The Research on Urban Expansion and Spatial Correlation Based on VIIRS/DNB Data: A Case Study of Shandong Province

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Abstract. The appearance of nighttime light (NTL) data allows us to experience urban development from more angles. This paper uses VIIRS/DNB monthly composite data to extract the urban built-up areas of 17 cities in Shandong Province. Then the built-up area extraction results in 2012 and 2017 are compared to determine the expansion type of each city. Finally, based on the intensity of city lights, we calculated the correlation between cities to show the strength of the connections between them. We find that the NTL values of Qingdao, Jinan, Yantai, and Weifang occupy the top four in Shandong Province, and this result is consistent with economic statistics. Laiwu, Qingdao, and Weifang have shown strong spatial expansion. Based on the growth area of built-up areas and urban development patterns in the past five years, the 17 cities in Shandong Province can be divided into four types: central expansion type (Jinan), multi-core development type (Rizhao), satellite diffusion type (Weifang) and mixed type (Zibo). We have summarized the characteristics of various types. There is little change in the spatial correlation between cities in 2012 and 2017. Cities such as Jinan, Zibo, Weifang, and Qingdao are closely related to other regions. The location degree of the city is also highest in these four cities, and the north and south sides of Shandong Province are lower.

Keywords: VIIRS/DNB, urban expansion, spatial association, Shandong Province.

1. Introduction
Currently, China’s urbanization has gradually shifted from quantitative growth to quality improvement. How to improve the quality of urbanization and take a sustainable urbanization path has become the focus of exploration by the government and academic circles. According to statistics, the proportion of my country’s urban population in the total population (urbanization rate) in 2018 was 59.58% (National Bureau of Statistics http://www.stats.gov.cn/). It is predicted that for a long time in the future, the process of urbanization in China will continue to develop. However, with the process of urbanization, urban issues such as land use contradictions have become increasingly prominent. Shandong Province, as a large economic and population province, has an urbanization rate of 61.18% of its permanent population in 2018. The geographical distribution of cities in Shandong Province is typical and representative. Therefore, we study the law of urban spatial expansion in Shandong
Province, summarize the types of urban expansion, and further measure the inter-city correlation. The research results have reference significance for reflecting the types of urban expansion in the country and promoting the sustainable development of urban areas.

Compared with population transfer and cultural renewal, the spatial expansion of urban land is a more direct manifestation of the spatial behavior of the urbanization process. Urban geographers first studied the urban spatial structure. Burgess (1925) and Hoyt (1939) successively proposed relevant theories of urban land use. Based on this, a large number of foreign scholars began to conduct more in-depth research on the construction of urban spatial association models [1]. As a functional connection between cities at different spatial scales, the urban network provides a new perspective for the study of urban spatial association [2]. In recent years, the development of remote sensing technology and geographic information system has provided many conveniences for urban space research. Numerous studies have shown that brighter areas in NTL images can be regarded as built-up areas [3,4]. This feature lays the foundation for the application of NTL to urban research. In recent years, many scholars have used NTL data for construction land extraction [5,6]. Liao et al. [7] and Fan et al. [8] introduced the analysis method of landscape index into urban lighting research to explore the changing characteristics of urban development spatial patterns. Wu et al. [9] divided the city NTL into multiple levels, and dynamically studied the proportion and change characteristics of different types of areas to reveal the law of urban development. Yu et al. [10] proposed an algorithm to quantitatively express the spatial proximity between cities for city cluster analysis, and successfully identified city clusters.

