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Article

Potential of NPP-VIIRS Nighttime Light Imagery for Modeling the Regional Economy of China

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Abstract: Historically, the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) was the unique satellite sensor used to collect the nighttime light, which is an efficient means to map the global economic activities. Since it was launched in October 2011, the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi National Polar-orbiting Partnership (NPP) Satellite has become a new satellite used to monitor nighttime light. This study performed the first evaluation on the NPP-VIIRS nighttime light imagery in modeling economy, analyzing 31 provincial regions and 393 county regions in China. For each region, the total nighttime light (TNL) and gross regional product (GRP) around the year of 2010 were derived, and a linear regression model was applied on the data. Through the regression, the TNL from NPP-VIIRS were found to exhibit R^2 values of 0.8699 and 0.8544 with the provincial GRP and county GRP, respectively, which are significantly stronger than the relationship between the TNL from DMSP-OLS (F16 and F18 satellites) and GRP. Using the regression models, the GRP was predicted from the TNL for each region, and we found that the NPP-VIIRS data is more predictable for the GRP than those of the DMSP-OLS data. This study demonstrates that the recently released NPP-VIIRS nighttime light imagery has a stronger capacity in modeling regional economy than those of the DMSP-OLS data. These findings provide a foundation to model the global and regional economy with the recently availability of the NPP-VIIRS data, especially in the regions where economic census data is difficult to access.

Keywords: nighttime light; gross regional product; Visible Infrared Imaging Radiometer Suite; linear regression

1. Introduction

Regional and global economic data is important to understanding the developing world, and performing an economic census plays a major role in collecting such data. However, the economic census data is sometimes difficult to acquire at both the regional and global scales. In addition, the economic census data is always coarse in the spatial dimension, because the data in the basic administrative regions is inaccessible in many countries. Therefore, surveying the world economy in spatial dimensions using technical approaches as alternatives to the traditional economic census is an important and challenging task for the academic community [1,2].

Compared to the high cost of performing a traditional economic census, a remote sensing technique provides an efficient approach to survey the economy. A typical example is using remotely sensed optical imagery for mapping the urban land use distribution, which is an important indicator of the economic status of a country [3–5]. In addition, remote sensing can also be used to investigate agriculture [6,7], fishery [8,9] and forestry [10], which are important components of a country's economy. Among the various sources of remote sensing data, nighttime light imagery has played a direct and unique role in investigating economic activities, because the artificial nighttime light can reflect the use of public lighting and commercial lighting, which are strongly associated with the state of the economy. A number of studies have indicated that the nighttime light has a very high correlation with the national and regional economic volume [11,12]. Compared to the census approach, the mapping of nighttime light can help to investigate the economics on a large scale with very low cost; thus, the nighttime light imagery has been used to investigate the regional economics in many countries [13–17].

Traditionally, the nighttime light data is acquired by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) sensors, which is owned by the U.S. Air Force and archived by National Oceanic and Atmospheric Administration (NOAA) of the United States. The first DMSP satellite was launched in 1972, and the digital format of the imagery has been recorded since the year of 1992. From 1992 to the present, there were a series of DMSP satellites (e.g., F10–F18) imaging nighttime light. A DMSP-OLS sensor can acquire images every day, but the daily acquired imagery is usually improper for further analysis, because such image signal strength reduces due to sensor noise, atmospheric effects and moonlight variation. Thus individual DMSP-OLS images taken over a year should be combined together to produce a global annual stable light product, namely the average visible, stable lights and cloud-free composite, which has been produced by the Earth Observation Group in the NOAA National Geophysical Data Center. The composites, at spatial a resolution of 30 arc second, have pixel values ranging between 0 and 63. All the DMSP-OLS composites are available at the website of NOAA (http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html). Although some nighttime light imagery at higher spatial resolution have been evaluated in environmental and economic fields [18,19], the only practical nighttime light data on economic evaluation was DMSP-OLS data, due to its large coverage area and low price.

A new generation of nighttime light imagery emerged in 2012, the Visible Infrared Imaging Radiometer Suite (VIIRS) nighttime light imagery, acquired by the Suomi National Polar-orbiting Partnership (NPP) Satellite. Similar with the DMSP-OLS nighttime light data, the NPP-VIIRS was initially designed to monitor the atmosphere and environment, and its nighttime light imagery is a byproduct of the data under the cloud-free condition. A more detailed introduction on NPP-VIIRS is provided in the website of National Aeronautics and Space Administration (http://npp.gsfc.nasa.gov/index.html). On January 3rd, 2013, National Oceanic and Atmosphere Administration (NOAA) released the first global nighttime light imagery derived from the NPP-VIIRS data at its website (http://www.ngdc.noaa.gov/dmsp/data/viirs_fire/viirs_html/viirs_ntl.html). The imagery was generated by using the VIIRS day/night band data acquired on nights with zero moonlight. The observed individual NPP-VIIRS images in 18–26 April 2012 and 11–23 October 2012 were used, and a cloud mask was introduced using the VIIRS M15 thermal band to produce the global nighttime light imagery.

Although DMSP-OLS nighttime light imagery has shown strong capacity in evaluating economic distribution over both global and regional scales, its weakness is obvious—no on-board radiometric calibration and limited radiometric detection capacity, which results in the over-saturation problem in urban centers [20–23]. All these weaknesses may reduce the correlation between the detected nighttime light and the economic activities. Fortunately, the arrival of NPP-VIIRS, with its on-board radiometric calibration and wider radiometric detection range, can provide a more accurate nighttime light source for economic modeling. Therefore, the purpose of this study is to investigate the potential of NPP-VIIRS nighttime light imagery in modeling a regional economy, with a comparative analysis between the DMSP-OLS data and the NPP-VIIRS data.

