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The Dynamic Analysis between Urban Nighttime Economy and Urbanization Using the DMSP/OLS Nighttime Light Data in China from 1992 to 2012

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Abstract: Along with rapid urbanization, nighttime activities from places, such as restaurants, pubs and bars, and theatres, have created enormous economic and social benefits. The nighttime economy (NTE), as a newly developed social phenomenon, has been used to describe economic activities at night. However, few studies have investigated urban nighttime economy and its relation to urbanization from nighttime light (NTL) data perspective. To fill this gap, this study proposed a nighttime light economy index (NLEI). The correlation analysis was performed between the NLEI and economic indicators at both the city and provincial levels in China from 1992 to 2012 using the DMSP/OLS (Defense Meteorological Satellite Program/Operational Linescan System) time series data. Results revealed that correlations between the NLEI and all kinds of economic indicators were statistically significant. It was observed that both the urbanization and nighttime economy levels increased greatly from 1992 to 2012 in China. Cities and provinces in east China displayed relatively higher annual growth rates of NLEI compared to those in southwest and northwest China. Based on the quadrant map of urbanization and nighttime economy levels, most of the provincial capitals and provinces in east China were in the advanced coordination pattern while those in west China in the low-level coordination pattern.

Keywords: nighttime economy; urbanization; DMSP/OLS; NLEI

1. Introduction

Since the reform and opening policy in 1978, the accelerated urbanization processes in China have triggered the soaring national economy. Despite the low temporal resolution, economic statistical indicators, such as the GDP (Gross Domestic Product) and demographic variables, have been mainly utilized to assess urbanization levels in previous many societal and economic studies [1]. In this context, nighttime light (NTL) data from the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) provide a new avenue in mapping urbanization growth and economic activities at local, regional, and global scales from a long-term perspective. In the past decades, the DMSP/OLS NTL data have been widely utilized to analyze economic development [2–16], population/population density patterns [17–24], energy consumption [25–30] and urban extent/growth/expansion [31–44].

It has been shown that urban lighting constructions have increased vastly, as evidenced by the number of city streetlights growing from 2,765,984 in 1996 to 20,622,200 in 2012 according to the

China Statistical Yearbook [45]. With rapid urbanization, the social life rhythm is accelerated, and social activities of citizens and leisure life are enriched gradually. As such, shopping, recreation, and entertainment have been transferred into nighttime, resulting in a brand-new growth for the nighttime economy (NTE) which refers to economic activities occurring between 6:00 p.m. and 6:00 a.m.

Initially, the term NTE was coined by Hobbs et al. [46] to specifically describe bars and clubs operating with extended licenses into the early hours of the morning. The development of night markets, such as restaurants, pubs and bars, and theatres, has been an important and diverse part of the whole economy and has potentials in generating social and economic benefits. As a key focus of urban public policy, NTE reflects economic activities pertinent to leisure, tourism and service sectors [47]. It creates thousands of jobs and brings huge economic profits for the national economy. Since the early 1990s, with the increase of national pub and bars, the "nighttime high street" has been introduced as a brand to attract customers in many cities and urban centers. Many European cities are energetically developing the urban NTE because of the economic recession. In the UK, the urban NTE has been regarded as a driver for reviving urban centers and developing a strong urban cultural economy and production system [48]. As such, recent years have witnessed rapid expansions of the NTE in the UK. Roberts [49] stated that the numbers and capacities of licensed premises more than doubled since 1997 in some major cities of England and Wales.

It should be noted, however, that NTL data were mainly used to characterize the overall economy in china rather than the nighttime economy (NTE). Nowadays, the NTE has played a significant role in the urban economy and covers a wide range of activities in Asia, especially in China. As stated from the China Statistical Yearbook 2014, the output of the primary and secondary industries declined significantly while that of the tertiary industry increased from 24.5% in 1978 to 48.1% in 2014 [50]. In other words, the percentage of the service industry in the GDP has risen to a high level. Meanwhile, urbanization levels mainly depend on the proportion of the secondary and tertiary industries to the GDP. The NTE is considered as an extension of time for the urban daytime economy and takes the tertiary industry as the main body. Thus, the increase of the NTE may contribute to the rise of urbanization levels. However, few studies have assessed urban NTE and its relation to urbanization from nighttime light (NTL) data perspective.

Thus, this paper proposed a nighttime light economy index (NLEI) to investigate the urban NTE level and its relation to economic indicators at the city and provincial scales in China from 1992 to 2012. Then, spatial variations of the compounded night light index (CNLI) and NLEI were analyzed by using the mean CNLI and NLEI values from 1992 to 2012 at the provincial capital city level and provincial level for seven geographic regions. Finally, the relationship between urbanization and NTE from 1992 to 2012 was explored by using the compounded night light index (CNLI) and NLEI. By using the DMSP/OLS NTL data, the annual growth of the NTE (NLEI) and urbanization levels (CNLI) was assessed.

2. Data and Pre-Processing

2.1. The DMSP/OLS Nighttime Light Data

The Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) sensor is an oscillating scan radiometer with a swath of ~3000 km. The sensor has a unique capability to detect visible and thermal-infrared emissions. The OLS has two channels, i.e., a visible and near-infrared band (VNIR) from 0.4 to 1.10 μm and a thermal infrared (TIR) band from 10.0 to 13.4 μm. There are two spatial resolution modes for the imagery acquired: 0.56 km at fine mode and 2.7 km at smooth mode.

The version 4 time series of annual night stable light (NSL) dataset between 1992 and 2012 from the NOAA (National Oceanic and Atmospheric Administration) NGDC (National Geophysical Data Center) were obtained for this study [51]. The data were acquired by six different DMSP satellites: F10 (1992–1994), F12 (1994–1999), F14 (1997–2003), F15 (2000–2007), F16 (2004–2009), and F18 (2010–2012). The annual night stable light (NSL) composite has a 0–63 digital number (DN) and covers an area from

−180 to 180 degrees longitude and −65 to 75 degrees latitude. The NSL images were subset to the study area according to the Chinese administrative boundary maps, re-projected into the Albers projection system, and resampled to a spatial resolution of 1 km. Due to the lack of on-board calibrations, sensor degradations, and inter-annual and intra-annual variations, NTL data cannot be directly used for long-term temporal analysis. As such, this study followed Liu et al. [52] to correct the NTL data systematically and remove the unstable lit pixels. The method in Liu et al. [52] consists of three steps: inter-calibration, intra-annual composition, and inter-annual correction.

2.2. Ancillary Data

This study focused on Mainland China only, including 31 provinces and 27 provincial capital cities (Figure 1). Three types of data were used in this study:

(1) The administrative boundary maps for those provinces and capital cities at a scale of 1:4,000,000 were obtained from the National Geomatics Center of China. Given the geographic differences, this paper divided Mainland China (the study area) into seven geographic parts: East (Shandong, Jiangsu, Anhui, Zhejiang, Fujian, and Shanghai), South (Guangdong, Guangxi, and Hainan), Central (Hubei, Hunan, Henan, and Jiangxi), North (Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia), Northwest (Ningxia, Xinjiang, Qinghai, Shaanxi, and Gansu), Southwest (Sichuan, Yunnan, Guizhou, Tibet, and Chongqing), and Northeast (Liaoning, Jilin, and Heilongjiang) (Table 1).