In general, domestic scholars have mostly studied the internal expansion of Chinese urban space. Liu et al. [11] proposed to use the convex hull principle to measure and describe the urban spatial growth in Anhui Province. Ye et al. [12] extracted the three major functional areas of residential area, industry and service industry, and studied the Spatio-temporal characteristics and driving forces of the expansion of functional land in Changsha from multiple scales. Liu and Shen [13] divided the urban expansion of Shanghai into four stages and discussed the dynamic mechanism of urban expansion from the aspects of agricultural development, industrial expansion, and transportation. With the concept of urban agglomerations and economic belts being put forward, more and more scholars have shifted their research focus to the developing relationship between multiple cities, and many scholars have begun to use related models to study urban spatial relationships. Among them, the gravity model is the most widely used [14]. The construction of comprehensive indicators based on statistical data is more comprehensive than using a single indicator of population or total GDP to represent the comprehensive strength of a city. However, the problem of differences in administrative boundaries of statistical indicators has not been resolved. The interconnection between cities mainly affects the built-up areas, and the rural areas do not contribute much to the connection. However, social and economic statistics cover the entire administrative unit, so simple statistics cannot accurately represent the city's quality and participate in the calculation of correlation. Besides, the reliability and spatial resolution of economic statistics are often criticized. The emergence of NTL remote sensing data provides a more reliable data source for reflecting human social activities, so it is widely used in spatial data mining in the socio-economic field [15]. For example, Li and Yu [16] studied the spatial structure and spatiotemporal evolution trend of urban systems in countries along the "Belt and Road" based on long-term NTL data from 1993 to 2012. Xu et al. [17] combined luminous remote sensing data with statistical data to study the pattern and process of urbanization in the Yangtze River Delta. Based on DMSP/OLS data, Chen et al. [18] used the gravity model to measure the urban spatial correlation strength of the Beijing-Tianjin-Hebei region from 1993 to 2013, and analyzed the temporal and spatial trend of urban socio-economic location. Most of the existing luminous remote sensing data to study urban spatial evolution are DMSP/OLS data. However, the lack of DMSP data in recent years has caused such studies to be limited to before 2013. Compared with other luminous remote sensing data, NPP/VIIRS data has the advantages of more current, higher spatial resolution, and easier data acquisition. But due to the lack of period, there are few studies on using it for urban expansion.
2. Materials and methods

2.1. Data

The data used in this research is the VIIRS day/night band luminous data V1.0, which is the average radiation fusion image data produced by the US Earth Observation Board (EOG) using the VIIRS satellite DNB (day/night data). The data has excluded the influence of stray light, lightning, moonlight and cloud cover before forming the fusion image, and been divided into monthly average and annual average. The monthly fusion data filter filters out the lights from aurora, fire, boat, and other temporary light sources. Due to the limitation of data integrity, this paper uses the monthly average fusion images of December 2012 and December 2017 as the research data. The vector map of county-level administrative regions in Shandong Province (2016) and the traffic maps are obtained from the National Basic Geographic Information System website (http://nfgis.nsdi.gov.cn/). Socio-economic statistics are from the 2013-2018 “Shandong Province Statistical Yearbook”.

This paper uses the threshold method [19] to remove the background noise of the image. We choose the highest value of the light data in the city center as the highest light threshold of the city, which is recorded as DN_{max}, and the DN of pixels exceeding DN_{max} in other areas is directly assigned as DN_{max}. We select lakes, reservoirs and other large-scale water bodies in the most interesting areas in the Google Earth image, and calculated the DN value of the VIIRS image by prefecture and city, and took the average as the city’s lowest light threshold and recorded it as DN_{min}. Areas below this value are directly assigned a value of 0. The VIIRS night light images after denoising are shown in Figure 1.

![Figure 1. The denoising result of VIIRS NTL image](image)

2.2. Methods

2.2.1. Urban built-up area extraction. This research assumes that the urban built-up areas of various cities will not die out during the research year [20]. We refer to the built-up area of each city in Shandong Province in 2012 and 2017, and compare the DN value of VIIRS images to determine the threshold DN_{L} for extracting built-up areas. The noise-removed images are divided into two values based on the threshold value [21]. If the DN value is bigger than or equal to DN_{L}, the original DN is assigned to 1, otherwise it is assigned to 0.

To reflect the spatial expansion rate of the cities in Shandong Province within 5 years, considering that the administrative area of each city is quite different, which may affect the expansion of built-up areas, we introduce the spatial expansion intensity index. This index uses the total area of the city to standardize its average expansion speed, making the spatial expansion of urban agglomerations at different time intervals comparable. The calculation formula is as follows:

\[
UEI_{2012-2017} = [(BUP_{2017} / UTP - BUP_{2012} / UTP) / 5] \times 100\%
\]
In the formula, $\text{UEI}_{2012-2017}$ represents the city's annual average spatial expansion intensity index. $\text{BUP}_{2017}$ and $\text{BUP}_{2012}$ respectively represent the number of pixels in the built-up area extracted from the lighting image in 2017 and 2012, and $\text{UTP}$ represents the total number of pixels contained in the NTL image.