2. Study Area and Data

To evaluate the potential of NPP-VIIRS nighttime light imagery in modeling a regional economy, we used China's provincial and county level administrative regions for analysis. In China, there are three major levels of administrative areas: province, prefecture and county. In this study, all the provincial regions, except Hong Kong, Macau and Taiwan, were selected, resulting in 31 provincial regions for analysis. At the county level, there are over 2000 counties in China, of which the administrative boundary is difficult to acquire one by one. Counties in five provinces, Anhui, Fujian, Guangdong, Jiangxi and Zhejiang were used, and as a result, there are 393 county level regions for analysis. More specifically, in this study, the county level regions include three types: municipality in a prefecture-level city, county and county level city. In fact, the municipality has a higher administrative rank than a county, but the economic data and boundaries of its districts are difficult to collect from public sources; thus, each municipality is treated as a statistical region along with the county level region. Figure 1 and Figure 2 illustrate the 31 provinces and 393 county level regions as maps, respectively, and Table 1 lists the number of county level regions in the five provinces.

Figure 1. The 31 provinces in China's mainland for analysis in this study. Note: this map is not a full map of China and only shows the regions used in this study, so that Hong Kong, Macao, all the islands and the ocean are not illustrated in this map.

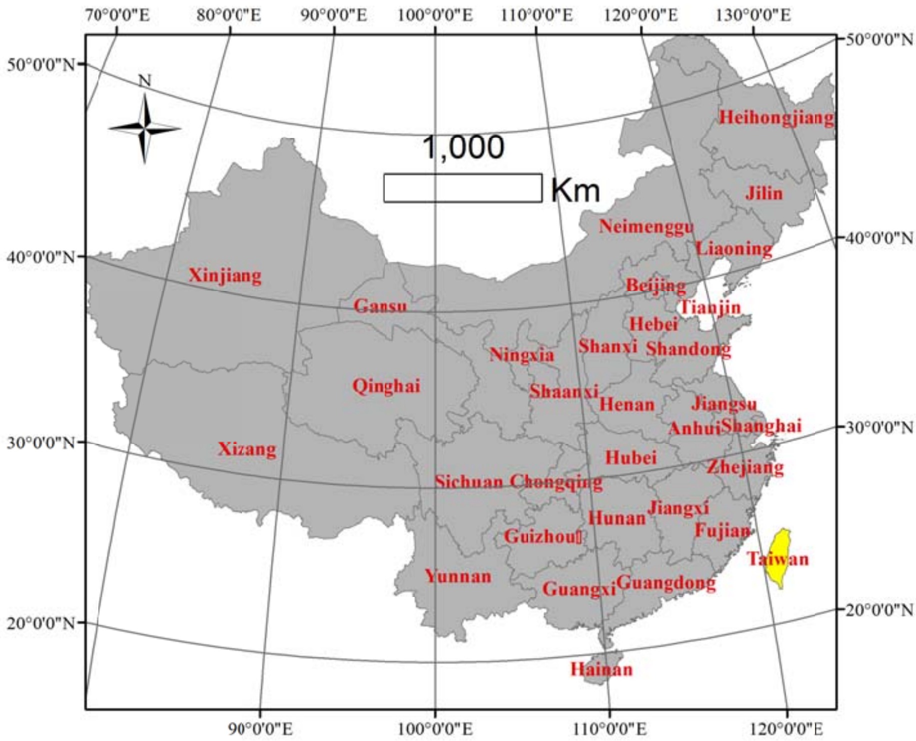


Figure 2. The 393 county level regions in the five provinces for analysis in this study.

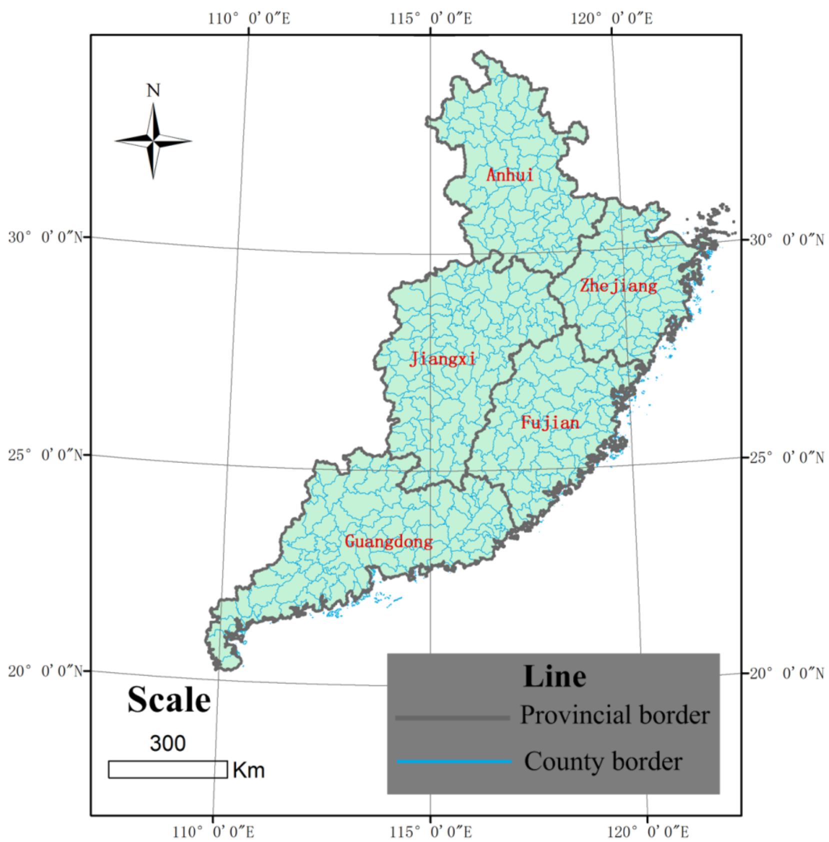


Table 1. The numbers of the county level regions in the five provinces.

