Measuring urban sprawl in China by night time light images

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Abstract. In the process of urbanization, a phenomenon called "urban sprawl" usually occurs. This phenomenon may exaggerated the negative effects of urbanization on environment, public and social health, energy efficiency, and maintenance of farmland. Therefore, the understanding of this phenomenon is urgently required for us to achieve sustainable development. This study proposed a group of night time lights (NTL) indicators of urban sprawl, which intend to use the distribution of lightness to quantify urban sprawl. These measures are proved to be efficient in describing urban sprawl. In addition, they are consistent and easy calculating, making comparison analysis easy to be done. These indicators are used to study urban sprawl in China during the year 2000 to 2010, the results show that in the last ten years, metropolitan areas in the northern part of China have undergone a more sprawl-like urban growth compared with other parts of China.

1. Introduction
In the process of urbanization, a phenomenon called "urban sprawl" usually occurs. Urban sprawl refers to spontaneous urban development pattern, which is scattered, fragmented, and with low density. This phenomenon may be caused by fragmented local government, poor planning, or exclusionary zoning. Many previous studies that urban sprawl has exaggerated the negative effects of urbanization on environment, public and social health, energy efficiency, and maintenance of farmland. A profound understanding of this phenomenon is therefore highly demanded.

Therefore, the definition of sprawl and the indicators selected to measure it are mainly based on the perspective and objectives of a specific study. In this study, we refer to urban sprawl as an unplanned, fragmented, low-density process of urban growth. Moreover, the urban sprawl here should be deemed a phenomenon to describe, rather than to define [1, 2]. In other words, the measures of urban sprawl should focus on depicting this phenomenon from some specific aspects based on the research problem rather than trying to find a comprehensive measuring method. Furthermore, relative measurement, instead of absolute measurement should be adopted to study urban sprawl, which means that the degree of sprawl is assessed based on the comparison analysis among different regions (relatively more sprawl-like, or less sprawl-like), rather than giving an absolute black and white definition to this phenomenon(sprawled or not sprawled).

The previous studies of ‘urban sprawl’ have focused primarily on the US [3, 4], where new growth has often been discontinuous and extensive in the past few years; very few studies have focused on China. This research gap may be attributed to the usually high population density of urban areas in China, causing people to ignore the occurrence and possible effects of urban sprawl. However, the dramatic expansion of urban land in the last few decades has been accompanied by serious urban
sprawl. As proven by several previous studies, the urban land in China has increased exponentially to become more than two times its size in the last twenty years, and some places are very inefficiently developed. Therefore, a comprehensive understanding of urban sprawl in China, which may raise the concern of making better policy and plan on urban land development, is required.

Therefore, this study aims to introduce a set of night time lights measures of urban sprawl, which are consistent and easy to measure. Also, the urban sprawl in China is scrutinized based on the indicators introduced in this study.

2. Data and methodology

2.1. Study Areas
To measure the degree of urban sprawl, two difficulties typically arise. The first is how to select the appropriate scale to measure the phenomenon. The second is how to identify the spatial extent of "urban area".

In previous studies, a scale to study urban sprawl is usually selected based on the objective of the research and the limitation of datasets. In this study, the metropolitan scale is used, because NTL imagery has coarse resolution (30 arc), and is thus inappropriate for the analysis at small scales, such as the local and city scales. Moreover, lit-up areas in the NTL imagery can reveal the extent of various metropolitan areas, which are composed of one or several cities, because the lit-up areas of spatially related cities are always continuous.

Second, previous research often adopts political boundaries to delineate the spatial extents of metropolitan areas. For instance, in the "Report on Development of Metropolitan Areas in China in 2010" [5], 23 metropolitan areas in China have been determined based on the economic and political relationships among cities, and the extents are delineated by the administrative boundaries of these cities. However, this approach appears to be an unreliable means of delineating the metropolitan area, because it may overestimate or underestimate actual urban extent. Meanwhile, the extracted extents are incomparable among nations[6], thus leading difficulty to conduct a comparative analysis. Therefore, we propose a more reasonable and consistent strategy to delineate the extent of the metropolitan areas using NTL images.