2.2.2. Types of urban expansion. Existing researches mainly use the convex hull theory proposed by Liu et al. [11] to determine the type of urban expansion quantitatively. The convex hull theory is more effective for discriminating the infill and extended types of cities, but it ignores other forms of urban expansion. This paper proposes a method to distinguish the types of urban expansion based on the difference in the increment of primary and secondary built-up areas. We superimpose the extracted built-up areas of 2017 and 2012, and make a difference to obtain the area expanded in the built-up area in 5 years. According to the development status of each city, the primary built-up area and the secondary built-up area are delineated. The delimitation of built-up areas should follow the two principles. Firstly, the level of built-up areas is determined according to the current status of urban development by referring to Google Earth satellite imagery. Secondly, the primary built-up area is a continuous area where the urban economic and administrative center is located, and there is only one in each city. At the same time, there can be multiple secondary built-up areas in one city. We separately count the pixel increments of the two types of built-up areas. Finally, the types of urban expansion in Shandong Province are comprehensively determined based on the pixel increment, supplemented by factors such as the area of primary and secondary built-up areas and the number of secondary built-up areas.

2.2.3. City location and relevance. The basic function of a city lies in its external functions, that is, the role played by the city in the economic and social development of a certain area, and the division of labor undertaken is embodied in the activities of providing goods and services outside the city [22]. The external functions of cities are realized through inter-city associations. The degree of urban relevance is an important characterization of the close degree of relevance between cities. The attraction between cities is generally used as a reflection of urban relevance. The most commonly used is a gravity model constructed based on the principle of distance attenuation and the Newtonian formula for universal gravitation. The general form [23] is:

$$F_{ij} = K \left( \frac{Q_i Q_j}{d_{ij}} \right)^r$$

In the formula, $F_{ij}$ represents the strength of the correlation between city i and city j. $K$ is the gravitational constant, which is generally taken as 1. $Q_i$ and $Q_j$ represent the quality of the two cities respectively. The $d_{ij}$ is the distance between the two cities, and $r$ is the distance friction coefficient. The value is affected by factors such as the transportation network, the quality of the information network, and the composition and proportion of regional transportation modes [24]. For the city quality $Q$, the extracted sum of NTL brightness in the urban built-up area is used for characterization.

Location degree refers to the degree of superiority and inferiority of a city relative to other cities in the location system [24]. The inter-city correlation strength obtained from different perspectives represents the location degree of different nature. Since night light data is a comprehensive manifestation of social and economic factors, the location degree obtained based on the inter-correlation strength of cities in this paper can be defined as the city's socio-economic location degree.

3. Results

3.1. Urban expansion intensity and socio-economic location degree

The thresholds for each city to extract the built-up area of the city and the pixel statistics of the increase in the built-up area in 2017 compared to 2012 are shown in Table 1. It can be seen that the
threshold for extracting built-up areas in 2017 is generally higher than that in 2012, and most of the values are between 5 and 10.