Provincial Region	Number of Regions		
	Municipality	County and County Level City	All
Anhui	17	61	78
Fujian	9	58	67
Guangdong	19	69	88
Jiangxi	11	80	91
Zhejiang	11	58	69
All five provinces	67	326	393

In this study, the DMSP-OLS data and NPP-VIIRS data were used. Because the NPP-VIIRS data is only available for the year 2012, we chose the DMSP-OLS data with an acquisition year close to 2012; the closest available DMSP-OLS data are the annual stable nighttime light composites in 2009 and 2010, which were acquired by the F16 and F18 satellites, respectively. The NPP-VIIRS imagery is a preliminary product, which contains lights from cities, towns, transportation corridors, gas flares, and biomass burning and background noise, and in some places has features associated with the reflectance of light off bright surfaces, such as snow covered mountains or bright playa lake beds. In addition, the confounding factors that are irrelevant to economic activities must be removed. We propose a simple and approximate process for removing the confounding factors, which uses a hypothesis that the lit areas in 2010 and 2012 are the same, and is based on the following process: generate a mask with all positive value pixels from the DMSP-OLS imagery in 2010 and multiply the NPP-VIIRS imagery by the mask to derive a denoised nighttime light imagery. The hypothesis is approximately correct because there should be a small number of pixels where the lit value increased from zero to positive. Nevertheless, the process is efficient and the data quality has been improved.

All the nighttime light imagery was reprojected to a Lambert azimuthal equal area projection with a spatial resolution at 500 m. The two types of nighttime light data are described in Table 2. The nighttime light imagery of China in 2009, 2010 and 2012 are shown in Figures 3–5, respectively. In addition, the nighttime light imagery in Guangzhou municipality was shown as a local case in Figure 6.

The gross regional production (GRP) data for each county level region and provincial region is derived from China Statistical Yearbook for Regional Economy and Urban Statistical Yearbook of China [24,25]. The Chinese currency unit of the GRP is Renminbi (RMB), also called Chinese Yuan.

Table 2. Spatial resolution of the nighttime light imagery in this study

Year	Satellite/Sensor	Spatial Resolution		
		Original Imagery	Archived Composites	Resampled Imagery in this Study
2009	DMSP(F16)/OLS	2700 m	30 arc second	500 m
2010	DMSP(F18)/OLS	2700 m	30 arc second	500 m
2012	NPP/VIIRS	742 m	15 arc second	500 m

Figure 3. DMSP-OLS (F16 satellite) nighttime light imagery of China's land in 2009.

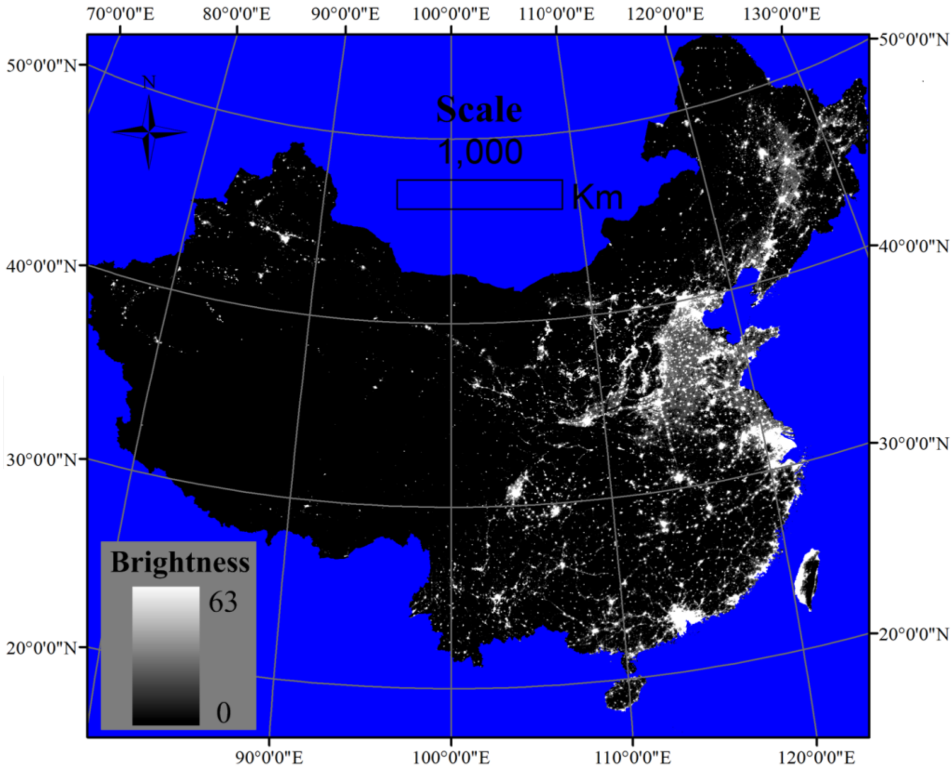


Figure 4. DMSP-OLS (F18 satellite) nighttime light imagery of China's land in 2010.

