliminate them. Additionally, the resolution of the DMSP/OLS nighttime light remote sensing data is relatively low, the spatial resolution of the nighttime light data is 1 km, and small-scale rural light is difficult to identify. Therefore, the light intensity and the degree of light intensity fluctuation were zero in some of the rural areas. Spatial identification of urban-rural fringe areas using nighttime light data together with traditional higher-resolution remote sensing images is worth studying in the future.

In this study, there are still some other related issues that need to be further considered and researched. Like many cities, the main city area of Beijing is annularly developed from the center to the outer area, so the city center is selected as the center of the circle to make profile lines in 360 directions to extract the urban-rural fringe. However, there are also some modern metropolises that are formed by combining multiple cities growing toward each other. As far as these particular cases are concerned, how to define a central point and deal with the remaining areas between urban and rural areas is still a problem that needs further study in the future. In addition, only the DMSP-OLS nighttime light time data in 2013 is used in this study. In the future work, NPP-VIIRS data can also be used to extract the urban-rural fringes using our method. The urban-rural fringes are dynamically changing with the development and change of the cities. Therefore, attention on the dynamic changes of the urban-fringe areas using long time series lighting data is necessary in the future. It can provide a more accurate and scientific reference for urban planning.

## 6. Conclusions

Night light data have the advantages that data acquisition is convenient and available in real time, and the data can break the administrative boundaries to reflect the differences within the administrative regions. In this study, an attempt was made to provide a convenient feasible and real-time approach for the identification of the urban-rural fringe areas using DMSP/OLS nighttime light data. DMSP/OLS night light data were used to analyze the characteristics of the light intensity and the degree of light intensity fluctuation in “urban,” “urban-rural fringe,” and “rural” areas. The light characteristic combination value model was built to analyze the maximum distance mutation value attenuation in 360 directions. Then, the breakpoints in each direction were extracted to identify the scope of the urban-rural fringe of Beijing.

Finally, we drew the conclusion that the urban-rural fringe area in Beijing is mainly located in the annular band with Tian An Men as the center. The average inner radius is 19 km, and the outer radius is 26 km. The area includes the outer edges of the four city center districts Haidian, Fengtai, Chaoyang, and Shijingshan. Part of the urban-rural fringe area is located along the border of the Fangshan, Daxing, Changping, Mentougou, Shunyi, Tongzhou, and Fangshan Districts. The area of the urban-rural fringe area is approximately 765 km<sup>2</sup>.

Through the study of relevant literature [19,47–49], the results showed that the spatial identification of the urban-rural fringe based on DMSP/OLS night light data was practical and reliable. The method is feasible and more convenient than the traditional methods, and the data and the recognition results are available in real time.

**Acknowledgments:** This research was supported by the Special Project of Science and Technology Basic Work (Grant No. 2014FY210800-5), the Project of Youth Science and Technology Foundation of Gansu in China under Grant No. 1610RJYA011, and in part by the Alumni Foundation of Civil Engineering 77, Lanzhou University

of Technology of China, under Grant No. JK2015-29, and the Youth Project of the National Natural Science Foundation of China under Grant No. 41601066.

**Author Contributions:** Mingguo Ma and Yuli Yang designed the study. Yuli Yang and Wangping Li processed the data. Yuli Yang and Mingguo Ma drafted the paper. Chao Tan contributed to the English editing. All of the authors contributed to the result discussion and paper writing.

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

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