Table 1. The threshold and pixel statistics of urban built-up area extraction

| Cities    | Threshold 2012 | Threshold 2017 | Increment of pixels |
|-----------|---------------|----------------|---------------------|
|           | Primary | Secondary | Difference |
| Jinan     | 7.91    | 10.52     | 708 | 113 | 595 |
| Qingdao   | 10.25   | 10.37     | 748 | 631 | 117 |
| Zibo      | 7.1     | 7.87      | 251 | 179 | 72  |
| Zaozhuang | 5.08    | 5.94      | 129 | 175 | -46 |
| Dongying  | 10.74   | 13.28     | 90  | 59  | 31  |
| Yantai    | 7.27    | 7.23      | 493 | 451 | 42  |
| Weifang   | 7.82    | 8.13      | 542 | 870 | -328|
| Jining    | 6.12    | 6.22      | 320 | 428 | -108|
| Taian     | 4.48    | 5.05      | 384 | 247 | 137 |
| Weihai    | 7.28    | 7.71      | 161 | 179 | -18 |
| Rizhao    | 8.08    | 8.27      | 102 | 144 | -42 |
| Laiwu     | 5.87    | 5.02      | 261 | 11  | 250 |
| Linyi     | 7.9     | 8.24      | 678 | 485 | 193 |
| Dezhou    | 5.11    | 9.85      | 540 | 306 | 234 |
| Liaocheng | 7.45    | 9.93      | 341 | 362 | -21 |
| Binzhou   | 8.05    | 9.99      | 208 | 217 | -9  |
| Heze      | 5.34    | 6.78      | 161 | 518 | -357|

We calculated the urban land expansion intensity of 17 cities in Shandong Province over the past 5 years based on the annual average spatial expansion index of the city. Among the 17 cities, Laiwu and Qingdao have the highest spatial expansion intensity, reaching over 0.2% (Figure 2). Weifang and Zaozhuang are in the second level. Dongying, Yantai, Rizhao and Binzhou have the lowest urban land expansion in the past five years, less than 0.1%. We find that the four cities with higher expansion intensity can be divided into two categories. The urban expansion areas of Laiwu and Zaozhuang are not large, but the overall result is higher because of the small total area. The overall areas of Qingdao and Weifang are relatively large, and their spatial expansion intensity index is very high, indicating that the expansion of urban land in the two cities in the past five years is much larger than that of other cities.

Figure 2. The changes in urban expansion rate and location degree
In order to visually show the changes in the social and economic location of cities in Shandong Province, we further calculated the slope of the changes in the location of each city (the average annual location changes). It can be seen from Figure 2 that the variation range of the urban location degree slope is within -0.5% to 1%. Qingdao has the fastest rate of rising, with a slope of change of 0.82%. The rate of change in cities such as Rizhao, Dezhou, and Jinan is second only to Qingdao. The location degrees of Zibo and Yantai declined the fastest, with the slopes of change being -0.486% and -0.438% respectively.

3.2. Types of urban expansion

According to the pixel increment difference of the primary and secondary built-up areas in Table 1, taking into account the difference in the area of built-up areas, the number of secondary built-up areas and other factors, we divide the urban expansion of 17 cities in Shandong Province into four types. Various types of characteristics and standards are shown in Table 2.

Table 2. The types of urban extension

| Types                  | Features and criteria                                                                 | Typical cities          | Images |
|------------------------|---------------------------------------------------------------------------------------|-------------------------|--------|
| Central expansion type | The central urban area has expanded significantly, and there are no other obvious developed urban areas. The pixel increment of the primary built-up area is much larger than the secondary. | Jinan                   |        |
| Multi-core development type | There is not much difference between the primary urban area and the secondary. The area of the secondary built-up areas is not less than 1/3 of the primary, and the primary and sub-urban areas have developed to a considerable extent in recent years. | Qingdao, Zaozhuang, Dongying, Rizhao |        |
| Satellite diffusion type | There is a clear scope of the main city, with no less than 3 secondary built-up areas, and the area of each secondary built-up area is less than 1/3 of the primary. Numerous secondary areas surround the primary area and are connected to the main city by traffic arteries. | Yantai, Weifang, Taian, Weihai, Heze |        |
| Mixed type             | Combining the characteristics of the above categories, and does not belong to the above three categories. | Zibo, Jining, Dezhou    |        |

Among the multi-core development cities, Qingdao has three development cores: the main urban area (Shinan and Shibei), Chengyang, and Huangdao. The development of Zaozhuang is driven by three cores: central, western and northwest. The two economic development cores of Rizhao City are located in the coastal area of the southeast of the city, relying on the development of important ports. The central part of Dongying is where the administrative center of the city is located. But in recent years the economy in the southern part of the city has developed rapidly, and an obvious dual-core development model has been formed in NTL remote sensing images.