(2) Land use/land cover data of China in 1995, 2000, 2005, and 2010 were downloaded from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences [53]. A total of five land cover types were identified: arable land, forest lands, waters, grassland, and urban construction and rural housing. The urban land from urban construction and rural housing were used as the ancillary data to define thresholds so that built-up areas could be extracted from the NTL data between 1992 and 2012.

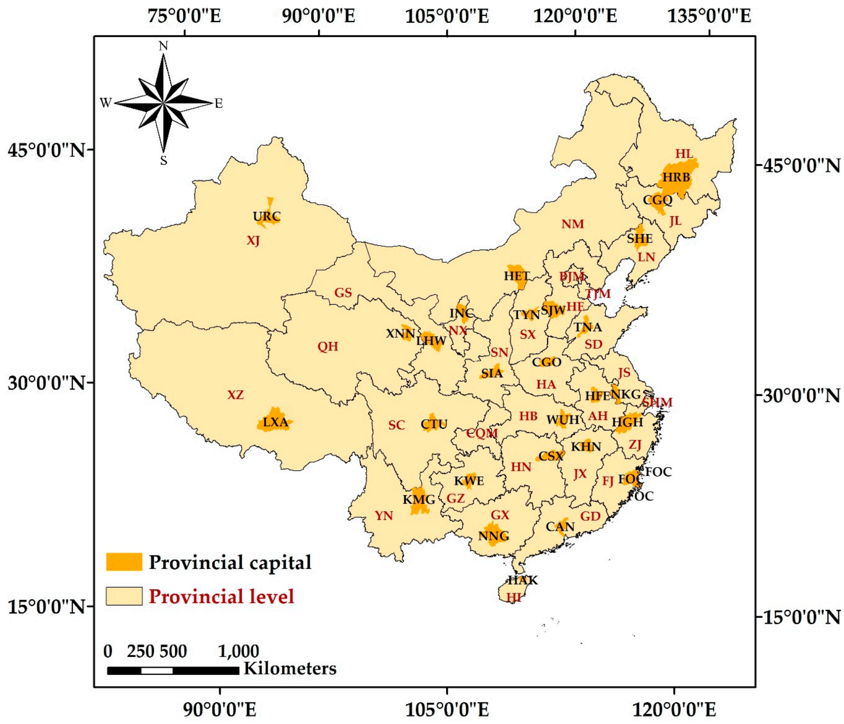

Figure 1. The study area.

Table 1. The 31 provinces and 27 provincial capital cities of Mainland China.

Geographic Region	Provincial Level	Provincial AB.	Provincial Capital	Provincial Capital AB.
North	Beijing	BJ	Beijing	
	Tianjin	TJ	Tianjin	
	Hebei	HE	Shijiazhuang	SJW
	Shanxi	SX	Taiyuan	TYN
	Niemen	NM	Huhehaote	HET
Northeast	Liaoning	LN	Shenyang	SHE
	Jilin	JL	Changchun	CGQ
	Heilongjiang	HL	Ha'erbin	HRB
Southwest	Chongqing	CQ	Chongqing	
	Sichuan	SC	Chengdu	CTU
	Guizhou	GZ	Guiyang	KWE
	Yunnan	YN	Kunming	KMG
	Xizang	XZ	Lasa	LXA
South	Guangdong	GD	Guangzhou	CAN
	Guangxi	GX	Nanning	NNG
	Hainan	HI	Haikou	HAK
Northwest	Shaanxi	SN	Xian	SIA
	Gansu	GS	Lanzhou	LHW
	Qinghai	QH	Xining	XNN
	Ningxia	NX	Yinchuan	INC
	Xinjiang	XJ	Wulumuqi	URC
Central	Henan	HA	Zhengzhou	CGO
	Hubei	HB	Wuhan	WUH
	Hunan	HN	Changsha	CSX
East	Shanghai	SH	Shanghai	
	Jiangsu	JS	Nanjing	NKG
	Zhejiang	ZJ	Hangzhou	HGH
	Anhui	AH	Hefei	HFE
	Fujian	FJ	Fuzhou	FOC
	Jiangxi	JX	Nanchang	KHN
	Shandong	SD	Jinan	TNA

Economic statistics for the 27 provincial capital cities and 31 provinces were collected from national and local statistical yearbook (China Statistical Yearbook and China City Statistical Yearbook) [54,55]. In previous studies [56], five recognized statistical indicators that were used to relate to the urbanization level included the per capita GDP (C1), percentage of the secondary and tertiary industries GDP (C2), percentage of nonagricultural population (C3), percentage of built-up area (C4), and percentage of population density (C5). The seven indicators that were used to evaluate the urban NTE level included the per capita GDP (E1), per capita cultural entertainment consumption level of urban residents (E2), percentage of built-up area (E3), population density (E4), percentage of employment in the tertiary industry (E5), tertiary industry GDP (E6), and percentage of the tertiary industry GDP (E7). The selection of the per capita GDP (E1) and per capita cultural entertainment consumption level of urban residents (E2) is due to the fact that the NTE level can contribute the overall economy level and depends on expenditures on recreation and entertainment. Since nighttime economic activities occur in the urban cores and high population density areas, the percentage of built-up area (E3) and population density (E4) are selected. The proportion of employment in the tertiary industry (E5), tertiary industry GDP (E6) and the percentage of the tertiary industry GDP (E7) are selected because NTE takes the tertiary industry as the main body and creates many job opportunities.

3. Methods

In this paper, the NLEI was developed to represent the urban NTE level and was correlated to the urbanization level at both the provincial capital city and provincial levels. First, the built-up areas were extracted from 1992 to 2012 and then used to compute the compound night light index (CNLI) to reflect the urbanization level. Then, the NLEI was proposed based on the findings concluding the power function between the total nighttime light brightness and the tertiary industry and was evaluated by the composite nighttime economy level indices (CNEI) at provincial level. Finally, strong correlations between the NTE and urbanization levels were analyzed by the composite urbanization level indices (CUI) and NLEI.

3.1. Extraction of Built-Up Areas

Time series NTL data were capable of revealing urban expansions at the regional and global scales [38,43,57,58]. The empirical threshold technique is widely used for mapping urban areas from NTL data because of its simplicity and relatively high accuracy and reliability [1]. This study adopted the threshold technique to extract the urban built-up areas in China from 1992 to 2012 [52]. Figures 2 and 3 show the optimal threshold, the maximum kappa coefficient and the OA (overall accuracy) for each capital city and province in the years 1995, 2000, 2005, and 2010. Figure 4 shows the dynamics of built-up areas using the optimal thresholds applied to the NSL data from 1992 to 2012. The built-up areas were extracted from NTL data with an average overall accuracy of 97.8% at the provincial capital city level and of 98.4% at the province level in 1995, 2000, 2005 and 2010. However, there was a tendency of overestimating for large cities in east region, especially shanghai city. Thus, we manually corrected the optimal threshold of shanghai city using the ancillary urban land cover data as the true data of built-up area.