In this study, the extents of metropolitan areas are extracted from NTL imagery based on the continuous lit-up areas. First, dim lights (pixels with a DN value lower than 12), which are more probably emitted by rural areas with sparse population, are excluded. Each continuously lit-up area is then deemed as an individual urban patch, and urban patches larger than 1000 km² are identified as metropolitan areas. Moreover, urban patches within a distance of 10 km² from these metropolitans are merged to them, given that these small urban patches may be largely influenced by the metropolitan areas and are thus a part of them. We do not consider other small urban patches outside the metropolitan areas in this research, because they are not included in any metropolitan area. Moreover, to divide the urban area into city center and suburban area, we set a single threshold of DN value 54 to discriminate urban and suburban areas, this threshold is obtained by overlaying the TM derived urban center with NTL images.

2.2. NTL Imagery
In this study, we use the distribution of DN value in NTL imagery to describe urban sprawl, because brightness is highly related to urban activities on the Earth's surface[7,8]. In many previous studies, the summed lights and the lit-up areas for a region on NTL imagery have been proven to be highly related to various indicators of urbanization, including economic activities, population and area of urban land. Furthermore, the brightness of each pixel has also been proven to represent population density to some extent and has thus been used as an assistive data set for mapping the world population density in the Global Rural Urban Mapping Project (GRUMP)[9]. Therefore, describing the distribution of urban development using NTL imagery is reasonable. The NTL imagery is obtained from the data sharing Infrastructure of Earth System Science Web site (http://www.geodata.cn/, assessed on 15 May, 2014).
2.3. Temporal Measures of Urban Sprawl

We define sprawl like urban growth as a process during which the extents of the urban areas expand significantly outward in a specific period of time. Meanwhile, the expanded regions have relatively low intensity of development, and insignificant urban development has occurred to fill the existing urban or sub-urban area. Table 1 lists the indicators for the three dimensions that are considered to describe this process, and their NTL-based indicators are explained as follows.

2.3.1. Expansion of urban extent

The expansion of urban extent measures the degree to which the whole metropolitan area expands its urban land. The NTL-based indicator for this dimension is calculated by:

$$EU = \frac{(A_{t2} - A_{t1})}{A_{t1}}$$ (1)

where $EU$ refers to the expansion of urban extent, and $A_t$ represents the area of the metropolitan area at the time point $t$. $t1$ represents the previous point of time, and $t2$ represents the latter point of time.

A very high $EU$ value indicates that the metropolitan area has significantly expanded its urban land. However, a sprawl like urban growth cannot be signified only based on a high value of $EU$. The intensity of expansion should also be further examined to verify the efficiency of such development.

2.3.2. Intensity of Expansion

The intensity of expansion tends to measure the intensity of development at places that were originally rural lands, but were later transformed to parts of urban or suburban areas. As illustrated in Fig. 1, the blue regions are the expanded regions of metropolitan areas from year 2000 to year 2010.

The indicator of this dimension is obtained by calculating the mean $DN$ value of expanded regions at time point $t2$. A low value may imply that, the expanded regions are not efficiently developed with low intensity, that is, the regions exhibit more sprawl-like urban growth.

![Figure 1. The change of urban extent during 2000 to 2010 in Beijing-Tianjin-Tangshan area.](image)
2.3.3. Infilling of suburban area This dimension measures the degree to which development is concentrated in the already existing suburban area. A compact development should generally focus on efficiently utilizing the already existing urban land, rather than developing new urban land. Therefore, much infilling development in suburban area may indicate a less sprawl like urban growth.

The indicator for this dimension is obtained by calculating the change of intensity (intensity is represented by mean DN value on NTL imagery) in the suburban area. A higher value of intensity change in the region may indicate that significant development has occurred in the already existing suburban region, and a less sprawl-like growth can be signified.

| Dimension          | Definition                                                                 | Operationalization                                      | Measure of sprawl                               |
|--------------------|-----------------------------------------------------------------------------|--------------------------------------------------------|-------------------------------------------------|
| Expansion of urban extent | The degree to which the urban extent has been expanded                     | EU=($A_{t2}$-$A_{t1}$)/$A_{t1}$                        | Higher value signifies more sprawl like urban growth |
| Intensity of expansion | The degree to which the expanded region are intensely developed            | Mean DN value in $t2$, in the expanded urban areas (IE) | Higher value signifies less sprawl like urban growth |
| Infilling of suburban | The degree to which the original suburban areas are developed              | Change of Mean DN value during $t1$ and $t2$, in places where are suburban area in both $t1$ and $t2$ (INS) | Higher value signifies less sprawl like urban growth |

2.4. Analysis Method

The urban sprawl in China is then examined based on the measures introduced above. The analysis is processed in three steps.