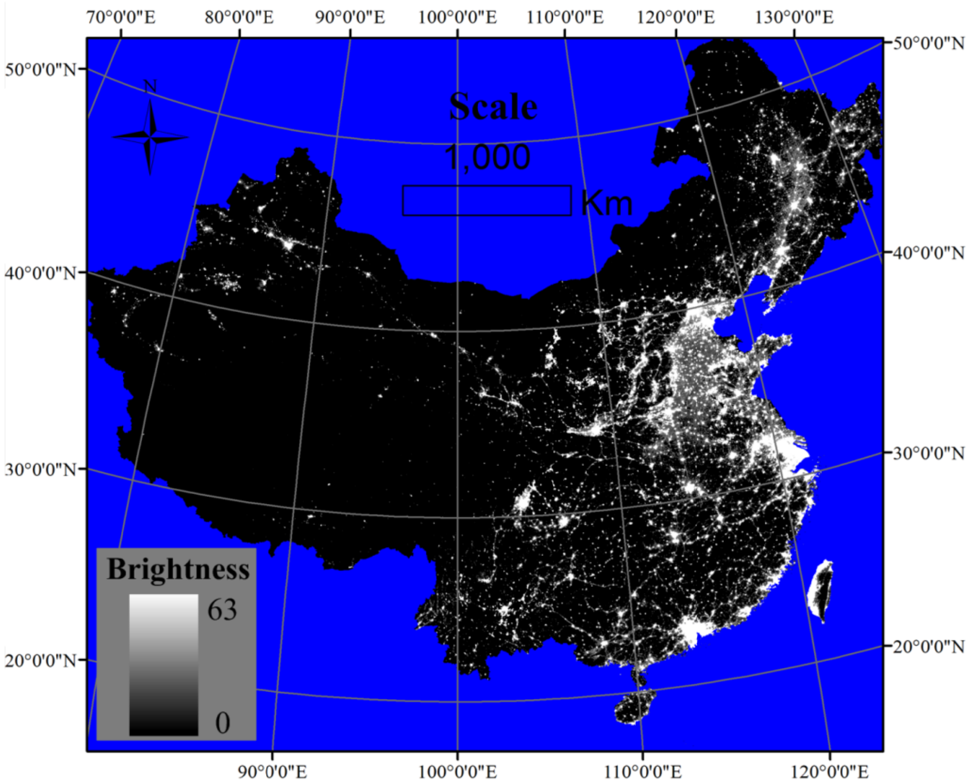


Figure 5. NPP-VIIRS nighttime light imagery of China's land in 2012. Note: the VIIRS imagery has a wide radiometric detection limit, so that there is a number of pixels with values greater than 63, but pixels of this type only occupy approximately 0.05% of all the pixels with positive values, so the pixel values larger than 63 is set to the brightest color in the map to keep it consistent with the DMSP-OLS data for illustration.

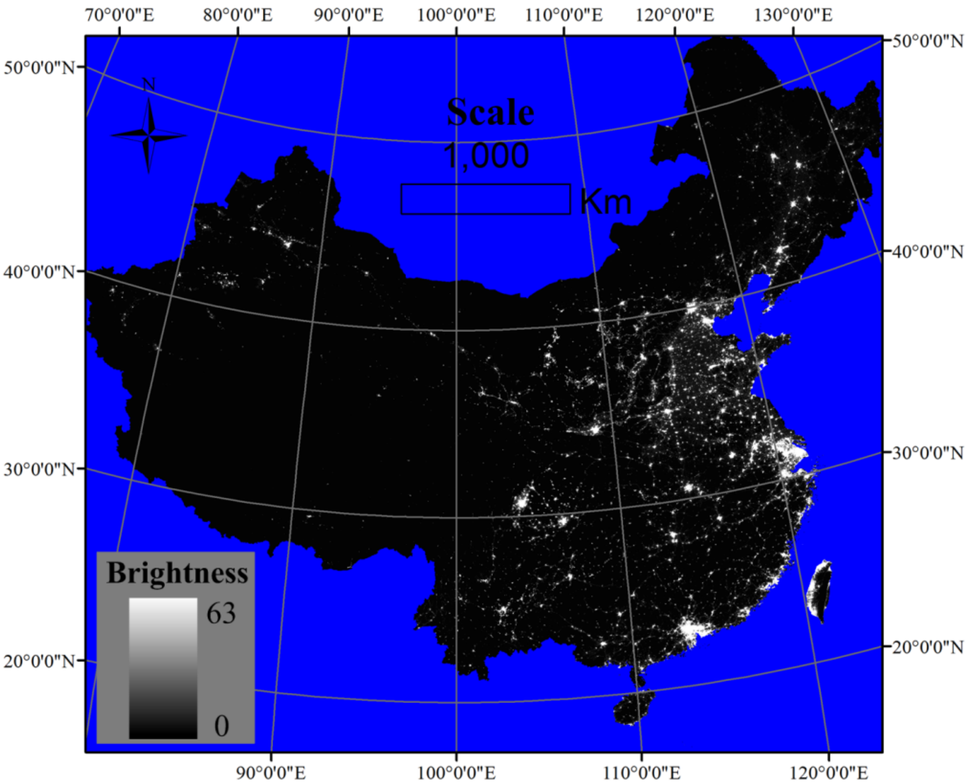


Figure 6. The nighttime light in Guangzhou municipality: (**a**) DMSP-OLS (F16 satellite) data in 2009, (**b**) DMSP-OLS (F18 satellite) data in 2010, and (**c**) NPP-VIIRS data in 2012.

