Urbanization Process Monitoring in Northwest China based on DMSP/OLS Nighttime Light Data

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Abstract. In recent years, the DMSP/OLS nighttime light data have been widely applied to various fields such as monitoring and evaluation of urbanization, estimation of social economy, economical environment and health effects, hazards analysis, and fisheries research. The general urbanized level in China has rapidly developed since the 1990s, and the cities in northwest China, which were important population centres of the ancient silk road, have also been developed in a high speed thanks to China's national strategy of Western Development. Given the Xinjiang autonomous region as a core area of One Belt and One Road, it is very necessary to study the urbanization processes and changes of its urban system and the whole northwest region of China. In this paper, we extracted built-up areas of the cities in northwest China in 1992, 1997, 2002, 2007, and 2012, evaluated urban expansion and spatial pattern through appropriate indexes, and also quantitatively analyzed the urbanized level of each city. The results showed that the cities in northwest China generally presented high strong and rapid expansion, but there were some large differences among cities. Urban expansion forms alternate with exterior expansion and interior filling, in general, the cities externally expanded after 2002 and internally filled before 2002, meanwhile, there were a high positive correlation between urban built-up areas and population growth in Xinjiang autonomous.

1. Introduction
In order to promote globalized socio-economic development deeply, China presented a new international cooperation initiative, i.e., One Belt and One Road (OBOR), which promotes the trade relations between different countries and their urbanization development along the OBOR, and nowadays, it is widely responded and supported by the countries of the OBOR[1,2]. City serves as a complex and integrated object and its urbanization reflected the mankind activities and effects synthetically also contains an abundant meaning, including various factors as land,
economy, population and so on. The monitoring of urbanization process is the premise to regulate every aspect in a city, and it is also the realistic basis for urban planning and making sustainable development strategy. Since the industrial revolution taking place in the 18th century, global urbanization rate has maintained a rapid growth. Today, there are more than 50% population living in cities around the world[3], and the increasing number of cities has contributed to the regional economic growth as well. At the same time, China’s urbanization process also has entered a stage of rapid development since the 1990s, and its rural population is gradually turning to the city population[4]. Along with the implementation of the OBOR, urbanization along the OBOR will have a big jump. Faced with the rapid development of urbanization, it is an urgent and important problem to monitor the urbanization process in a quick and effective method among a wide range, and to study the urban expansion modes, the spatial pattern and economic culture.

DMSP/OLS nighttime light data recording the night light levels in worldwide is acquired at night by Operational Linescan System (OLS) sensor in American defense meteorological satellite program (DMSP). Nighttime light signal can be enhanced thanks to its unique photomultiplier tube (PMT), so it was designed to observe the changes of night clouds at beginning, and then it is also used to monitor the fire points of cities, fish boats, gas combustions, etc. At present, the DMSP/OLS nighttime light data have been widely applied in various fields, such as economic evaluation[5, 6, 7], population estimation[8, 9], and research of urbanization expansion[10, 11, 12]. And their results show that the nighttime light data is a good embodiment for human activities and the comprehensive effects, that is to say, it can better characterize the urban socio-economic conditions, population density, population growth rate, urban expansion, etc. In the studies of urbanization, there are researches on extraction of urban scope, for example the research of Mi et al.[14], by consulting MODIS land cover product, they set a float threshold and extracted the central urban area; there also has some researches on spatial patterns, for instance, Wu et al.[16] extracted Zhengzhou’s built-up area and analyzed its expansion intensity and direction features based on DMSP/OLS nighttime light data, and Zhang et al.[15] also used this data to study the spatial expansion in new first-tier cities.

In this paper, based on the DMSP/OLS nighttime light data in 1992, 1997, 2002, 2007 and 2012, we selected the expansion speed, expansion intensity, shape index and compactness index as our evaluation indexes referencing to Mi et al.’s urban extraction method, and then analyzed the urbanization process of northwest China in a long time series. Acting as important centers of the ancient silk road, the cities’ urbanization levels in northwest China had been improved significantly. Given Xinjiang as the core area in the OBOR, it was very necessary to study the urbanization process and urban system evolution in this region as well as in the whole northwest China.

