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Letter

Dynamics of Urbanization Levels in China from 1992 to 2012: Perspective from DMSP/OLS Nighttime Light Data

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Abstract: The authenticity and reliability of urbanization levels measured by different indicators in China have not reached a consensus, which may impede our understanding of the process of urbanization and its impacts on the environment. The objective of this study was to describe a reliable method of estimating urbanization level based on the Operational Line-scan System (OLS) on the Defense Meteorological Satellite Program (DMSP) nighttime light data and to analyze the dynamics of urbanization levels in China from 1992 to 2012. We calculated the comprehensive urbanization level at the national, provincial, and county scales using a compounded night light index (CNLI) and compared the change rate of CNLI with those of the other two conventional urbanization level indicators, proportion of the nonagricultural population and proportion of built-up area. Our results showed that CNLI derived from the DMSP/OLS data set provided a relatively reliable and accurate measure of the comprehensive urbanization level in China. During the last two decades, China has experienced continued and rapid urbanization with large regional variations. The CNLI increased 3.12 times, from 1.72×10^{-3} to 7.09×10^{-3}. The annual increases of CNLI in eastern provinces were much faster than those in western provinces. In addition, we found that the rates of change in these three indicators were consistent for most provinces with the exception of the four municipalities (Beijing, Tianjin, Shanghai, and Chongqing) and a few eastern coastal provinces (Jiangsu, Zhejiang, Fujian, and Guangdong). Because the imbalance among population growth, urban expansion and socioeconomic development may affect cities' sustainable development, we should pay more attention to these regions with large disparities between different indicators.

Keywords: urbanization level; DMSP/OLS; compounded night light index; multi-scale; China

1. Introduction

Urbanization level is an indicator that could be used for characterizing urbanization in terms of demographic dynamics, socioeconomic development and spatial expansion simultaneously. It is an important basis for evaluating the development stage [1], assessing the effects of urbanization on society and the environment [2,3], and formulating a regional development strategy [4]. Along with the rapid urbanization and dramatic economic growth in China from late 1978, some environmental problems, such as air pollution [5], water pollution [6], increase in greenhouse gas emissions [7], and enhanced urban heat islands [8], are increasing in many Chinese cities. Monitoring the dynamics of urbanization levels in China accurately and quickly plays a fundamental role in understanding the process of urbanization and evaluating its environmental influence [9].

However, the authenticity and reliability of China's urbanization level has not reached a consensus [10–12]. For example, according to the National Bureau of Statistics, China's urbanization level was 36.22% in 2000, but Shen [10] claimed that it was actually 37.04% in the same year. The difference in urban population between these two studies was 3.74×10^6. The difference was due to the underreporting of urban populations and changes in the definitions of urban populations in China. The main reason for the controversy is because researchers often simply use a single indicator (*i.e.*, a population index or a land index) to measure the urbanization level, but both of them have deficiencies in terms of comparability and comprehensiveness [13]. For instance, the population index lacks continuity and temporal comparability because the criteria used to define "urban" and "urban population" have changed several times for different censuses in China [14,15]. Specifically, in the fifth national census in 2000, the urban population accounted for 36.09% of the total population, but the percentage would change to 31.39% if we were to use the criteria applied in 1990 [4]. Also, the land index derived from different data sources is incomparable. For example, according to the National Bureau of Statistics of China [16], the built-up area in China increased from 20,465 km^2 in 1995 to 32,520 km^2 in 2005. However, according to the land use/cover data sets produced by the Chinese Academy of Sciences, the built-up area increased from 31,756 km^2 to 43,852 km^2 during this period [17]. In addition, revealing the whole picture of the regional urbanization level is difficult if we just use a single index because urbanization is a complicated process involving economic, demographic, and societal changes [9]. Therefore, how to monitor and understand the dynamics of urbanization levels quickly and accurately remains a challenging problem in China.

An Operational Line-scan System (OLS) on the Defense Meteorological Satellite Program (DMSP) provided a valuable data source for elucidating the dynamics of China's urbanization [18–21]. This sensor can detect city lights, gas flares, and fires at night with a low-light detecting capability [22]. The DMSP/OLS dates back to the 1970s but was not widely noticed until 1992 when the images became available in digital format. In January 2010, the National Oceanic and Atmospheric Administration (NOAA)/National Geophysical Data Center (NGDC) published the Version 4 DMSP-OLS Nighttime Lights Time Series (V4DNLTS) data set. The files in this data set came from sensors with identical onboard design and continuous space platform, providing a unique and valuable resource for monitoring the long-term dynamics of urbanization [9]. More importantly, the DMSP/OLS nighttime light images have been utilized in several studies for quantitatively estimating and mapping socioeconomic activities related to urbanization processes from regional to global scales [23]. For example, Sutton *et al.* [24] estimated the global human population using the statistical relationship between nighttime lighted area and urban population, while Doll *et al.* [25] created regional disaggregated maps of the gross domestic product (GDP) based upon the relationships between nighttime radiance data and the GDP. Also, Zhang *et al.* [26] adopted multi-temporal DMSP/OLS nighttime lights data to estimate regional and global urban growth based on a linear correlation between night light brightness and the urban population. However, using DMSP/OLS data, there were few studies focused on monitoring the dynamics of urbanization level for the last two decades at multiple scales in China, especially the dynamics after 2000, and at the county scale.