Among the mixed type cities, Zibo and Jining are both a mixture of multi-core and satellite proliferation, showing that they contain two built-up areas with the same area, and there are many
smaller secondary built-up areas around them. Dezhou is different from them in that it is a mixture of two types of central expansion and satellite diffusion. The specific manifestation is that the downtown area has expanded significantly in the past five years, and there are a considerable number of suburban areas around the city.

3.3. Urban spatial relevance
Due to differences in the level of economic development and actual traffic accessibility between cities, the spatial correlation between cities is quite different. With the highest correlation value of 100, we standardize the urban spatial correlation, and the result is shown in Figure 3. Many cities such as Tai'an-Jinan-Zibo-Weifang-Qingdao have a high degree of urban relevance. In addition to the relatively high economic level of these cities, the reason for this phenomenon is more due to their location on the east-west traffic arteries of Shandong Province. Therefore, the transportation links with other cities in the province are more convenient. In addition to the above cities, the spatial correlation between Jining, Zaozhuang, Rizhao, Yantai, Dongying and other cities has also been greatly improved.

![Figure 3. Urban spatial relevance of Shandong province in 2012 and 2017](image)

By summing the spatial relevance of each city and other cities, the overall relevance of the city and other cities can be obtained. This indicator can reflect the role of the city in the region. The determination of socio-economic location is a process of standardizing the overall relevance of cities, so that the social and economic influence of cities in Shandong Province can be more intuitively reflected. The results of the study show that the socio-economic location of cities in Shandong Province did not change much from 2012 to 2017. Jinan, Qingdao, Weifang and Zibo have always occupied the top four locations in Shandong Province, while Laiwu has always been at the bottom due to its small economy. The socio-economic location of cities such as Rizhao, Jining, and Dezhou increased slightly, while the degree of cities such as Yantai and Dongying declined.

4. Conclusions
The NTL data provides new material for urban development research. Among the four urban expansion models summarized in this paper by extracting urban built-up areas, the central expansion type has the lowest development potential. A series of urban problems will arise with urban development in this pattern. The "multi-core development type", especially the "satellite proliferation type" urban development process formed a multi-core spatial form to prevent the extension of the city's "spreading pie" style. At the same time, the cores at all levels are connected through the main traffic roads, which can appropriately share the pressure of the main city. This model enables urban development to achieve organic concentration based on relatively scattered forms, and promotes the coordinated development of cities.
The degree of urban spatial relevance is an effective measure of the closeness of connections between cities. The overall relevance of a city and other cities is an important manifestation of the basic functions of the city. The degree of socioeconomic location measures the core economic status of the city in the overall area. Qingdao and Jinan are at the highest level of spatial association with multiple cities, which can reflect their core leading role in Shandong Province. Qingdao’s socioeconomic location has the highest growth rate, which indicates that Qingdao’s economy has achieved rapid development in the past five years, and its economic core position in the province has been continuously consolidated. This phenomenon is inseparable from the plan to promote the construction of the Shandong Peninsula city cluster in Jinan and Qingdao in recent years. The future development of Shandong Province should continue to play the leading role of Qingdao and Jinan. At the same time, we should also pay attention to the links between cities and keep the gap between cities within a reasonable range. All cities in Shandong should give full play to their respective advantages and form characteristic industries. Adhering to sustainable development is the correct way to urban construction.