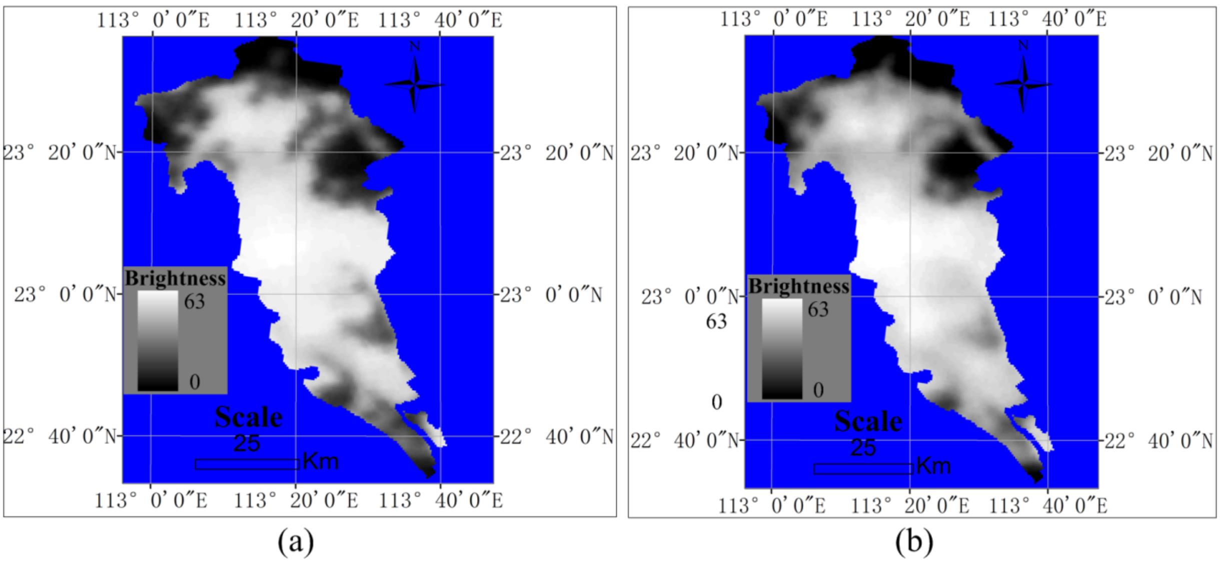
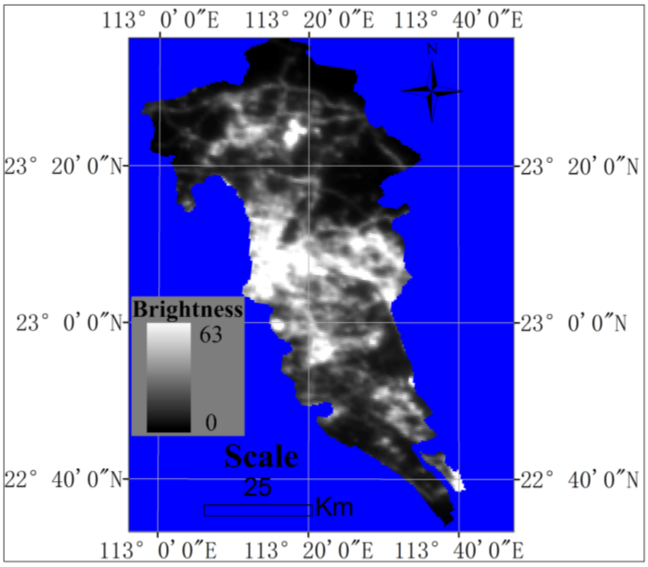


Figure 6. *Cont.*



(c)

3. Methodology and Analysis

3.1. Linear Regression Model

To evaluate the capacity of nighttime light imagery in modeling the economy, we prepare the GRP data and nighttime light data for each administrative region and perform a regression analysis to quantify the relationship between the two types of data. The total nighttime light (TNL), defined as the sum of all pixel values in a region of an image [22], is used as the nighttime light data to characterize an administrative region. Because the GRP data in 2012 is not available, the TNL data in 2012 was associated with the 2010 GRP data. A linear regression model without an intercept was used to describe the relationship between GRP and TNL as

$$g = wt \tag{1}$$

where g denotes the GRP, t denotes the TNL and w represents the slope. At the provincial level, the GRP data and the TNL data were analyzed for the 31 provincial regions using the regression analysis. At the county level, the GRP data and the TNL data were analyzed for the 393 county level regions. To describe the regression analysis more clearly, the analysis data is listed in Table 3.