The objective of this study was to describe a reliable method of estimating urbanization level based on DMSP/OLS nighttime light data and to analyze the dynamics of urbanization levels in China from 1992 to 2012. First, we calculated the compound night light index (CNLI) [18], which reflects the regional comprehensive urbanization level. Second, we analyzed the dynamics of urbanization levels at national, provincial, and county scales based on the CNLI. Last, we compared the rate of change in CNLI with that in two other conventional urbanization level indicators, the proportion of the nonagricultural population (PNP) and the proportion of built-up area (PBA), to explore the coordination among these three indicators.

2. Data

Three types of data were used in this research. The first type is nighttime stable light (NSL) data from 1992 to 2012 in the V4DNLTS data set. The data were obtained from the NGDC Web site and included data from six DMSP satellites: F10, F12, F14, F15, F16, and F18 [27]. Annual composites were produced for each satellite using the highest-quality data collected. Several constraints were considered to identify the best-quality nighttime light data to produce the composite [22]. For example, ephemeral events such as wildfires were discarded. In the annual composites, the Digital Number (DN) value of each pixel was the average of the visible-band DN values of lights from urban areas and other sites with persistent lighting. Background noises in the composite were identified and replaced with values of zero, and the final DN values for lit pixels ranged from 1 to 63. Data were in 30 arcseconds (approximately 1 km at the equator and 0.8 km at 40°N), spanning −180° to 180° in longitude and −65° to 75° in latitude. After obtaining the global NSL data for 1992–2012, NSL data were extracted according to the Chinese administrative boundary. Last, data were projected using the Lambert Azimuthal Equal Area projection and resampled to a pixel size of 1 km.

Due to the differences between sensors, differences in crossing time between satellites, and the degradation of sensors, these NSL data collected by sensors onboard different satellites could significantly differ (*i.e.*, discrepancies could exist in DN values between two satellites for the same year, as well as abnormal fluctuations in DN values from the same satellite for different years), even if no real changes occurred on the ground [28]. Therefore, these data cannot be used directly to extract the dynamics of urbanization levels in China [9]. To reduce yearly variations among sensors, we used a systematic correction method proposed by Liu *et al.* [28] to correct multiyear, multi-satellite NSL data. This cross-calibration method achieved the goal of improving the continuity and comparability of NSL data based on three main steps: intercalibration, intra-annual composition and inter-annual series correction. The process of intercalibration was used to guarantee that DN values among different years and different satellites were comparable. The objective of intra-annual composition was to remove any intra-annual unstable lit pixels. The last step, inter-annual series correction, could reduce the inter-annual discrepancies of DN values to the minimum level. Then, to calculate the CNLI, we adopted the threshold technique developed by Liu *et al.* [28] to determine the optimal thresholds (Table 1) for extracting lighted urban areas in different regions of China (Equation (1)). For each economic region, optimal thresholds were determined for each period when the urban areas extracted using NSL data matched the ancillary data best (Table 1).

Table 1. Optimal thresholds for lighted urban area extraction in eight economic regions of China. Note: We divided China into eight economic regions: Northeast China (NEC), Northern Coastal China (NCC), Southern Coastal China (SCC), Eastern Coastal China (ECC), the Middle Reaches of the Yellow River (MRYLR), the Middle Reaches of the Yangtze River (MRYTR), Southwest China (SWC), and Northwest China (NWC). We determined the thresholds based on the method provided by Liu *et al*. [28]

Economic Region	Provinces in the Economic Region	Optimal Threshold				
		1992	1993–1997	1998–2002	2003–2007	2008–2012
NEC	Liaoning, Jilin, Heilongjiang	50	51	54	58	59
NCC	Beijing, Tianjin, Hebei, Shandong	51	56	57	61	59
SCC	Fujian, Guangdong, Hainan	61	62	63	61	61
ECC	Shanghai, Jiangsu, Zhejiang	50	54	58	59	59
MRYLR	Shaanxi, Shanxi, Henan, Inner Mongolia	49	56	54	59	59
MRYTR	Hubei, Hunan, Jiangxi, Anhui	41	42	42	52	51
SWC	Yunnan, Guizhou, Sichuan, Chongqing, Guangxi	40	44	46	58	57
NWC	Gansu, Qinghai, Ningxia, Tibet, Xinjiang	39	50	51	59	60

The second type of data is socioeconomic census data, including the nonagricultural population, production of secondary industry and tertiary industry (PST), and built-up area of each province and city. These data were obtained from the China Population and Employment Statistics Yearbook, China Statistical Yearbook, and China City Statistical Yearbook [29,30]. The third type is the GIS auxiliary data. The administrative boundaries for the provinces, cities, and counties in China at a scale of 1:4,000,000 were obtained from the National Geomatics Center of China [31]. The boundaries for the 23 urban agglomerations in China came from Fang *et al.* [32]. Our study focused only on Mainland China due to the lack of statistical data for Taiwan, Hong Kong, and Macao.