2. Data and study area

2.1 Data

DMSP/OLS nighttime light data was provided by National Geophysical Data Center under National Oceanic and Atmospheric Administration, and acquired in local 20:30 to 21:30[13]. The OLS sensor with total image breadth in 3000km and sampling distance in 0.55km, includes 2 channels, that is visible light (VNIR, 0.4~1.0um) and thermal infrared (TIR, 10-13UM). This study selected the DMSP/OLS nighttime stable light data in 1992(F-10), 1997(F-12/F-14), 2002(F-12/F-14), 2007(F-12/F-14), 2012(F-12/F-14),...
2007(F-15/F-16) and 2012(F-18) as a basis to research. This data with 0.008333 ° spatial resolution and 0~63 gray level belongs to visible light channel, and it mainly in cities, towns, and other places with stable light, which can eliminate fires and other transient events caused by flammable gas[14]. Considering the data in 1997, 2002, 2007 were all made up by two satellites, so we adopted average pixel value of two images as the subsequent analysis basis.

2.2 Study area
In this paper, we mainly studied urbanization processes of large and medium cities in northwest China (including Shanxi, Gansu, Ningxia, Qinghai and Xinjiang) (fig.1) in recent 20 years.

![Fig.1 Study area](image)

Cites with rapid development and in a large scale in recent years were selected as the major study regions, including Urumchi, Shihezi, Kuitun, Kramay, Hami, Xi’ning, Jiayuguan, Jinchang, Lanzhou, Yinchuan, Shizuishan, Xi’an and Hanzhong. Most of these cities are important centers in the ancient silk road, and once had prosperous histories, even in recent times, they also played important roles in the OBOR, and are the support cities in international trade.

3. Study method
Urbanization process is the procedure of economic and social structure evolution in a city during a period time, which has diversely measured indexes and generally can be embodied as a change in spatial and temporal scale. In order to study urbanization processes and analyze the changes of population and economy in northwest China comprehensively and exactly, we firstly adopted Mi et al.’s method to extract the urban scope, and then calculated the northwest cities’ expansion speed, expansion intensity, shape index and compactness index. Based on these results, we finally analyzed each city’s spatial expansion law and evolution process quantitatively, and revealed the changes mechanisms in its economy and social structure, that is to say, analyzed the northwest cities’ urbanization tendency with a long time series data.

3.1 Analysis of urban expansion
1) Expansion Speed
Expansion speed shows the expansion speed of urban during the study period, and can reveal the
expansion tendency and whole scale of urban[15]. Bigger expansion speed presents the bigger annual growth rate of urban area. Expansion speed can be calculated as follows:

\[ AGA = \frac{U_{A(n+i)} - U_{Ai}}{n} \]  

(1)

Where \( AGA \) = expansion speed, \( U_{A(n+i)} \) = the area in the \((n+i)_{th}\) year, \( U_{Ai} \) = the area in the \(i_{th}\) year, and \( n \) = the time interval.

2) Expansion Intensity

Expansion intensity shows the expansion area in urban occupied percentage of total area during certain time interval, and it reveals growth rate of built-up area[16], which also can analyze the expansion intensity, speed and tendency of built-up area at different times[17]. It can be calculated as follows:

\[ I = \frac{U_{A(n+i)} - U_{Ai}}{U_{Ai}} \times \frac{1}{T} \times 100\% \]  

(2)

Where \( I \) = expansion intensity, \( U_{A(n+i)} \) = the area in the \((n+i)_{th}\) year, \( U_{Ai} \) = the area in the \(i_{th}\) year, and \( T \) = the time interval.

3.2 Analysis of urban spatial pattern

1) Shape Index

Urban shape index is defined as the ratio between the area and square perimeter of built-up region, and it shows the shape feature of urban spatial exterior outline. With a bigger index, it shows that the shape of built-up area tends to roundness, conversely, it will tend to strip. It can be calculated as follows:

\[ S = \frac{4A}{P^2} \]  

(3)

Where \( S \) = shape index, \( A \) = built-up area, and \( P \) = the square along its exterior outline.