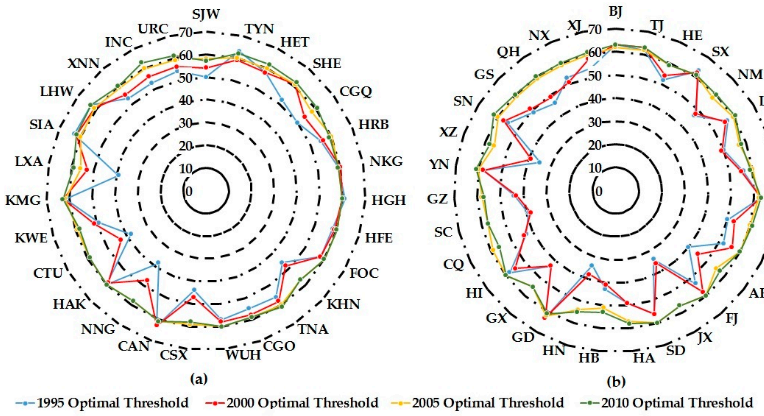

Figure 2. The optimal threshold for extracting built-up areas in each: provincial capital city (**a**); and province (**b**).

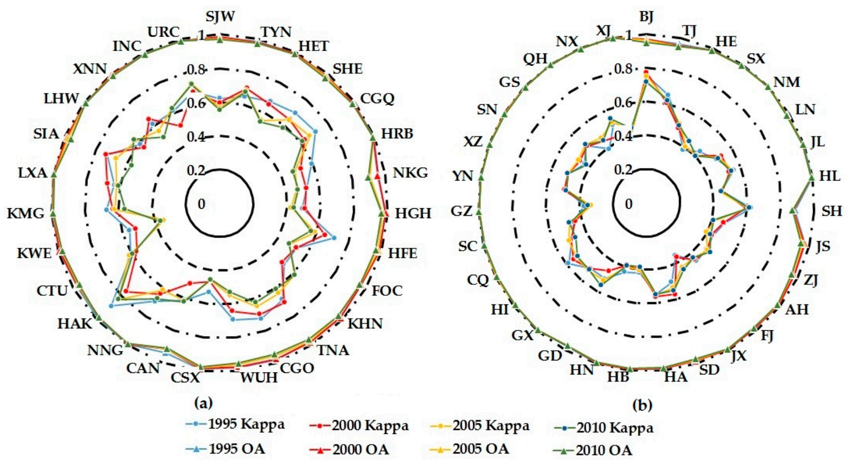

Figure 3. The maximum kappa coefficient and OA for each: capital city (**a**); and province (**b**).

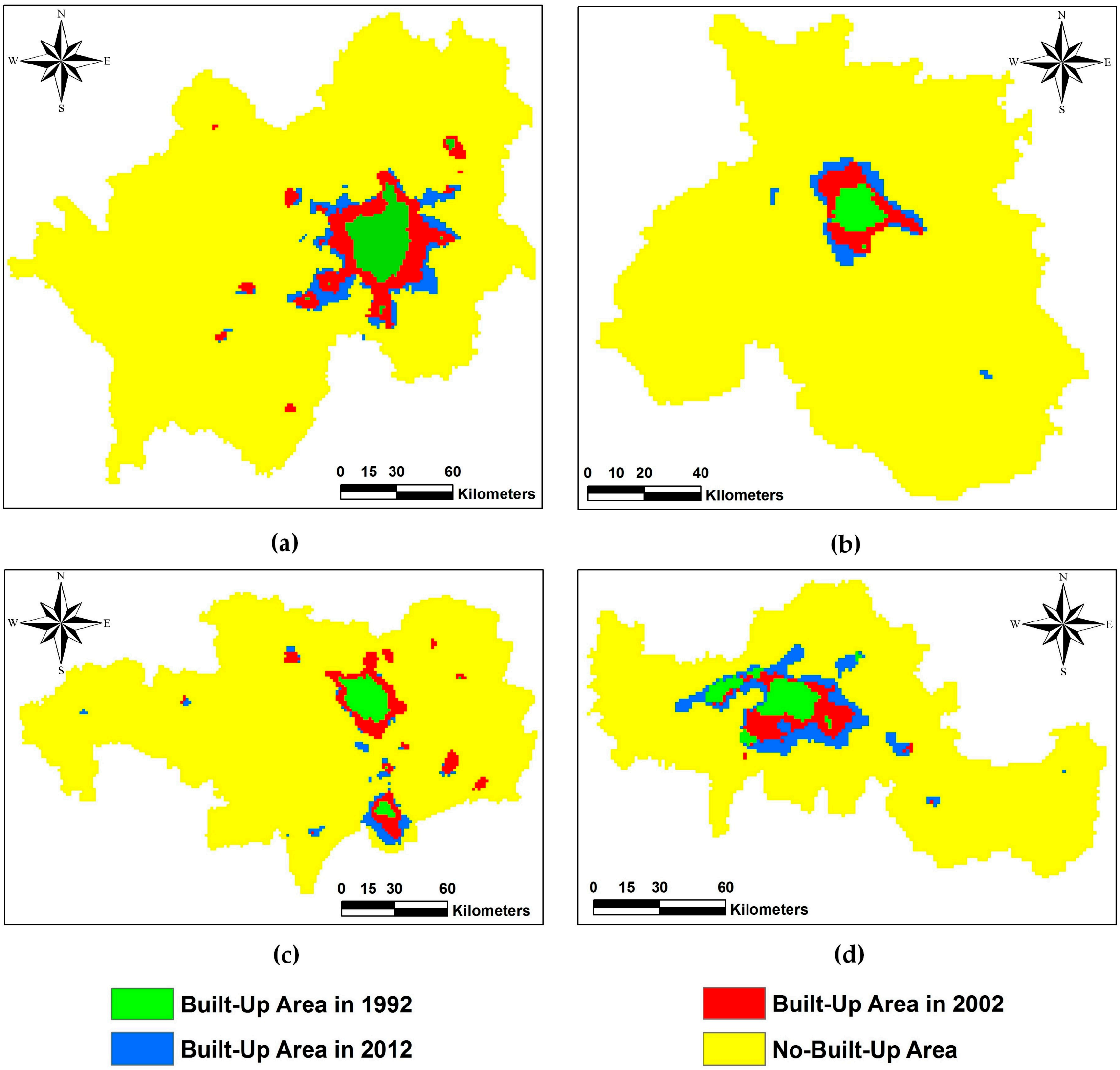

Figure 4. The dynamics of urban expansion using optimal thresholds applied to NSL data from 1992 to 2012 (Left to right and top to bottom: (**a**) Beijing, (**b**) Tianjin, (**c**) Nanjing, and (**d**) Nanchang).

3.2. The Compound Night Light Index (CNLI)

It has been proven that the CNLI was an effective and applicable index to reflect the regional urbanization level at the national, provincial, and county scales [33,56]. Here, the CNLI was calculated to reflect the urbanization level at the provincial capital city and provincial scales using the Equation (1).

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

where I is the average night light brightness of all lit pixels in a region (Equation (2)), and S is the proportion of lit urban areas to the total area of a region (Equation (3)). Thus, the CNLI can be re-expressed in the Equation (4).

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

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

$$\mathrm{CNLI} = \mathrm{I} \times \mathrm{S} = \frac{\sum_{i=T}^{DN_M}(DN_i \times n_i)}{N_L \times DN_M} \times \frac{Area_N}{Area} = \frac{\sum_{i=T}^{DN_M}(DN_i \times n_i) \times \sum_{i=T}^{DN_M} DN_i}{N_L \times DN_M \times N_T} = \frac{\sum_{i=T}^{DN_M}(DN_i \times n_i)}{DN_M \times N_T} \quad (4)$$

where DN_i is the DN value of the ith gray level; n_i is the number of lit pixels at the ith gray level; T is the optimal threshold to extract the lighted urban area from the DMSP/OLS image; DN_M is the maximum DN value; N_L is the number of lit pixels with a DN value between T and DN_M; N is the number of total pixels of the region; $Area_N$ is the area of lit urban areas in a region; and Area is the total area of the region.