3. Methods

Our method for analyzing the dynamics of urbanization levels in China included two steps: calculating the CNLI index at the national, provincial, and county scales, and analyzing the dynamics of urbanization levels based on the annual increase in the CNLI.

3.1. Calculating the Compounded Night Light Index (CNLI)

We used the CNLI proposed by Zhuo *et al.* [18] to reflect the regional comprehensive urbanization level. The CNLI takes two parameters, night light brightness and lit urban areas, into account simultaneously. The former is closely correlated with urban population and economic scale [25,33], and the latter is closely correlated with urban area [34,35]. Therefore, changes in the CNLI can reflect the dynamics of urban population size, economic scale, and urban expansion simultaneously. We computed the CNLI at the national, provincial, and county scales using the following formula [18]:

$$CNLI = I \times S \tag{1}$$

where I is the average night light brightness of all lit pixels in a region. It can be described as follows:

$$I = \frac{1}{N_L \times DN_M} \times \sum_{i=P}^{DN_M} (DN_i \times n_i) \tag{2}$$

where DN_i is the DN value of the ith gray level, n_i is the number of lit pixels belonging to the ith gray level, P is the optimal threshold to extract the lighted urban area from the DMSP/OLS image (Table 1), DN_M is the maximum DN value, and N_L is the number of lit pixels with a DN value between P and DN_M.

S is the proportion of lit urban areas to the total area of a region. It can be described as follows:

$$S = \frac{Area_N}{Area} \tag{3}$$

where $Area_N$ is the area of lit urban areas in a region and $Area$ is the total area of the region.

3.2. Analyzing the Dynamics of Urbanization Levels

Because the spatiotemporal dynamics of urbanization levels appears to be significantly different at different scales [36], we examined it at the national, provincial, and county scales. We used the annual increase in the CNLI to reflect the dynamics of urbanization levels [17]:

$$U = \frac{CNLI^{t+n} - CNLI^{t}}{n} \tag{4}$$

where U is the annual increase in the $CNLI$, and $CNLI^{t+n}$ and $CNLI^{t}$ are the CNLI in the $t+n$th year and tth year, respectively.

3.3. Accuracy Assessment

We used the method proposed by Zhuo *et al.* [18] to evaluate the credibility of using the CNLI to monitor dynamics of the urbanization level in China. First, we calculated Composite Urbanization

Level Indices (CUI) by adding three types of census data, percentage of nonagricultural population, percentage of PST, and percentage of built-up area, with equal weights for 31 provinces and 157 cities in 1992, 1995, 2000, 2005, and 2008. Then, we established a regression equation between the CUI and CNLI. Last, we simulated the CUI in 2011 based on the regression equation, and we calculated the differences between the simulated CUI and the actual CUI from census data in 2011. The result showed that the CNLI was significantly correlated with the CUI at the national, provincial, and county scales in 1992, 1995, 2000, 2005, and 2008. The correlation coefficients were 0.96, 0.71, and 0.69, respectively, and the differences between simulated CUI and actual CUI in 2011 were 0.51%, 10.53%, and 12.26%, respectively, at the three scales (Table 2). Therefore, we believe that the dynamics of urbanization levels over the past two decades derived from DMSP/OLS NSL data were consistent with the actual conditions in China.

Table 2. Validation results between the compounded night light index (CNLI) and the composite urbanization level index (CUI).

Scale	Regression Equation	Correlation Coefficient	Difference between Simulated CUI and Actual CUI in 2011 (%)
National	$y = 1705.43x + 30.91$	0.96 ($p < 0.01$)	0.51
Provincial	$y = 90.52x + 36.23$	0.71 ($p < 0.01$)	10.53
County	$y = 72.81x + 43.22$	0.69 ($p < 0.01$)	12.26

4. Results

4.1. Dynamics of Urbanization Levels at the National Scale

The urbanization levels in China increased rapidly from 1992 to 2012 (Figure 1). The CNLI increased 3.12 times, from 1.72×10^{-3} to 7.09×10^{-3}, with an average annual growth rate of 7.34%. Furthermore, the rate of change in CNLI varied over time. Between 1992 and 1995, it exceeded the average annual growth rate slightly, with an annual growth rate of 10.59%. Then it slowed down during 1996–2000, with an annual growth rate equal to 2.90%. After 2000, it increased quickly, with an annual growth rate of 6.73%.