2) Compactness Index

Compactness index is a significant index to reflect urban spatial form, and it shows the aggregation extent of urban space. This index can quantificationally analyze urban space structure, and the bigger value shows the more compact structure, otherwise, the more loose structure. It can be calculated as follows:

\[ BCI = \frac{2\sqrt{\pi A}}{P} \]  

(4)

Where \( BCI \) = shape index, \( A \) = built-up area, and \( P \) = the square along its exterior outline.

3.3 Correlation analysis of population and urban built-up area

Urban population is a significantly measured index to urbanization, which has a great influence on the development of economy and society and the utilization of resources. Positive correlation in urban population and built-up area is bigger showing that it has a more close relationship between them. On
the contrary, negative correlation is bigger revealing that the urban population reduces along with the urban expansion, that it is to say, the population is falling, and then we can infer that the city has some changes, for example the change of its function. Certainly, urban population stops growing along with urban expansion when the correlation index is 0. It can be calculated as follows:

\[
 r = \frac{\sum_{i=1}^{n}(P_i - \bar{P})(A_i - \bar{A})}{\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2} \sqrt{\sum_{i=1}^{n}(A_i - \bar{A})^2}}
\]

(5)

Where \( P_i \) = urban population in the \( i^{th} \) year, \( \bar{P} \) = the average urban population, \( A_i \) = built-up area in the \( i^{th} \) year, and \( \bar{A} \) = the average built-up area.

4. Results and discussion

4.1 Analysis of urban expansion

We extracted the built-up areas scope of 13 significant cities in 1992, 1997, 2002, 2007 and 2012 based on DMSP/OLS nighttime light data (fig. 2), and calculated the built-up areas (table 1). Through analyzing the extraction results and counting the geometric information, we calculated the expansion speed (fig. 3(a)) and expansion intensity(fig. 3(b)).

(1) According to fig. 2 and table 1, cities had the largest built-up areas from 2007 to 2012. In these years, the built-up areas, they were even beyond 1000 km² in Xi’an and Urumchi, and between 400-600 km² in Lanzhou, Yinchuan and Kramay, but below 300 km² in the rest cities. We also can get a conclusion from the fig. 2 that the built-up areas in provincial capital and autonomous capital was the largest, especially in Xian and Urumchi, where area growth was high on the list of the whole cities.

(2) According to fig. 3(a), the total expansion speed in all cities reached 650 km²/a from 2007 to 2012, and Xi’an and Urumchi had the highest values. In view of expansion speed from 1992 to 2012, Xi’an
had the most prominent character among all cities, especially from 1997 to 2002 and from 2007 to 2012, and Urumchi took the second place.

Table 1. Built-up area of each city from 1992 to 2012 (km²)

| year | 1992  | 1997  | 2002  | 2007  | 2012  |
|------|-------|-------|-------|-------|-------|
| Urumchi | 287.91 | 359.21 | 374.57 | 470.99 | 1152.64 |
| Shihezi | 55.13  | 56.33  | 94.67  | 107.9  | 283.05 |
| Kuitun  | 34.8   | 62.38  | 115.18 | 122.38 | 312   |
| Kramay  | 134.94 | 101.77 | 166.82 | 271.05 | 433.87 |
| Hami    | 58.72  | 91.34  | 66.54  | 64.67  | 280.56 |
| Xin'ning| 53.38  | 80.07  | 114.22 | 144.12 | 275.46 |
| Jiayuguan | 15.62 | 23.43  | 51.32  | 65.82  | 133.86 |
| Jinchang | 19.71  | 16.43  | 21.8   | 35.05  | 120.47 |
| Lanzhou | 154.82 | 215.23 | 271.44 | 292.65 | 459.11 |
| Yinchuan | 67.87 | 77.71  | 147.77 | 276.97 | 569.33 |
| Shizuishan | 40.8 | 48.51  | 60.64  | 83.79  | 135.62 |
| Xi'an   | 265.37 | 309.93 | 572.22 | 620.91 | 1600.41 |
| Hanzhong | 11.24  | 16.35  | 26.58  | 36.8   | 104.26 |

Expansion speed, which is related to the urban scale in early time, is an absolute figure. Generally, city with a certain scale is easier to expand when it gets an advantage orientation. Oppositely, thanks to the limited scale of population and economy in small cities, it is also limited for their absolute expansion scale in a short time. That is to say, expansion intensity can give good explanations to these phenomena.