3.3. The Urban Night Light Economy Index (NLEI)

Nighttime economic activities usually occur in the urban center in which places, such as big shopping centers, pubs and bars, theatres, and eye-catching landmarks, are located. Previous studies showed the log–linear relationship between the nighttime light brightness and GDP [14,59,60]. Here, the urban night light economy index (NLEI) was developed based on the findings concluding the power function between the total nighttime light brightness and the tertiary industry.

$$\mathrm{TNLI} = \phi(\text{tertiary GDP}) = \alpha \cdot (\text{tertiary GDP})^{\beta} \quad (5)$$

Equation (5) can be re-expressed as Equation (6):

$$\left(\frac{\mathrm{TNLI}}{\alpha}\right)^{\frac{1}{\beta}} = \text{tertiary GDP} \quad (6)$$

Thus, the NLEI was defined in Equation (7) by replacing the tertiary GDP with the nighttime economy and treating $\frac{\mathrm{TNLI}}{\alpha}$ as the total nighttime lights in built-up area and $\frac{1}{\beta}$ as $\frac{Area_N}{Area}$ in Equation (6).

$$\mathrm{NLEI} = \mathrm{TNLI}^{\mathrm{S}} = \left(\left(\sum_{i=T}^{DN_M}(DN_i \times n_i)\right)^{\frac{Area_N}{Area}}\right) \quad (7)$$

where TNLI is the total amount of night lights, S is the proportion of lit urban areas to the total area of a region, 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, and T is the optimal threshold to extract the lighted urban area from the DMSP/OLS image.

3.4. Effectiveness of the NLEI

To measure availability of the CNLI to map urbanization levels, the composite urbanization level indices (CUI) was presented by Zhuo et al. [56]. Similarity, to evaluate effectiveness of the NLEI to characterize NTE levels and to explore the relationship between urbanization and NTE, we proposed the composite nighttime economy level indices (CNEI). First, the composite urbanization level indices (CUI) and the composite nighttime economy level indices (CNEI) were computed with equal weights for selected economic indicators (Equations (8) and (9)). In the calculation of the CUI, five economic indicators (C1–C5) were selected. Similarly, the CNEI was derived from seven economic indicators (E1–E5).

$$\mathrm{CUI} = \sum_{i=1}^{N} w_i \times C_i \quad (8)$$

$$\mathrm{CNEI} = \sum_{i=1}^{N} w_i \times E_i \quad (9)$$

where w_i is the weight of the ith indicator, and C_i/E_i is the value of the ith indicator. Here the weight in the CUI is 1/5 and the weight in the CNEI is 1/6 for E1, E2, E3, E4 and E5; and the weight in the CNEI is 1/12 for E6 and E7.

Due to the lack of economic data at the provincial capital city level, the CNEI was only computed at the provincial level. A total of 26 provincial cities except the Lasa city were finally selected for the correlation analysis in 1995, 2000, 2005, 2008, 2010 and 2012 (156 samples in total). The correlation between the NLEI and economic indicators and CNEL were performed at the provincial levels in 1995, 2000, 2005, 2008, 2010 and 2012 (186 samples in total). Then, the regression equation was established between the CNEI and NLEI in 1995, 2000, 2008 and 2012 at the provincial levels. Finally, the regression equation was used to derive the NLEI in 2005 and 2010 which were compared against the real NLEI. Here the average of the relative error (ARE) was utilized to assess the comparisons.

$$\text{ARE} = \frac{\sum_{i=1}^{N} \frac{|Y_a - Y_e|}{Y_a}}{N} \times 100\% \tag{10}$$

where N is the number of samples, Y_a is the actual value of the CNEI, and Y_e is the simulated value of the CNEI.

4. Results

4.1. The Relationship between the NLEI and Economic Indicators and CUI

4.1.1. The Relationship between the NLEI and Economic Indicators

Table 2 shows the correlation coefficients between the NLEI and economic indicators and CNEI. The NLEI had significant correlation with all economic indicators. The correlation coefficients between the NLEI and economic indicators (except the tertiary industry GDP) at the provincial level were higher than those at the provincial capital city level. The lowest correlation coefficients were found between the NLEI and the tertiary industry GDP (E1) at the provincial level (0.336) and between the NLEI and the percentage of employment in the tertiary industry (E2) at the provincial capital city level (0.229). The highest correlation coefficients were observed between the NLEI and the percentage of built-up area (E3) at the two levels (>0.9). The correlation coefficient is 0.823 between the NLEI and the CNEI at the provincial level. Figure 5 shows the best regression of CNEI and NLEI at the provincial level is the logarithmic function (R^2 = 0.626, p = 0.000). Comparisons of the simulated CNEI derived from the NLEI with the real CNEI yielded an ARE of 15.7%, suggesting the NLEI could represent the urban NTE level (Figure 5).

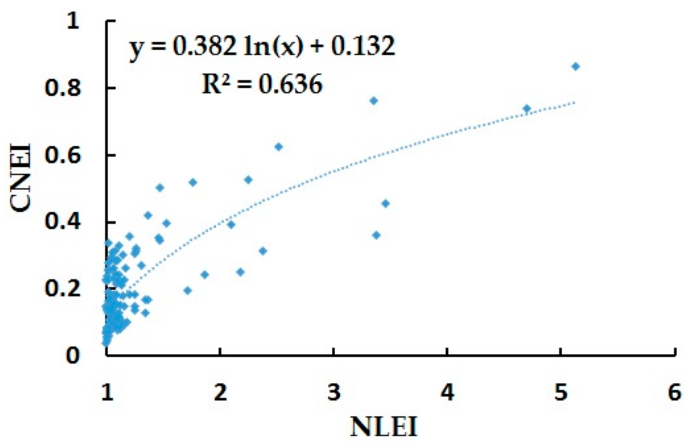

Figure 5. The regression analysis of the CNEI and NLEI at the provincial level.

Table 2. The correlation coefficients between the NLEI and economic indicators and CNEI at the provincial and provincial capital city levels.

Level	Indicator	E1	E2	E3	E4	E5	E6	E7	CNEI
Provincial Capital	NLEI	0.490 **		0.921 **	0.316 **	0.229 **	0.665 **	0.260 **	
Provincial	NLEI	0.620 **	0.554 **	0.979 **	0.893 **	0.513 **	0.336 **	0.615 **	0.823 **

Note: Economic indicators are per capita GDP (E1), per capita cultural entertainment consumption level of urban residents (E2), percentage of built-up area (E3), population density (E4), percentage of employment in the tertiary industry (E5), tertiary industry GDP (E6), and percentage of the tertiary industry GDP (E7). ** denotes statistically significant correlation coefficients with $p < 0.01$. The correlation between the NLEI and CNEI was missing at the provincial capital city level due to the lack of statistical data.

4.1.2. The Relationship between the CUI and NLEI

Significant correlation was observed between NLEI, and CUI and CNLI, as shown in Table 3. The correlation coefficients between the NLEI and CUI were 0.727 at the provincial capital city level and 0.857 at the provincial level. Figure 6 shows the best regression model between the NLEI and CUI at the provincial capital city and provincial scales. The R-square of the logarithmic regression model at the provincial level (R^2 = 0.773, p = 0.000) was higher than that at the provincial capital city level (R^2 = 0.579, p = 0.000). The correlation coefficients between the CNLI and NLEI were 0.968 at the provincial capital city level and 0.978 at the provincial level. Overall, it was concluded that there were strong logarithmic relationships between NTE and urbanization levels.