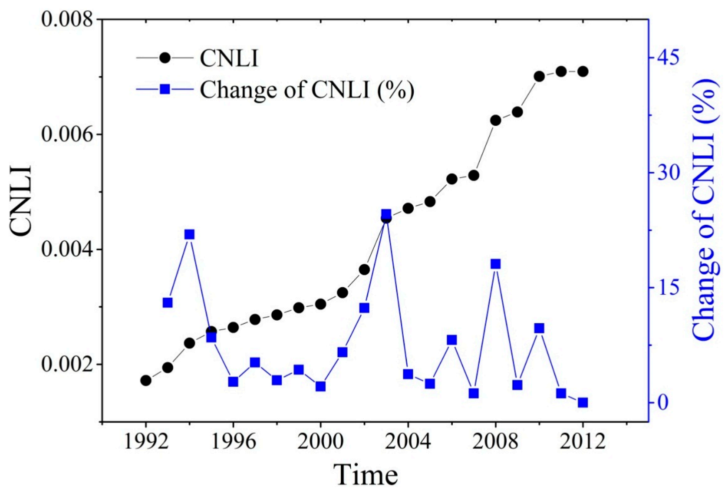

Figure 1. Dynamics of urbanization levels at the national scale from 1992 to 2012.

4.2. Dynamics of Urbanization Levels at the Provincial Scale

The rates of change in CNLI showed significant regional differences. The rates in eastern provinces were much faster than those in western provinces (Figure 2). The annual increase in the CNLI in Beijing, Shanghai, and Tianjin were the fastest, all above 5.0×10^{-3}, with the CNLI in 2012 was 2.92 times, 2.31 times and 1.82 times that in 1992. The annual increase in the CNLI in other eastern provinces, such as Zhejiang, Jiangsu, Shandong, and Guangdong, was between 1.0×10^{-3} and 5.0×10^{-3}, with the CNLI in 2012 was approximately 5.48–10.46 times that in 1992. In contrast, the annual increase in eight provinces in western China (e.g., Xinjiang and Tibet) was much less than in the aforementioned provinces, with an annual increase in the CNLI of less than 0.26×10^{-3}. It was slowest in Tibet, which was less than one-twentieth of the national average.