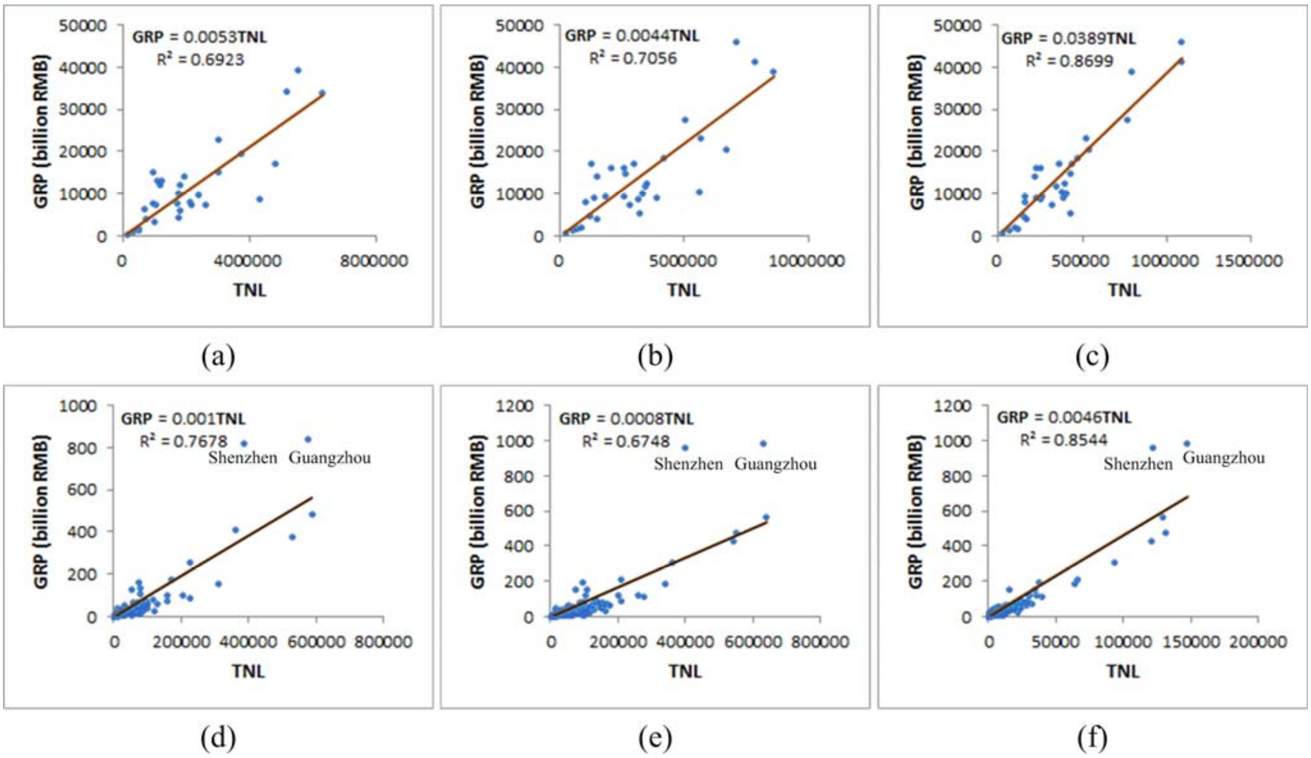
Table 3. The total nighttime light (TNL) and gross regional product (GRP) for the regression analysis of data from different satellite sensors and acquisition year.

Region	Independent Variable (TNL)		Dependent Variable (GRP)
	Sensor	**Year**	**Year**
31 provincial level regions	DMSP-OLS (F16)	2009	2009
	DMSP-OLS (F18)	2010	2010
	NPP-VIIRS	2012	2010
393 county level regions	DMSP-OLS (F16)	2009	2009
	DMSP-OLS (F18)	2010	2010
	NPP-VIIRS	2012	2010

3.2. Regression Results

Through the linear regression, the TNL-GRP relationship was analyzed, as shown in Figure 7. At the provincial level, the R^2 of the DMSP-OLS data with GRP are 0.6923 in 2009 (DMSP-F16 satellite) and 0.7056 in 2010 (DMSP-F18 satellite), whereas that of the NPP-VIIRS data with GRP is 0.8699 in 2010. The results show that the VIIRS data can better reflect the GRP than the DMSP-OLS data in provincial regions.

Figure 7. The scatter diagram of the regression variables in provincial regions and in county regions: (**a**) DMSP-OLS (satellite DMSP-F16) data in 2009 *versus* GRP data in 2009 of the provincial regions, (**b**) DMSP-OLS (satellite DMSP-F18) data in 2010 *versus* GRP data in 2010 of the provincial regions, (**c**) NPP-VIIRS data in 2012 *versus* GRP data in 2010 of the provincial regions, (**d**) DMSP-OLS (satellite DMSP-F16) data in 2009 *versus* GRP data in 2009 of the county regions, (**e**) DMSP-OLS (satellite DMSP-F18) data in 2010 *versus* GRP data in 2010 of the county regions and (**f**) NPP-VIIRS data in 2012 *versus* GRP data in 2010 of county regions.



At the county level, we found that the TNL-GRP relationship from the VIIRS data is stronger than those of the DMSP-OLS data. The R^2 values are 0.7678 and 0.6748 for the data from 2009 (DMSP-F16 satellite) and 2010 (DMSP-F16 satellite), respectively, which are lower than 0.8544, the R^2 value from the NPP-VIIRS data. Thus, NPP-VIIRS data is more strongly correlated with GRP than those of DMSP-OLS data from both the DMSP-F16 and DMSP-F18 satellites at the county level.

From the regression analysis, it is easy to determine that the NPP-VIIRS imagery has higher capacity in modeling the GRP. Here, we use the regression model to predict the GRP from nighttime light to evaluate the capacity of TNL in predicting GRP. For each region, a predicted GRP is calculated from the slope values and TNL using Equation (2). Because the numbers of provincial regions and county regions are 31 and 393, respectively, of which the latter is too large to be shown in a table; thus, we only list the real GRP and predicted GRP of the provincial regions in Table 4 and list the county data in the Appendix. Next, a relative error was used to evaluate the capacity of TNL in predicting GRP as

$$e = \frac{g' - g}{g} \tag{2}$$

where g denotes the real GRP and g' denotes the predicted GRP. The relative error values of all the provincial regions are listed in Table 4.

Table 4. Real GRP, predicted GRP and relative error in the provincial regions. RG represents real GRP, PG represents predicted GRP and RE represents the relative error.