Table 3. The correlation coefficients between NLEI, and CUI and CNLI at the provincial and provincial capital city levels.

Scale	Indicator	CUI	CNLI
Provincial Capital	NLEI	0.727 **	0.968 **
Provincial	NLEI	0.857 **	0.978 **

Note: ** denotes statistically significant correlation coefficients with $p < 0.01$.

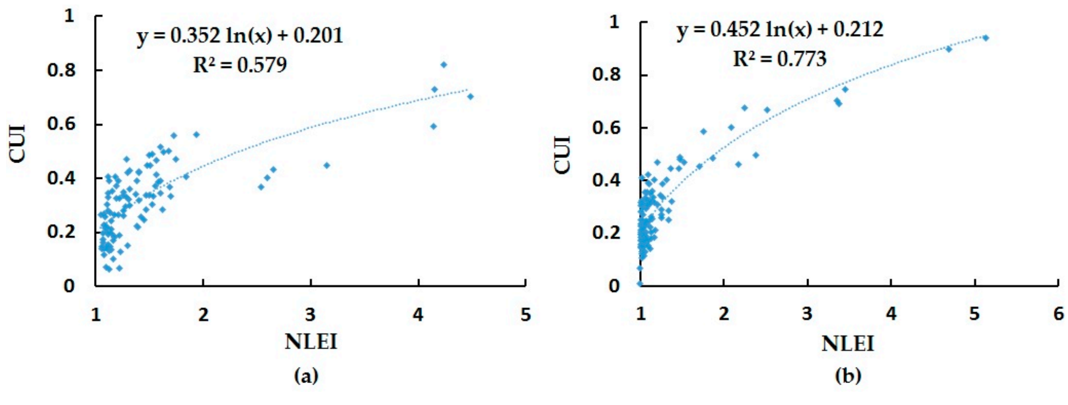

Figure 6. The regression analysis of the CUI and CNLI at the: provincial capital city level (**a**); and provincial level (**b**).

4.2. Spatial Variations of the CNLI and NLEI

Figures 7 and 8 show the mean CNLI and NLEI values from 1992 to 2012 at the provincial capital city level and provincial level for seven geographic regions. Generally, an increase trend was observed for the NLEI and CNLI values for the seven geographic regions from 1992 to 2012.

The NLEI and CNLI values at the provincial capital city level were higher in eastern, central and southern China from 1992 to 2012 than those in the northern and northeastern China. The lowest CNLI and NLEI values were in the southwestern and northwestern China. Sharp increases of CNLI and NLEI values occurred in the northern (the CNLI value increased by 0.01, and the NLEI value increased by 0.116) and southern (the CNLI value increased by 0.037, and the NLEI value increased by 0.507) China from 1992 to 1995. The CNLI and NLEI values grew rapidly between 2000 and 2005 in the eastern (the CNLI increased from 0.024 to 0.047, and the NLEI increased from 1.280 to 1.814) and central (the CNLI increased from 0.031 to 0.049, and the NLEI value increased from 1.379 to 1.729) regions.

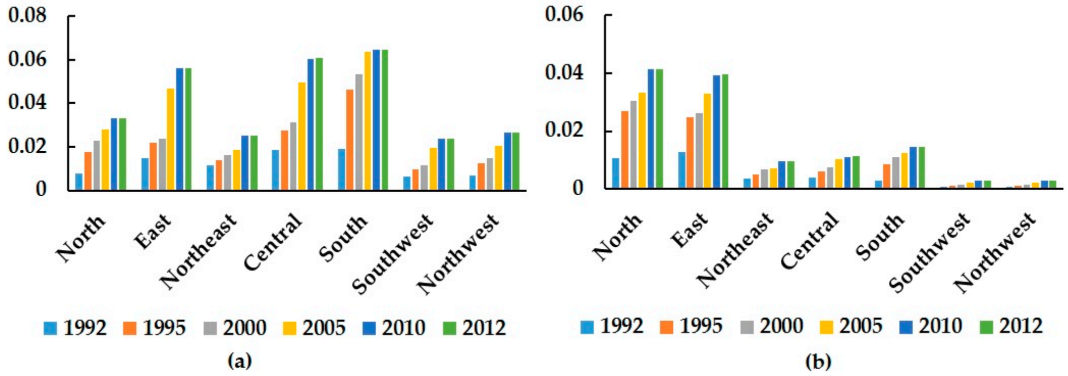

Figure 7. The mean CNLI values: at the provincial capital city level (**a**); and at the provincial level (**b**) for the seven geographic regions.

However, the CNLI and NLEI values at the provincial level were different from those at the provincial capital city level. Northern and eastern China had the highest CNLI and NLEI values from 1992 to 2012 among the seven geographic regions, followed by northeastern, central and southern China. The CNLI and NLEI values increased from 0.011 to 0.027 and from 1.152 to 1.515, respectively, in the northern region and increased from 0.013 to 0.024 and from 1.156 to 1.436, respectively, in the eastern region from 1992 to 1995. In addition, between 2005 and 2010, huge increases of CNLI and NLEI values were observed in the northern and eastern regions. Notably, northwest and southwest China exhibited the lowest mean CNLI and NLEI values at the provincial level. Overall, the urbanization and NTE levels in the eastern regions were much higher than those in the western regions.

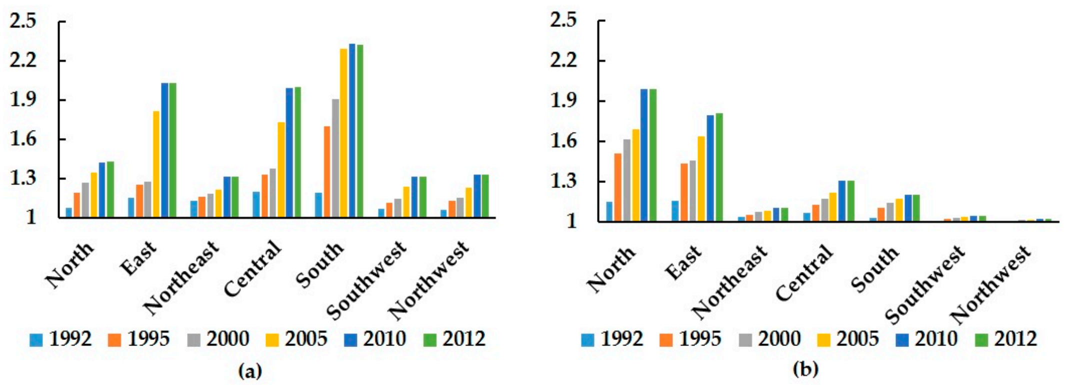

Figure 8. The mean NLEI values: at the provincial capital city level (**a**); and at the provincial level (**b**) for seven geographic regions.

4.3. The Type of the Relationship between the Nighttime Economy and Urbanization

The quadrant map presented by Chen et al. [61,62] was utilized to characterize dynamics of urbanization and economy over time. In this paper, the CNLI was used to represent the urbanization level and the NLEI to indicate the urban NTE level. The quadrant map displays four types of relationship: advanced coordination, advanced urbanization, low-level coordination, and urbanization lag. In Figure 9, the x-axis represents the nighttime economy (z-scored value) and the y-axis represents the urbanization level (z-scored value).