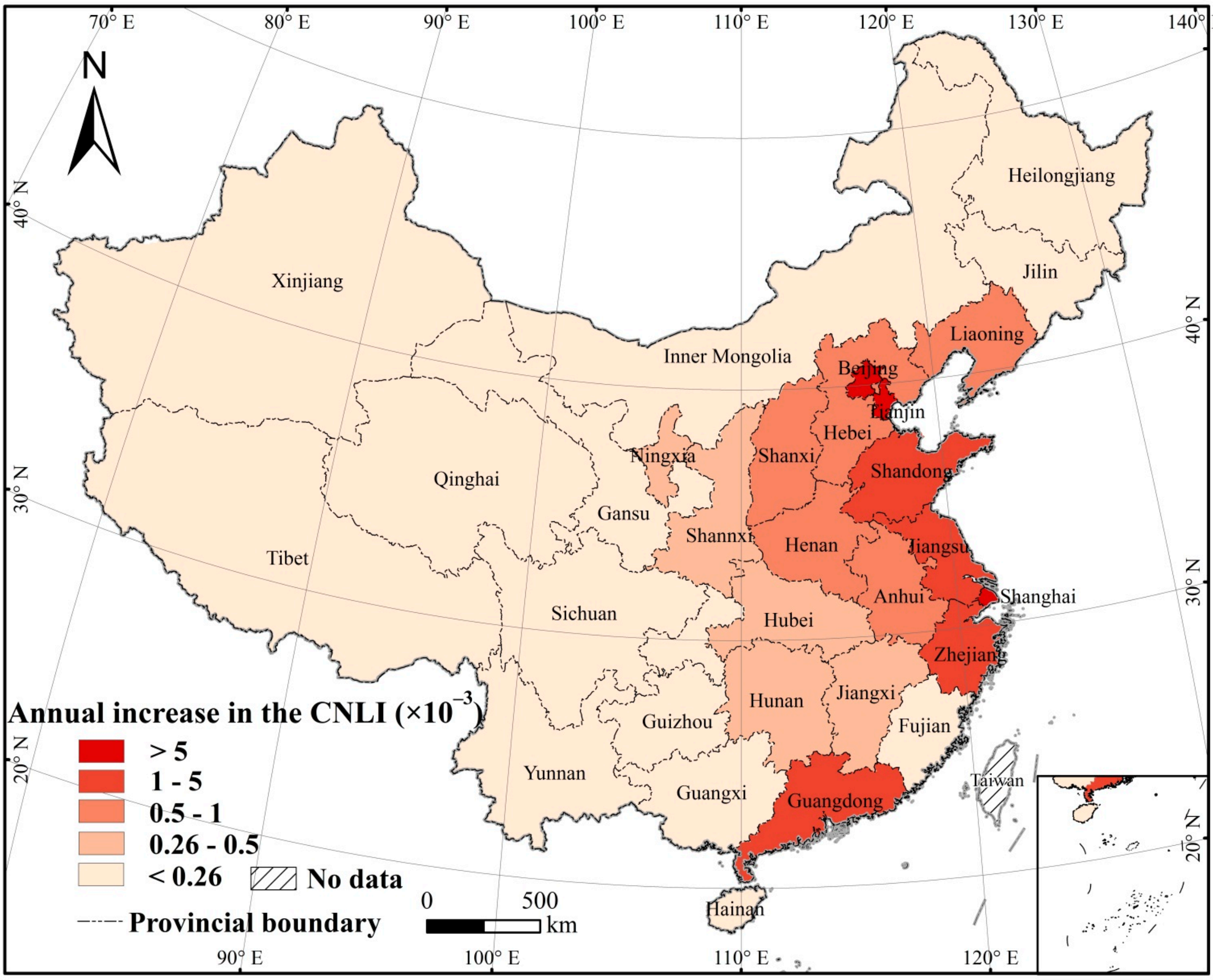

Figure 2. Dynamics of urbanization levels at the provincial scale in China from 1992 to 2012 (Note: We used the "natural breaks (Jenks)" method [37] to set the breaks for the annual increases in compounded night light index (CNLI)).

4.3. Dynamics of Urbanization Levels at the County Scale

Counties in which the annual increases of CNLI were higher than the national average were mainly located inside urban agglomerations (Figure 3a). The annual increases of CNLI were faster than the national average in 711 counties, and nearly 59.2% of these counties were located within urban agglomerations. Among the 23 urban agglomerations, the Yangtze River delta, Jing-Jin-Ji, and Shandong Peninsula ranked as the top three in the numbers of counties that had higher rate than the national average. Specifically, in the urban agglomeration of the Yangtze River Delta, the annual increases in the CNLI were larger than the national average in 67 counties. Among these counties, Jiading district in Shanghai experienced the highest increase in CNLI, with an annual increase in the CNLI of more than 0.035 (Figure 3d). In the Jing-Jin-Ji urban agglomeration, the number of counties exceeding the national average was 64. In this urban agglomeration, Jinnan district in Tianjin experienced the highest increase in CNLI, nearly 108 times greater than the national average (Figure 3b). For the urban agglomeration of Shandong Peninsula, 37 counties exceeded the national average. Among these counties, Qingdao experienced the highest increase in CNLI, with an annual increase in the CNLI of about 0.016, nearly 58 times the national average (Figure 3c).