(3) We get a further analysis on urban expansion intensity. As shown in fig. 3(b), cities with the highest expansion intensity were Kuitun, Jiayuguan, Yinchuan and Hami in 1992-1997, 1997-2002, 2002-2007 and 2007-2012 respectively. Although these cities had limited urban scale in early time, their built-up areas expansion were more positive and has higher intensity, especially in Hami, its expansion intensity is more than 70% from 2007 to 2012. The top four cities in expansion intensity over the whole 20 years were Hanzhong, Kuitun, Jiayuguan and Yinchuan, whose expansion intensity with little difference in each other were approach to 40%, and their expansion intensity were much bigger than the other cities’.

(4) Taking a comprehensive analysis on expansion speed and intensity, we can draw a conclusion that Xi’an, Urumchi and Yinchuan, whose expansion speed and intensity were higher than other cities’, had the fastest expansion. Meanwhile, these cities with faster expansion had a common feature because of the rapid urbanization process, there was a mergence between municipal district and its surrounding counties’ centers, which caused the increase of built-up area to some degree.

The northwest region located in the underdeveloped area of China presents an inconsistent development in economy and society, which leaded to the absonant urbanization level. Additionally, influenced by the landmark, location, policy and urban planning of every city in this region, the built-up areas showed significant differences in each city. However, along with the implement of the West Development strategy, the city in northwest region presented a good developmental tendency, and Xinjiang took the most remarkable progress, so its developmental level was relatively higher than
the other cities’. On the contrary, some cities’ expansive level were inferior to the others’ because of the poor location with many mountains, which led to the cities must distribute a shape of strip and restrict their development caused by the limited expansion space, for example Lanzhou.

On the whole, the cities in northwest China maintained high expansion speed and have a good development from 1992 to 2012.

a. Expansion speed
b. Expansion intensity

Fig. 3 Chart of expansion speed and expansion intensity

4.2 Analysis of spatial patterns of cities

Based on the extraction result of built-up areas, we selected the shape index and compactness index to evaluate the spatial pattern evolutions of cities, and the results are shown in fig.5.

a. Shape Index
b. Compactness Index

Fig.4 Chart of analysis of urban spatial patterns

(1) According to fig 4(a), the shape index of each city presents a constant change along with the time. Some of the shape indexes in partial cities increases overall and their exterior outlines tended to be rounded, which means that their shapes of built-up regions turned strip into round, such as Kuitun and Shihezi; inversely, some of other cities’ shape indexes decrease overall land their exterior outline tended to strip, which meant that their shapes of built-up regions became long and narrow, such as Lanzhou, Jiayuguan and Hanzhong; the rest cities’ shape indexes remain unchanged and these cities maintained their original shape.

(2) In view of the compactness index as shown in fig. 4 (b), except in a few cities, they increased in
general before 2002, but it presents a fluctuation after 2002 and finally becomes smaller. The reasons which caused this situation may be as follows. First, the urban scale has a big promotion than before, i.e., the larger urban scale and the faster expansion speed. In consequence, the cities with rapid expansion are mainly characterized by the externally sharp inflation and the suburbanization, which result in smaller compactness of exterior outline of cities. Second, because of the larger urban scale, the city is easier to be limited by the natural topography[18].

There are two forms of urban expansion, which are exterior expansion and interior filling. The expansion process of each city presents various characters, such as changing from large to small, varying from small to large or even revealing an alternant variation between large and small, and it showed that there are two expansion forms which appeared an alternative phenomenon in the process of urban expansion. In addition, the urban changes were mainly characterized by internal filling before 2002 while external expansion after 2002. What’s more, the fluctuations of compactness indexes in Lanzhou and Xi’ning remain stable and were smaller than the other provincial capitals’, while they kept fluctuant in Xi’an, Urumchi and Yinchuan, and the possible reason which resulted in this difference was the evenly urban expansion of Lanzhou and Xi’ning between exterior expansion and interior filling, inversely, the other cities were only outstanding on one aspect.