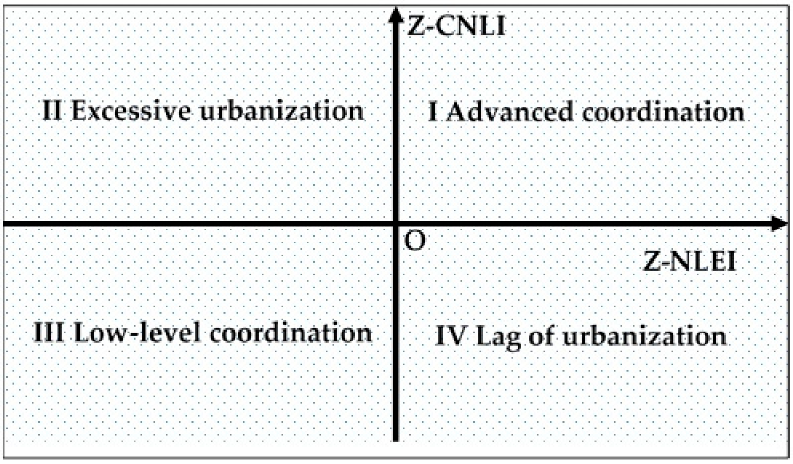

Figure 9. The quadrant map of urbanization and nighttime economy

The upper right quadrant (I) represents the advanced coordination and indicates a high level of both the NTE and urbanization. The second quadrant (II) is the advanced urbanization, representing a high level of urbanization but a low level of the NTE. In other words, the development of the NTE cannot keep pace with the urbanization levels. The Low-level coordination is in the third quadrant (III) and represents a low level of both the NTE and urbanization. The lag of urbanization is in the fourth quadrant (IV) and shows an extremely unbalanced relationship between a high level of the NTE and a low level of urbanization. In this section, different types of the relationship between the urbanization level and the NTE was examined by using the quadrant map.

Figures 10 and 11 show different types of the relationship between the urbanization level and the NTE level at the provincial capital and provincial scales from 1992 to 2012. No city had the advanced coordination (the quadrant (I)) pattern in 1992. It was not until in the year 1995 that four cities, Nanjing, Wuhan, Guangzhou, and Haikou, had both high NTE and urbanization levels (advanced coordination). Since 1995, there were an increasing number of cities that possess high levels of both NTE and urbanization and gradually progressed into quadrant I (the advanced coordination). In 2012, more than half of the provincial capital cities in Mainland China had the advanced coordination pattern. At the provincial level, Beijing and Shanghai were the only two areas with the advanced coordination pattern in 1992; followed by Tianjin and Jiangsu in 1995; and Shandong, Henan, Anhui, Zhejiang, and Guangdong in 2012. There were only a few cities or provinces possessing the type of excessive urbanization (the quadrant (II)) from 1992 to 2012, i.e., Wuhan and Nanjing in 1992; Zhengzhou and Jinan in 1995; Jinan in 2000; Shijiazhuang and Hangzhou in 2005; and Changsha in 2010 and 2012.

Many provincial capital cities in the third quadrant (low-level coordination) finally evolved into advanced coordination in 2012. However, some cities in southwest and northwest China, i.e., Kunming, Guiyang, Nanning, Lasa, Wulumuqi, Xining, Yinchuan, Huhehot, and Lanzhou, were in the low-level coordination pattern from 1992 to 2012. It was observed that many cities/provinces of high urbanization levels, for example, Tianjin in 1992, Guangdong in 1995, Henan in 2005 and 2010, and Hebei and Liaoning in 2010 and 2012, generally had low NTE levels. No provincial capitals and provinces were in the fourth quadrant (lag of urbanization).

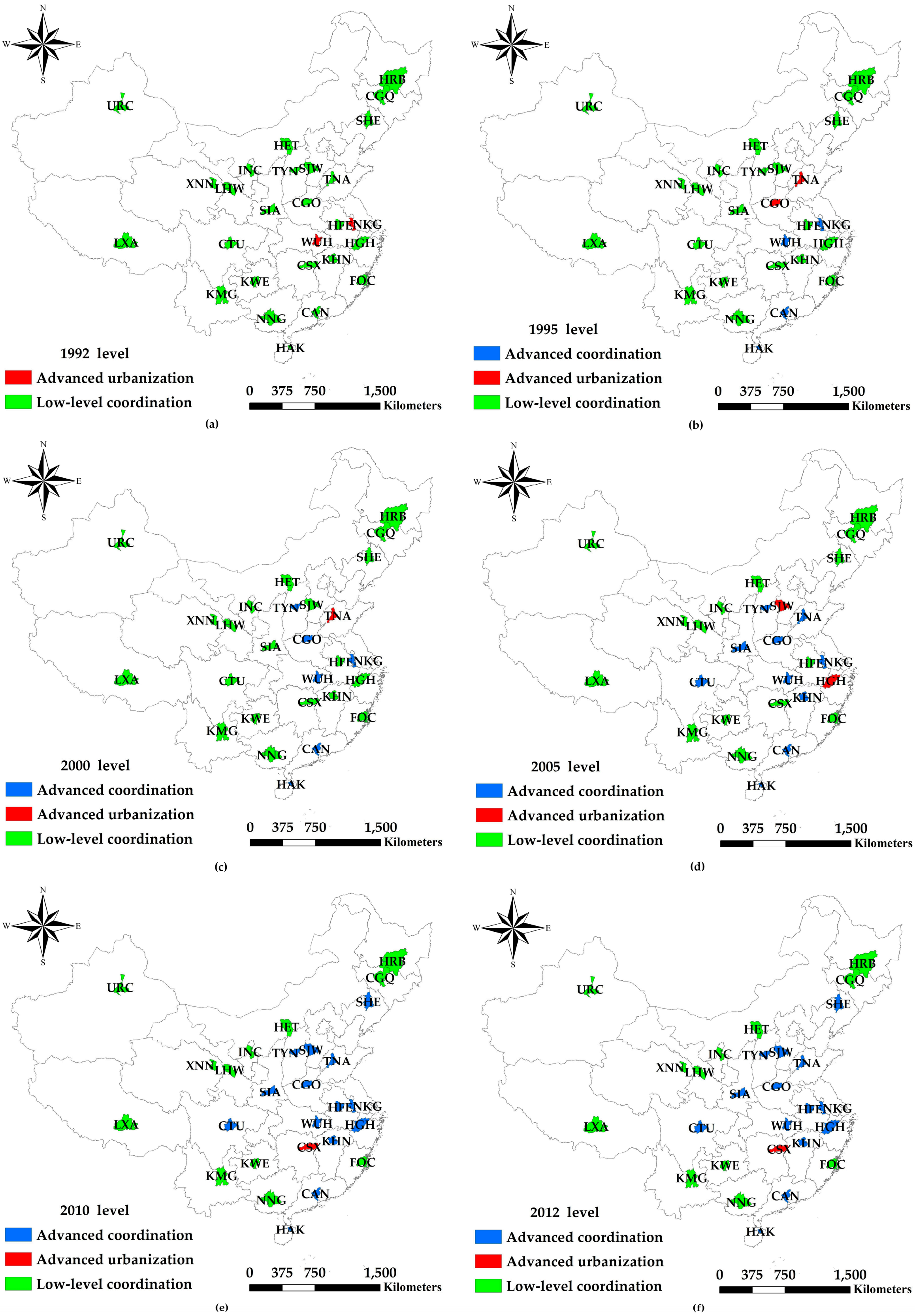

Figure 10. The type of the relationship between NTE and urbanization levels at the provincial capital city scale from 1992 to 2012: (**a**) 1992; (**b**) 1995; (**c**) 2000; (**d**) 2005; (**e**) 2010; and (**f**) 2012.