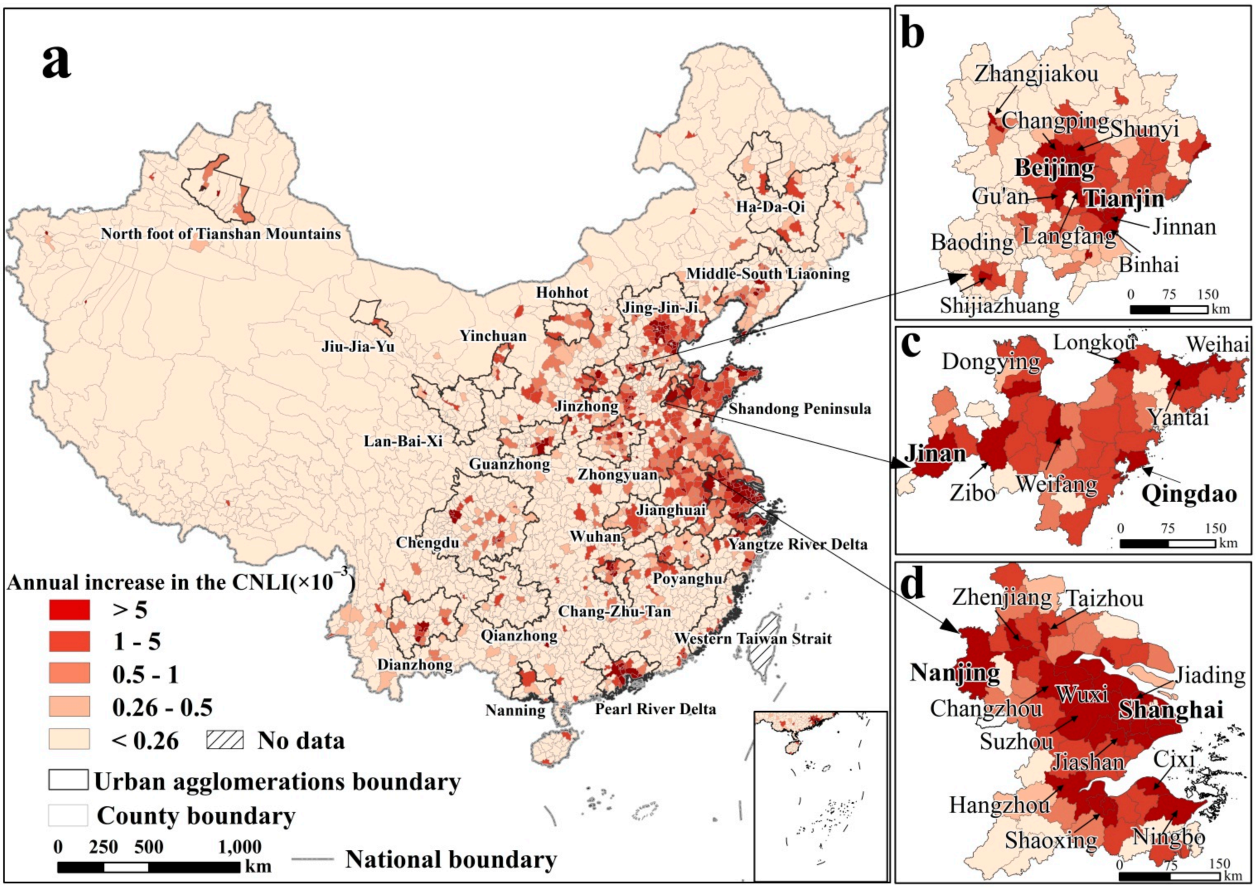

Figure 3. Dynamics of urbanization levels at the county scale in China from 1992 to 2012 (**a**) for the 23 urban agglomerations, (**b**) in the Jing-Jin-Ji urban agglomeration, (**c**) in the Shandong Peninsula urban agglomeration, (**d**) in the Yangtze River delta urban agglomeration. (Note: we used the "natural breaks (Jenks)" method [37] to set the breaks in the annual increases in the compounded night light index (CNLI)).

5. Discussion

5.1. We Provided Updated and Accurate Information about the Dynamics of China's Urbanization Level Based on DMSP/OLS Nighttime Data

First of all, our study provided timely information on the urbanization level based on DMSP/OLS NSL data for China, especially the dynamics after 2000. To our knowledge, almost all studies examining the urbanization level in China based on DMSP/OLS NSL data only covered the time period before 2000. Chen *et al.* [38] analyzed the dynamics of urbanization levels at the provincial scale in China from 1992 to 1998 using DMSP/OLS nighttime light data for the first time. In the same year, Zhuo *et al.* [18] constructed the new CNLI index to analyze the dynamics of urbanization levels from 1992 to 1998. Although these studies laid a good foundation for the research on urbanization levels based on DMSP/OLS NSL data, the information on the dynamics of urbanization levels needed to be updated urgently. We updated the information at the national, provincial, and county scales to the year 2012, and the result has provided a new data source for understanding the actual urbanization process in China.

Second, comparing the monitoring accuracy with previous studies (*i.e.*, Chen *et al.* [38] and Zhuo *et al.* [18]), we found that our result was more accurate. Specifically, the difference between the simulated CUI and the actual CUI at the provincial scale in our study is 10.53%, lower than the 14% in Chen *et al.* [38]. In addition, at the county scale, the accuracy of our study is 12.26%, also lower than the 16.21% in Zhuo *et al.* [18].

5.2. Dynamics of Urbanization Levels Measured by the CNLI Was Consistent with the Result Measured Based on the Population and Land Indicators

After standardizing the data, we compared the annual increase in the CNLI with that of the other two urbanization level indicators, the proportion of nonagricultural population (PNP) and the proportion of built-up area (PBA) from 1992 to 2012. To standardize the data, we calculated the ratio of the annual increase in the CNLI in a certain region relative to that of the whole country [39] (Equation (5)). Likewise, we standardized the annual increase in PNP and PBA in the same way. Then, we compared the disparities between the normalized annual increase in the CNLI and that of PNP (ΔV^{Pop}) and PBA (ΔV^{Land}). Due to the accessibility of data, the comparison analysis was only implemented at the provincial scale,

$$V_m^n = \frac{U_m^n}{U^n} \; (m = 1, 2, \ldots 31) \tag{5}$$

where V_m^n is the normalized annual increase of indicator n (*i.e.*, CNLI or PNP or PBA) in the mth province, U_m^n is the annual increase of indicator n in the mth province, and U^n is the annual increase of indicator n in the whole country.

The results showed no significant disparities between the normalized annual increase in the CNLI and that in the PNP in most provinces (Figure 4). The average of ΔV^{Pop} in 31 provinces was 4.33. Twenty-five provinces had ΔV^{Pop} values below the national average difference. However, in some eastern coastal provinces (*i.e.*, Beijing, Tianjin, Shanghai, Shandong, Jiangsu, and Zhejiang), the ΔV^{Pop} values were larger than 4.33 and ranged from 5.07 to 62.87, which indicated that the rates of change in CNLI were much faster than those derived from the PNP in these provinces.