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References
[1] Taylor P J. Specification of the World City Network [J]. Geographical Analysis, 2010, 33(2): 181-194.
[2] Wu K, Fang C L, Zhao M X. The spatial organization and structure complexity of Chinese intercity networks [J]. Geographical Research, 2015, 34(04): 711-728.
[3] Henderson M, Yeh E T, Gong P, et al. Validation of urban boundaries derived from global night-time satellite imagery [J]. International Journal of Remote Sensing, 2003, 24(3): 595-609.
[4] Small C, Pozzi F, Elvidge C D, et al. Spatial analysis of global urban extent from DMSP-OLS night lights [J]. Remote Sensing of Environment, 2005, 96(3): 277-291.
[5] Zhou Y, Smith S J, Elvidge C D, et al. 2014. A cluster-based method to map urban area from DMSP/OLS nightlights [J]. Remote Sensing of Environment, 147(18): 173-185.
[6] Small C, Pozzi F, Elvidge C D. 2005. Spatial analysis of global urban extent from DMSP/OLS night lights [J]. Remote Sensing of Environment, 96(3): 277-291.
[7] Liao B, Wei K X, Song W W. 2012. Assessment and application of DMSP/OLS nighttime light data in the spatial structure of urban system: A case of Jiangxi Province in nearly 16 years. Resources and Environment in the Yangtze Basin, 21(11): 1295-1300.
[8] Fan J F, Ma T, Zhou C H, et al. 2013. Changes in spatial patterns of urban landscape in Bohai Rim from 1992 to 2010 using DMSP/OLS data. Journal of Geo-information Science, 15(2): 280-288.
[9] Wu J S, Ma L, Li W F, et al. 2014. Dynamics of urban density in China: Estimations based on DMSP/OLS nighttime light data [J]. IEEE Journal of Selected Topics in Applied Earth Observations & Remote Sensing, 7(10): 4266-4275.
[10] Yu B L, Shu S, Liu H X, et al. 2014. Object-based spatial cluster analysis of urban landscape pattern using nighttime light satellite images: A case study of China [J]. International Journal of Geographical Information Science, 28 (11): 2328-2355
[11] Liu J Y, Wang X S, Zhuang D F, et al. Application of convex hull in identifying the types of urban land expansion [J]. Acta Geographica Sinica, 2003(06): 885-892.
[12] Ye Q, Mo Z X, Xu Y Q. The expansion and driving forces of the functional space land: A case study of Changsha from 1979 to 2014 [J]. Geographical Research, 2019, 38(05): 1063-1079.
[13] Liu S H, Shen Y F. A probe into the urban sprawl model and its drive mechanism in Shanghai [J]. Economic Geography, 2006(03): 487-491.
[14] Guan W, Zhou X T. The Spatio-Temporal Evolvement of Spatial Interaction Among Cities of South Central Liaoning [J]. Economic Geography, 2014, 34(09): 48-55.
[15] Li D R, Li X. An overview on data mining of nighttime light remote sensing [J]. Acta Geodaetica et Cartographica Sinica, 2015, 44(6): 591-601.
[16] Li D R, Yu H R, Li X. The spatial-temporal pattern analysis of city development in countries along the belt and road initiative based on nighttime light data [J]. Geomatics and Information Science of Wuhan University, 2017, 42(06): 711-720.
[17] Xu M J, Chen L, Liu H J, Wang H. Pattern and process of urbanization in the Yangtze Delta based on DMSP /OLS Data [J]. Remote Sensing for Land & Resources, 2011(03): 106-112.
[18] Chen X, Peng J, Liu Y X, Chen Y Q, et al. Measuring spatial expansion and correlations of cities in Beijing-Tianjin-Hebei Urban Agglomeration using DMSP/OLS nighttime light data [J]. Geographical Research, 2018, 37(05): 898-909.
[19] Li F, Wei A X, Mi X N, et al. An approach of GDP spatialization in Hebei province using NPP-VIIRS nighttime light data [J]. Journal of Xingyang Normal University Natural Science Edition, 2016, 29(01): 152-156.
[20] He, C., et al., The urbanization process of Bohai Rim in the 1990s by using DMSP/OLS data. Journal of Geographical Sciences, 2006. 16(2): p. 174-182.
[21] Milesi, C., et al., Assessing the impact of urban land development on net primary productivity in the southeastern United States. Remote Sensing of Environment, 2003. 86(3): p. 401-410.
[22] Xu X Q, Zhou Y X, Ning Y M. Urban Geography. Beijing: Higher Education Press, 2001.
[23] Gu C L, Pang H F. Study on spatial relations of Chinese urban system: Gravity model approach [J]. Geographical Research, 2008(01): 1-12.
[24] Dong Q, Liu H Z, Liu J Z, et al. The spatial structure of urban agglomerations system in China based on space interaction [J]. Economic Geography, 2010, 30(06): 926-932.