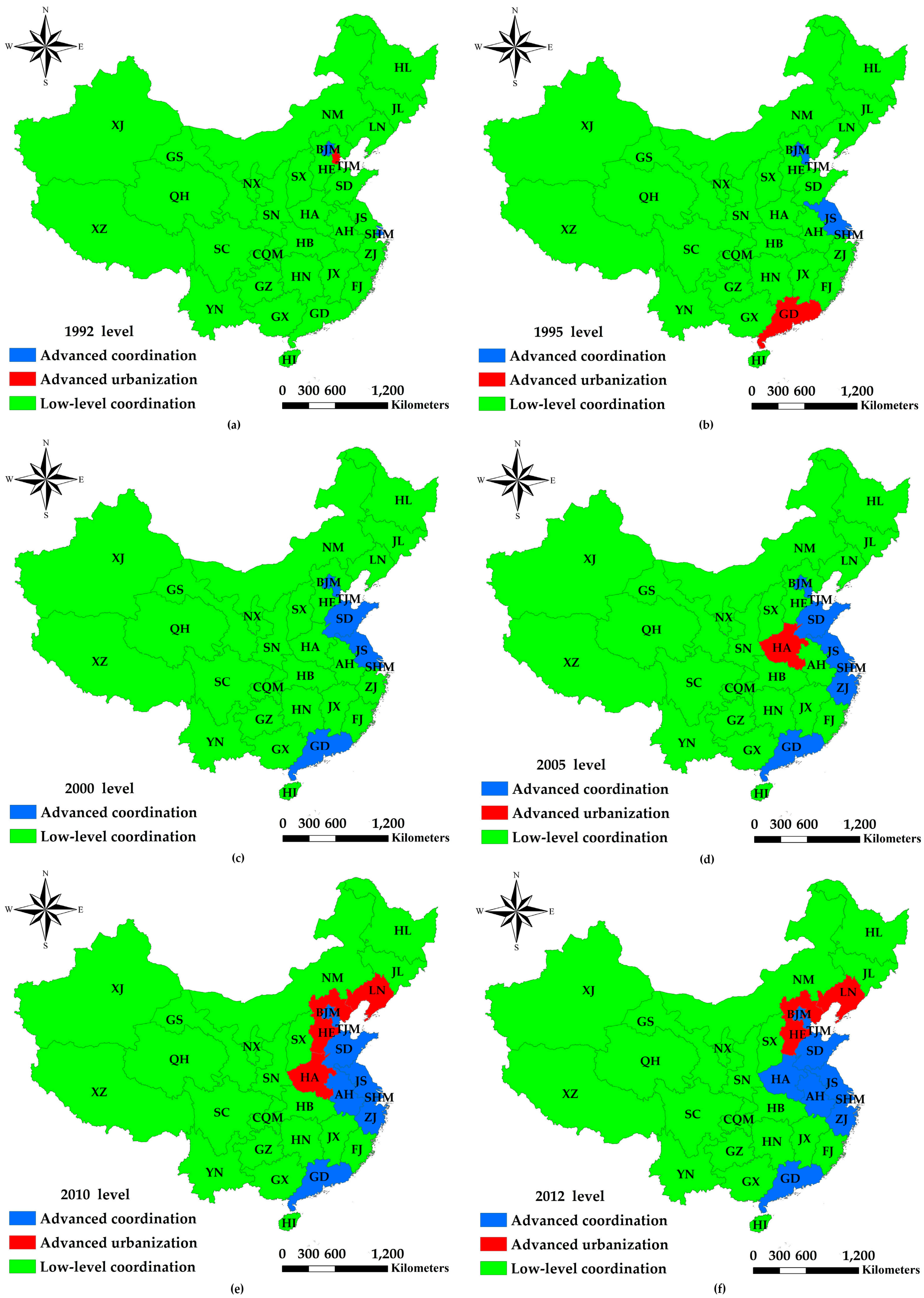

Figure 11. The type of the relationship between NTE and urbanization levels at the provincial scale from 1992 to 2012: (**a**) 1992; (**b**) 1995; (**c**) 2000; (**d**) 2005; (**e**) 2010; and (**f**) 2012.

5. Discussion

5.1. The Annual Change Rates of the NLEI and CNLI

It was shown that the mean CNLI and NLEI values in the eastern regions were much higher than those in the western regions from 1992 to 2012. To further clarify this point, the annual change rates of the CNLI and NLEI (Equations (11) and (12)) at both the provincial capital city and provincial levels were examined.

$$UL = \frac{CNLI^{t+n} - CNLI^{t}}{n} \tag{11}$$

$$NE = \frac{NLEI^{t+n} - NLEI^{t}}{n} \tag{12}$$

where UL is the annual change rate of the urbanization level, and $CNLI^{t+n}$ and $CNLI^{t}$ represent the CNLI in the $(t + n)$th year and tth year, respectively. NE is the annual change rate of nighttime economy, and $NLEI^{t+n}$ and $NLEI^{t}$ represent the NLEI in the $(t + n)$th year and tth year. n is the year.

Figure 12 shows the annual change rates of the NLEI and CNLI from 1992 to 2012 at the provincial capital city level. In the past decades, the NLEI and CNLI displayed an increase pattern. The annual increase rates of the CNLI and NLEI were higher in eastern China, especially in Nanjing where the increase rates of the CNLI and NLEI were approximately 5.0×10^{-3} and 15×10^{-2}. In the south and central regions, the annual change rates of the CNLI and NLEI had relative high values, especially in Guangzhou and Zhengzhou. In northwest and southwest China, the annual increase rates of the CNLI and NLEI were much lower. The highest annual increase rate of CNLI was in Chengdu in southwest China and the highest annual increase rate of the NLEI in Xian in northwest China. Among all the provincial capital cities, Lasa had the lowest annual increase rates of CNLI and NLEI.

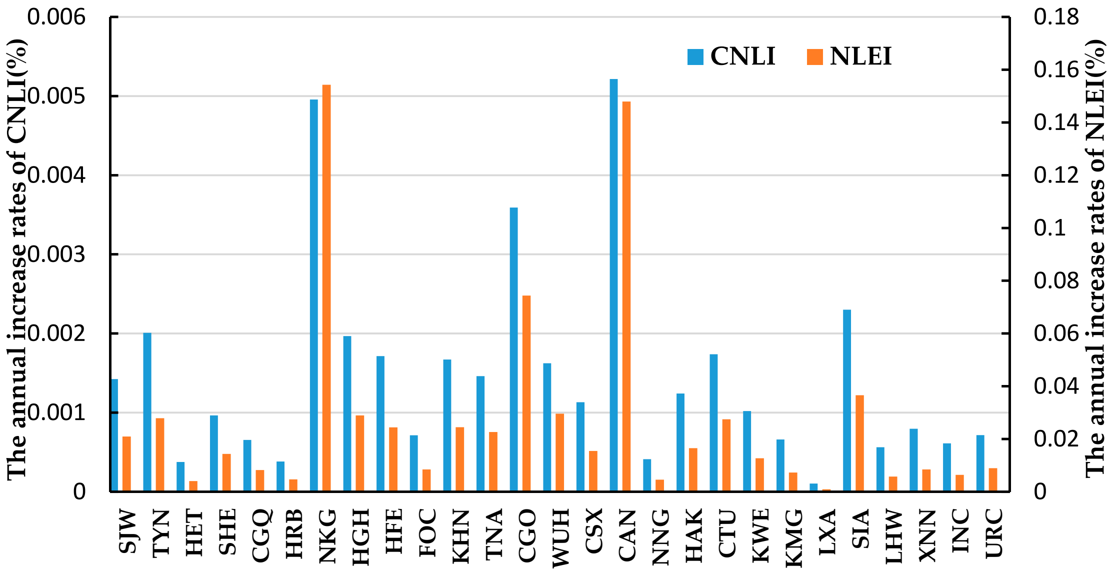

Figure 12. The annual increase rates of NLEI and CNLI from 1992 to 2012 at the provincial capital city level.