Region	GRP in 2009 and the Prediction from DMSP-OLS Data			GRP in 2010 and the Prediction from DMSP-OLS Data			GRP In 2010 And The Prediction From NPP-VIIRS Data		
	RG	PG	RE (%)	RG	PG	RE (%)	RG	PG	RE (%)
Anhui	1,006	921	−8.4	1,236	1,519	22.9	1,236	1,522	23.1
Beijing	1,215	606.9	−50.1	1,411	640	−54.6	1,411	839	−40.6
Chongqing	653	353.5	−45.9	793	456	−42.5	793	627	−21.0
Fujian	1,224	947.9	−22.5	1,474	1,164	−21	1,474	1,651	12.0
Gansu	339	517.7	52.8	412	646	56.8	412	637	54.5
Guangdong	3,948	2,961.5	−25.0	4,601	3,119	−32.2	4,601	4,233	−8.0
Guangxi	776	904.6	16.6	957	1,139	19	957	994	3.8
Guizhou	391	378.5	−3.3	460	525	14.1	460	571	24.1
Hainan	165	265.3	60.4	206	372	80.6	206	378	83.5
Hebei	1,724	2,558.6	48.4	2,039	2,928	43.6	2,039	2,078	1.9
Heilongjiang	859	2,304.9	168.4	1,037	2,463	137.5	1,037	1,456	40.4
Henan	1,948	1,995.8	2.5	2,309	2,481	7.4	2,309	2,032	−12.0
Hubei	1,296	636.7	−50.9	1,597	1,137	−28.8	1,597	984	−38.4
Hunan	1,306	560.4	−57.1	1,604	898	−44	1,604	879	−45.2
Jiangsu	3,446	2,752.7	−20.1	4,143	3432	−17.2	4,143	4,209	1.6
Jiangxi	766	498.5	−34.9	945	791	−16.3	945	627	−33.6
Jilin	728	1,143.3	57.1	867	1,375	58.6	867	979	13.0
Liaoning	1,521	1,602.4	5.3	1,846	1,843	−0.2	1,846	1,815	−1.7
Neimeng	974	1,262.7	29.6	1,167	1,509	29.3	1,167	1,348	15.5
Ningxia	135	267	97.3	169	300	77.5	169	438	159.2
Qinghai	108	167.6	55.0	135	218	61.5	135	240	77.9
Shandong	3,390	3,359.8	−0.9	3,917	3,773	−3.7	3,917	3,077	−21.5
Shanghai	1,505	504.8	−66.5	1,717	551	−67.9	1,717	1,410	−17.9
Shanxi	736	1,379.6	87.5	920	1,701	84.9	920	1,504	63.5
Shaanxi	817	1,127.2	38.0	1,012	1,451	43.4	1,012	1,572	55.3
Sichuan	1,415	1,032.1	−27.1	1,719	1,293	−24.8	1,719	1,698	−1.2
Tianjin	752	557.2	−25.9	922	594	−35.6	922	876	−5.0
Tibet	44	58.4	32.3	51	84	64.7	51	107	109.0
Xinjiang	428	935.4	118.7	544	1,409	159	544	1,656	204.4
Yunnan	617	949.1	53.8	722	1,234	70.9	722	1,224	69.5
Zhejiang	2,299	1,604.6	−30.2	2,772	2,218	−20	2,772	2,966	7.0

From Table 4, we found that the predictability of different nighttime light sensors varies in different provincial regions. For example, the relative error of the predicted GRP in 2009 derived from DMSP-OLS data in 2009 in Liaoning Province and Heilongjiang Province are 5.3% and 168.4%, respectively, which are very different. In comparison, the counterparts of the predicted GRP in 2010 derived from the NPP-VIIRS data in 2012 are −1.7% and 40.4%, respectively, which are much closer.

To evaluate the predictability of different nighttime light data for the GRP comprehensively, we classified the absolute relative error into three levels: 0–25% as high accuracy, 25–50% as moderate accuracy and >50% as wrong. Next, we calculated the percent of each level for the different estimation approaches. For example, when estimating the GRP from the DMSP-OLS data in 2009 in the provincial regions, there are nine provincial regions with high accuracy among the 31 regions, and the fraction of provincial regions of high accuracy is 29.03%. Based on this criterion, the predictability for each type of nighttime light imagery was quantified with the three indices listed in Table 5.

Table 5. Different levels of accuracies of the predicted GRP.

Region and Data		**Percent of Relative Error of the Predicted GRP (%)**		
		High Accuracy	**Moderate Accuracy**	**Wrong**
Provincial regions	DMSP-OLS 2009	29.03	29.03	41.94
	DMSP-OLS 2010	35.48	25.81	38.71
	NPP-VIIRS 2012	54.84	16.13	29.03
County regions	DMSP-OLS 2009	18.32	22.90	58.78
	DMSP-OLS 2010	10.69	9.92	79.39
	NPP-VIIRS 2012	34.10	30.03	35.87

In the provincial regions, the NPP-VIIRS data exhibits a high capacity in predicting the GRP, with a high accuracy percent of 54.84%, which is much higher than those of the DMSP-OLS data in 2009 and 2010, as indicated in the table. In addition, the fraction of the data providing wrong predictions from the NPP-VIIRS data (29.03%) is much lower than those of the DMSP-OLS data in 2009 (41.94%) and 2010 (38.71%) as Table 5 indicates. Therefore, the NPP-VIIRS data is more reliable for predicting the GRP data in China's provincial regions.