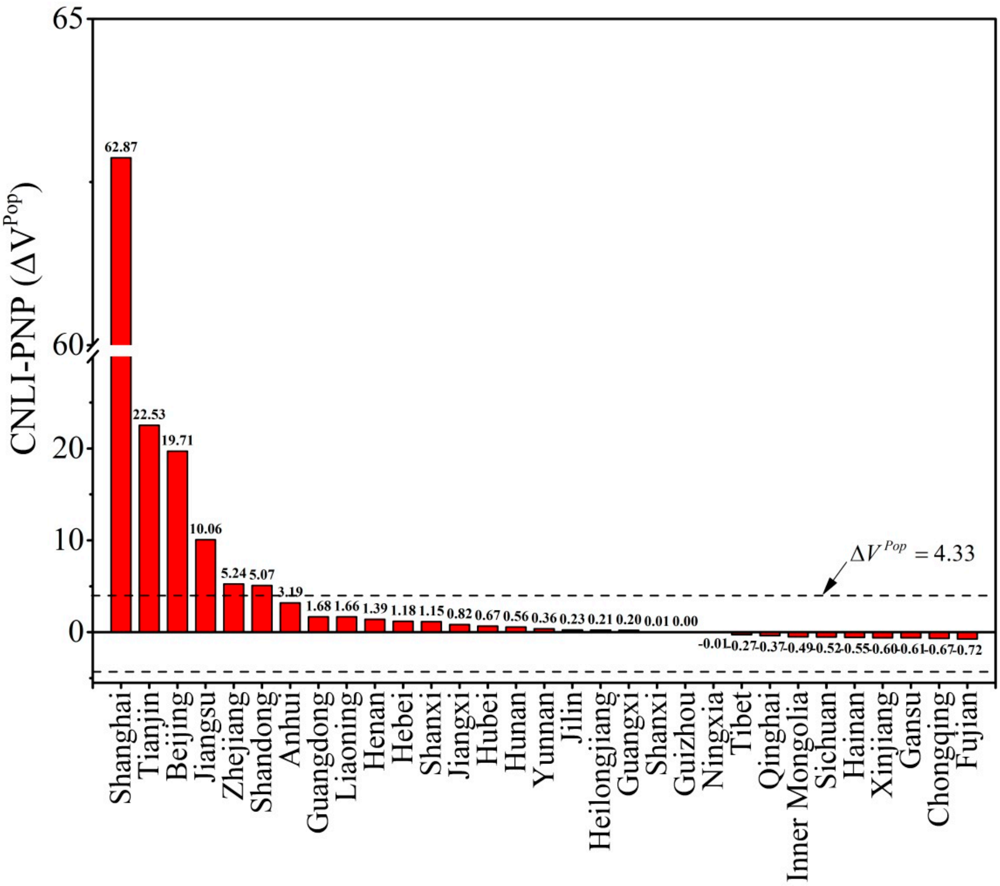

Figure 4. The differences between the standardized annual increase of the compounded night light index (CNLI) and that of the proportion of nonagricultural population (PNP) at the provincial scale (Note: the two dotted lines represent the average differences).

We did not find significant differences between the normalized annual increase in the CNLI and that of the proportion of built-up area in most provinces (Figure 5). The average ΔV^{Land} in 31 provinces was 1.05, and only nine provinces had a ΔV^{Land} value larger than 1.05. Notably, ΔV^{Land} in three municipalities (*i.e.*, Beijing, Tianjin, and Shanghai), Jiangsu, Zhejiang, and Anhui ranged from 1.37 to 21.51, equal to 1.37–21.51 times more than the national average, indicating that the rates of change in CNLI were much faster than those derived from the land indicator in these provinces. In contrast, ΔV^{Land} in Guangdong, Chongqing, and Fujian ranged from −2.27 to −5.42, which indicated that the rates of change in CNLI were slower than those in the PBA in these provinces.

In brief, the rates of change in CNLI were basically consistent with those derived from the population indicator (*i.e.*, PNP) and land indicator (*i.e.*, PBA) in most provinces of China from 1992 to 2012. These three indicators showed significant disparities only in four municipalities and a few eastern coastal provinces.