(3) Given the above factors, we can discover that the shape index and compactness index of each city in Xinjiang show more ideal results, which imply a more balanced development and higher spatial compactness in these cities. Meanwhile, these cities will have better opportunities for progress along with the development of Xinjiang acting as the core area in the OBOR. And the others, severing as the important cities in this line, will benefit from its leading effects, complete their industrial transformation and the establishment of emerging industries, and finally win a faster and better development.

4.3 Correlation analysis between population and built-up area

Severing as the core area in the OBOR and also playing an important role in the development of northwest China, we chose Xinjiang as the crucial region in our study and then selected its five key cities as the research objects for analyzing correlation between population and built-up areas, that are Urumchi, Shihezi, Kuitun, Kramay and Hami.

Based on the formula (5), we calculated the correlation coefficient between population and built-up areas in 1992, 1997, 2002, 2007 and 2012, and the results of Urumchi, Shihezi, Kuitun, Kramay and Hami are 0.833, 0.561, 0.710, 0.544 and 0.668 respectively (fig.5). According to the results, we can conclude that the population and built-up areas in Urumchi have a strongest correlation and the other cities’ also have a good one.

The results showed that the population growth in every city relies on its urban expansion, especially in Urumchi; but the correlation indexes of Shihezi and Kramay were relatively low, which revealed that their urban expansion speed were faster than the population growth. Although the lower-density population will form a well-regulated city, it will restrict urban development as well. In conclusion, severing as the core area in the OBOR, it was a crucial issue for Xinjiang to coordinate the relationship between urban population and expansion.
5. Conclusion

Based on the DMSP/OLS nighttime data, this study monitored the urbanization process of cities in northwest China, and measured their urbanization level through some evaluation indexes. In addition, we mainly analyzed the correlation between population and built-up areas for cities in Xinjiang.

1) According to the expansion speed and expansion intensity of each city in 1992-1997, 1997-2002, 2002-2007 and 2007-2012, we found that the cities in northwest China generally maintained a high expansion speed, but there were also great differences among them. Taking a comprehensive analysis on expansion speed and intensity, we can draw a conclusion that Xi’an, Urumchi and Yinchuan had the fastest expansion. However, because of restrict development caused by the poor location with many mountains, Lanzhou presented a lower expansion than other cities.

2) By using the shape index and compactness index to analyze the cities’ spatial patterns in 1992, 1997, 2002, 2007 and 2012, we found that the exterior outlines of Kuitun and Shihzei tend to be round while exterior outlines of Lanzhou, Jiayuguan and Hanzhong tended to be strip, and the other cities’ remained unchanged. There was a periodic change between exterior expansion and interior filling from 1992 to 2012, i.e., the cities externally expanded after 2002 and internally filled before 2002. On the whole, Xinjiang with balanced progress in every aspect showed an ideally developmental tendency. At the same time, the other cities also have good development in the future.

3) Electing five key cities in Xinjiang to analyze the correlation between its population and built-up areas, we drew a conclusion that the population and built-up areas had a strong correlation in every city. The highest correlation index of Urumchi was 0.833 while it was lowest in Kramay with the value of 0.544.

The following questions should be given a further discussion: ① we only adopted an uniform analysis for all cities, however, the urbanization processes in different scale and different region cities present diverse characteristics and driving mechanism, which needs a following research; ② we used Mi et al.’s urban extraction method in this paper to finish our research, and the result accuracy by employing this method was 80%, which was proved to be feasible; all indexes used in this study were calculated based on the vectorial data, which would cause a negative urbanization to some degree, because there were some loss of information when conversing the raster data to vector data. In order to improve the accuracy of results, we will employ the pixel statistics method in the future research;
The results showed that one reason, which leaded to the slower development of Lanzhou than the other provincial capitals, was the narrow topography, so it is important for our further works to discuss the topography factors when analyzing the urbanization process.

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