Figure 13 shows the annual increase rates of the NLEI and CNLI from 1992 to 2012 at the provincial level. Shanghai had the highest increase rates of 0.005 and 0.17 in CNLI and NLEI, respectively, among the seven economic regions. In the north region, Beijing and Tianjin had the increase rates of the CNLI at 0.004 and 0.003 and of the NLEI at 0.1 and 0.05. In northwest and southwest China, the annual increase rates of the CNLI and NLEI were much lower at the provincial level, especially in Tibet, compared to those at the provincial capital city level. The annual increase rates of CNLI derived in our study were consistent with a previous study [33], e.g., the annual increase rate of CNLI in Shanghai was the fastest (above 5.0 × 10^{-3}), and the annual increase rate of CNLI was the slowest in Xinjiang and Tibet. However, there were subtle differences in CNLI between our study and Gao et al. [33] in some areas (e.g., Beijing and Tianjin) due to the varying thresholds for extracting urban built-up areas.

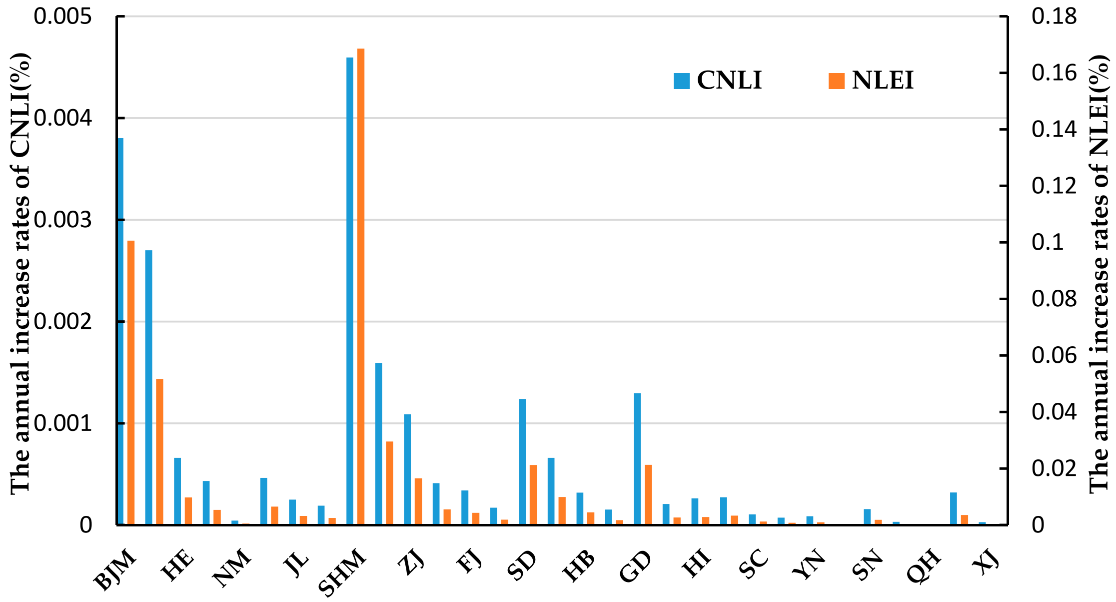

Figure 13. The annual increase rates of NLEI and CNLI from 1992 to 2012 at the provincial level.

5.2. Limitation and Future Work

It should be noted that effectiveness of the NLEI was not assessed by the direct economic indicators of the urban NTE. Due to the lack of appropriate nighttime economic data, this paper selected economic variables that have contributions from the NTE level for evaluating the proposed NLEI. The observed high correlation coefficients between the TNLI (total amount of night lights) and the tertiary GDP at both the provincial capital city (0.789) and provincial levels (0.786) may indicate the close relationship between total nighttime lights and the NTE level. Results showed a power function between the tertiary industry and TNLI at both the provincial capital city level (Tertiary GDP = 0.278*$(\text{TNLI})^{1.118}$, R^2 = 0.882) and provincial levels (Tertiary GDP = 0.365*$(\text{TNLI})^{0.992}$, R^2 = 0.840). Thus the DMSP/OLS nighttime light images have the potential to represent the nighttime economy by capturing lights emitted from the urban center. In addition, the nighttime light from the industrial and residential areas does not contribute to the NTE but it is correlated to the economic data in the study. Thus, correlation analysis in the study may be biased. Frolking et al. [63] concluded that verticality of built-up infrastructure had a sharp increase for Chinese cities and that it was not linearly reflected by nighttime satellite imageries. Further refinements can be made by using much more detailed nighttime data (e.g., VIIRS) [64–66] and high resolution land cover and land use data. Although this study focuses on the benefits of NTE, NTE may also bring some negative effects, such as the increase of criminal activities, noise, and environmental pollutions.

6. Conclusions

The relationship between urban NTE level and the urbanization level was investigated by correlating a newly proposed index, NLEI, with the economic data at both the provincial and provincial capital city scales. There were high correlation coefficients between the NLEI and the economic indicators, and the correlation coefficients at the provincial level were higher than those at the provincial capital city level. It was concluded that the NLEI could effectively reflect the urban

NTE level at the provincial scale with an overall accuracy of 84.3%. As such, the proposed NLEI may provide an alternative way to evaluate the NTE level in the absence of economic statistical data in China. It may also offer decision-makers and local authorities the information to reflect on the trajectories of the NTE level over time and on the impact of urbanization on the NTE level.

The logarithmic regression between the CUI and NLEL indicated a close relationship between the urban NTE and urbanization levels. Analyses of temporal dynamics of urbanization and urban NTE levels disclosed that the annual increase rates of the CNLI and NLEI were much higher in the eastern provinces of China than those in the western provinces. The quadrant map analysis showed that many provinces and provincial capital cities were in the low-level coordination pattern in 1992 and gradually evolved into the advanced coordination pattern in 2012. No provincial capitals and provinces were in the fourth quadrant (lag of urbanization), indicating that it was difficult to have a prosperous NTE with a low urbanization level. Provinces/cities of high urbanization levels were usually accompanied with high levels of the urban NTE. Regions that had a low level of the urban NTE were found in the west China due to poor traffic and hostile natural conditions. In 1992, most of the provincial capital cities had the low urbanization and NTE levels. With the urbanization development, the NTE level gradually increased, especially in central and east China. In 2012, the city of Lasa, and Xinjiang, Xizang, and Qinghai provinces still possessed low urbanization and NTE levels.

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