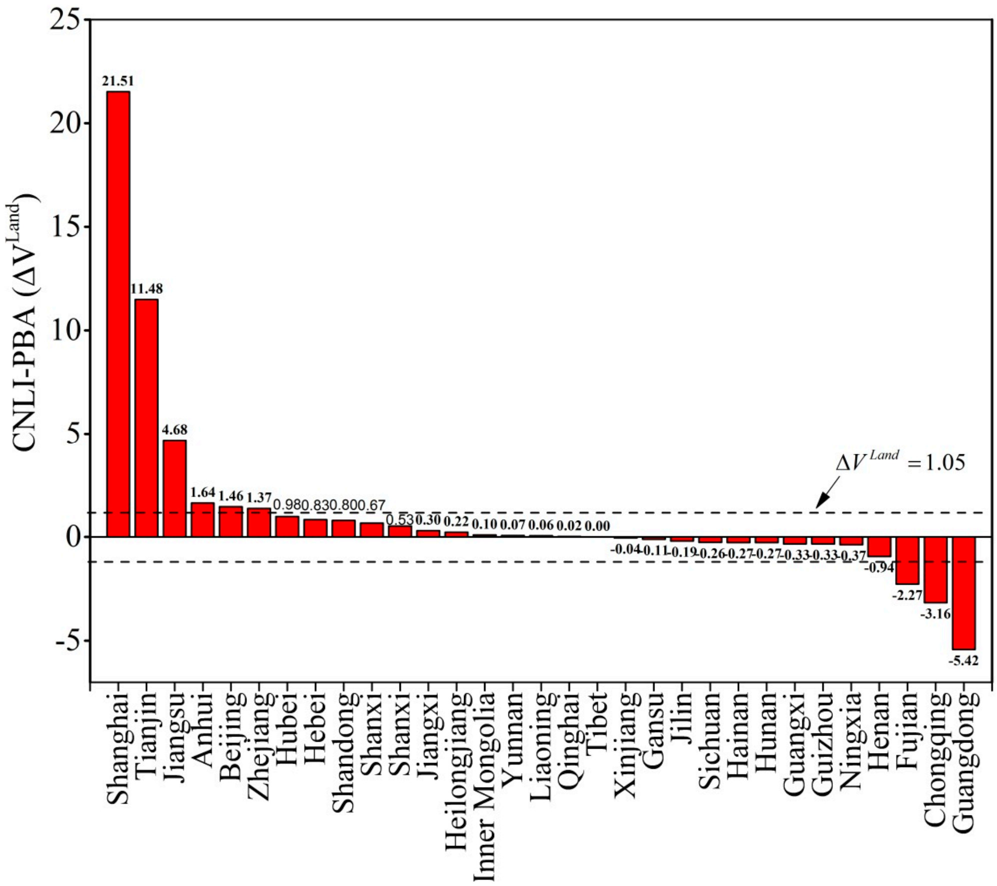

Figure 5. The differences between the standardized annual increase of the compounded night light index (CNLI) and that of the proportion of built-up area (PBA) at the provincial scale (Note: the two dotted lines represent the average differences).

5.3. Limitations and Future Work

Our proposed approach has a few limitations. First, the accuracy of the CNLI needs to be improved. Due to the limited radiometric range of DMSP/OLS, NSL data values in urban centers tend to be saturated and truncated [40]. This saturation problem may influence the accuracy of the CNLI by affecting the calculation of I (Equation (1)) for some regions with well-developed urban cores [26,41]. In addition, the ability of DMSP/OLS NSL data to characterize urbanization levels is limited because of the relatively coarse spatial resolution, especially in some regions with weak nightlight [28]. Second, we identified some hot spots where the rates of change in urbanization were remarkably different by comparing three indicators (*i.e.*, CNLI, the proportion of nonagricultural population, and the proportion of built-up area), but we still need to explore whether it was the different planning strategies between counties or other socioeconomic factors that caused the disparities [42–44]. Third, we set the optimal thresholds to extract lit urban information at the economic region scale, which could not consider the regional variation in physical environment and social-economic status within each economic region. Therefore, these thresholds may affect the accuracy at the provincial and county scale. This was also the reason that the accuracy assessment at the provincial scale and county scale were lower than that at the national scale (Table 2).

In future studies, we can try to alleviate the saturation effects of NSL data in urban cores by combining the NSL data with the Normalized Difference Vegetation Index to improve the accuracy of light brightness (Equation (1)) [41]. In addition, the availability of the global radiance calibrated nighttime lights with no sensor saturation is expected to provide a valuable alternative data source for improving the light-detecting capability [45].

6. Conclusions

The study found that the urbanization levels based on DMPS/OLS NSL data are relatively accurate and comprehensive. These data provided a new way to understand the real urbanization process in China. A significant correlation was observed between the CNLI and the CUI derived from socioeconomic census data.

The results showed that China has experienced continued and rapid urbanization during the last two decades. The dynamics of urbanization levels showed significant regional differences, with the annual increase of CNLI in eastern provinces much higher than those in western provinces. The annual increase in the CNLI in the eastern administrative unit, such as Shanghai, Beijing, and Tianjin, was 20 times larger than that of the 10 western provinces. In addition, rapidly urbanized areas were concentrated in the vigor development regions, *i.e.*, urban agglomerations. Nearly 60% of the counties with an annual increase in the CNLI larger than the national average were located inside the 23 urban agglomerations.

In the past two decades, the dynamics of urbanization levels derived from the CNLI were basically consistent with those taken from the other two conventional used indicators (*i.e.*, the proportion of nonagricultural population and the proportion of built-up area) in most provinces. Significant disparities only existed in the four municipalities and a few eastern coastal provinces of China. Specifically, the annual increases in CNLI were much faster than those derived from the other two indicators in Beijing, Tianjin, Shanghai, Jiangsu, and Zhejiang, whereas the annual increases in CNLI were much slower compared with those derived from the land indicator in Fujian, Chongqing, and Guangdong. Researchers and policy makers should pay more attention to these regions with large disparities between different indicators.

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Author Contributions

Bin Gao collected and processed the data, performed analysis and wrote the paper. Qingxu Huang and Chunyang He conceived and designed the study and the methods. Qun Ma contributed to analysis and interpretation of the data. All authors reviewed and edited the draft, approved the submitted manuscript, and agreed to be listed and accepted the version for publication.

Conflicts of Interest

The authors declare no conflict of interest.

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