The temporal measures of urban sprawl are used to scrutinize the historical trend of urban sprawl during years 2000 to 2010. The Z-score for these indicators are first derived, and the negative number is calculated for EU for consistency with the other two indicators. The summed value of all these Z-scores is then obtained to represents the degree to which the metropolitan area is developed in a sprawled manner. Finally we use a distribution map to examine and compare the trend of sprawl like growth in the last decade in various metropolitan areas of China.

3. Result and interpretation

3.1. Metropolitan Areas in China

The metropolitan areas in China are extracted based on the methodology introduced in Subsection 7.2.1. The metropolitan extents extracted from NTL imagery successfully include urban lands that are spatially closed and related to one another. Moreover, compared with the extent of BTT metropolitan areas used in previous studies, the NTL-derived metropolitan extents can delineate the densely urbanized area more accurately, and can separate urban areas that are not spatially continuous. Based on this method, we obtained 50 metropolitan areas, including two with areas of over 10,000km², eight with areas between 5,000 and 10,000 km², 14 with areas of approximately 2,000 km², and 23 with area between 1000 km² to 2000 km².

3.2. Correlation relationship of measures

As shown in Table 2, correlation is weak among these indicators, given that all pairs of indicators show low r value. This result may indicate that these three measures are independent in measuring sprawl. Moreover, the area of the metropolitan area shows a weak relationship with all other indicators, implying that these indicators are also independent of size.
### Table 2. Correlation analysis among temporal measures of sprawl

| Correlation r | EU    | IE  | INS | Area |
|---------------|-------|-----|-----|------|
| EU            | 1     | .559** | -0.046 | -0.44 |
| IE            | 1     | .485** | -0.107 | 0.56  |
| INS           | 1     |     | 0.56  |      |
| Area          | 1     |     |      |      |

**. Correlation is significant at the 0.01 level (2-tailed), N=50

3.3. Urban Sprawl in China

Fig. 2 depicts the map of these measures for 50 metropolitan areas in China. In the northern part of China, the metropolitan areas have undergone a more sprawl like urban growth in the last 10 years compared with other parts of China.

![Figure 2. Urban sprawl during year 2000 to 2010 by temporal indicators](image)

4. Discussion and conclusion

This study proposed a group of NTL indicators of urban sprawl, which intend to use the distribution of DN values to quantify urban sprawl. These NTL indicators can provide an overall idea of the level of urban sprawl, and are very easy to be calculated, especially for a group of large regions. These measures are proved to be efficient in describing urban sprawl. In addition, they are consistent and easy calculating, making comparison analysis easy to be done. These indicators are used to study urban sprawl in China during the year 2000 to 2010, the results show that in the last ten years,
metropolitan areas in the northern part of China have undergone a more sprawl-like urban growth compared with other parts of China.

However, NTL indicators have several limitations. First, the saturation of NTL may influence the analysis results, especially for densely developed urban areas. Second, the response of NTL to urban growth may vary across regions and years, and this variation causes bias in the analysis results. Third, the NTL indicators of urban sprawl cannot comprehensively reflect urban sprawl, such as the mixed use of urban functions. Therefore, these indicators are better combined with other datasets in future studies, to comprehensively understand urban sprawl.

Moreover, given that these indicators are calculated based on the distribution and changes in the DN value on the NTL imagery, more information should be obtained on how these DN values are correlated to urban activities on the earth surface when appropriate datasets are accessible. Moreover, although we have discovered the regional discrepancy in the urban sprawl of various metropolitan areas in China, the underlying causes are still unknown. Therefore, various socio-economic factors and government policies should be studied to identify these reasons. Finally, the manner by which urban sprawl affects the lives of the people should be further explored.

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