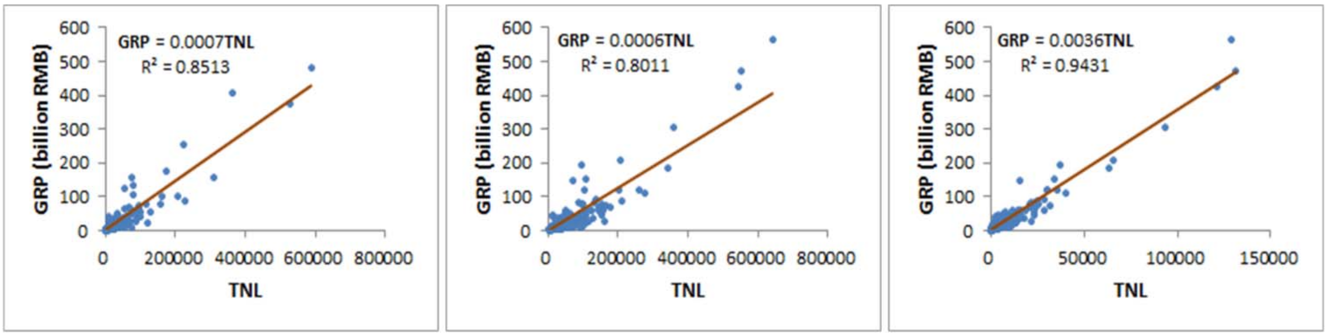
In the county regions, the fraction of high accuracy predictions from the NPP-VIIRS data is 34.10%, which is significantly higher than those of the DMSP data in 2009 and 2010, with values of 18.32% and 10.69%, respectively. The wrong percent index also demonstrates that the NPP-VIIRS data in more capable in accurately predicting the GRP than those of the DMSP data in 2009 and 2010, as indicated in Table 5.

Thus, we can conclude that the NPP-VIIRS data is more reliable for predicting the economic data than those of the DMSP-OLS data, and the NPP-VIIRS data is more robust in different spatial scales than those of the DMSP-OLS data. In addition, it is interesting to find a general underestimation in more developed regions (e.g., Beijing, Shanghai) and overestimation in less developed areas (e.g., Ningxia, Xinjinag, and Tibet). To explore this pattern in the NPP-VIIRS data, we performed a correlation analysis between the GRP Per Capita in 2010 and the relative error for the 31 provincial level regions, and found that the correlation coefficient is equal to −0.3849 under a significance level of 0.05, which indicates that the relative error has significant negative correlation with the GRP Per Capita.

3.3. Regression Analysis in the County Level Regions by Discarding Two Outliers

There are two obvious outliers in the regression analysis of the county regions in the above section (Figure 7), Guangzhou and Shenzhen, which are two major economic centers in Southern China. A possible reason for these outliers is that more GRP can be generated in these regions per unit NTL. Here, we discarded the two outliers and performed the regression analysis, which left 391 county regions for the regression analysis. The results of the regression analysis and its predictability analysis are shown in Figure 8 and Table 6, respectively.

Figure 8. The scatter diagram of the regression analysis in the county regions after discarding Guangzhou and Shenzhen as outliers: (**a**) DMSP-OLS data in 2009 *versus* the GRP data in 2009 of the county regions, (**b**) DMSP-OLS data in 2010 *versus* the GRP data 2010 of the county regions, and (**c**) NPP-VIIRS data in 2012 *versus* the GRP data in 2010 of the county regions.



(a) (b) (c)

Table 6. Different levels of accuracies of the predicted GRP by discarding the two outliers.

Counties	Percent of Different Relative Error of Predicted GRP (%)		
	High Accuracy	Moderate Accuracy	Wrong
DMSP 2009	36.06	22.76	41.18
DMSP 2010	19.18	18.41	62.40
VIIRS 2012	42.97	29.41	27.62

From Figure 8, the R^2 of the DMSP-OLS data in 2009, that in 2010 and the NPP-VIIRS data are 0.8513, 0.8011 and 0.9431, respectively, all of which are all significantly improved by discarding the two outliers, as demonstrated by comparison to the corresponding original R^2 values of 0.7678, 0.6748 and 0.8544 (Figure 7). In particular, the NPP-VIIRS data are perfectly correlated with the GRP data, with an R^2 of 0.9431. In addition, removing the outliers also greatly improved the predictability of all the nighttime light data, as indicated in Table 6—the high accuracy percentage increases and the wrongly predicted percentage decreases, as listed in Tables 5 and 6. These findings demonstrate that ability of the DMSP-OLS and NPP-VIIRS data to model the GRP can be greatly improved in county regions by discarding only very a few outliers. Furthermore, the NPP-VIIRS data is still more predictable in reflecting the GRP than those of the DMSP-OLS data under this condition.

3.4. Potential Factors behind the Results

From the experiments, the NPP-VIIRS nighttime light imagery exhibits a stronger ability than the DMSP-OLS nighttime light imagery to model and predict the gross regional product (GRP) in China. Due to absence of the GRP data in 2012, we made use of the 2012 NPP-VIIRS nighttime light imagery to model the GRP in 2010. Although there is a two-year gap between the NPP-VIIRS data and the GRP data, the NPP-VIIRS data exhibited good performance in modeling the GRP data. Naturally, we can infer that when using the NPP-VIIRS data to model the GRP data in the same year, the relationship should be stronger. Moreover, the NPP-VIIRS imagery we used is a primary product made by NOAA, who did not remove the background noise and some temporary lit sources, e.g., forest fires. To deal with this problem, we used a mask derived from the DMSP-OLS data in 2010 to only include the stable artificial lit sources to make the NPP-VIIRS data more efficient. Because the DMSP-OLS composites are generated from many individual images from one year with a series of advanced processing steps, such as denoising, while the NPP-VIIRS is only generated from several images without denoising, the two types of data cannot be directly compared. Nevertheless, the NPP-VIRRS data provided the best results, and there is significant room for improvement in the NPP-VIIRS data quality and NOAA is working to improve the data.

There are three potential factors that should make NPP-VIIRS imagery more efficient than the DMSP-OLS imagery in modeling the economy. First, the DMSP-OLS imagery has a serious problem of over-saturation in city centers because of the limitation of the radiometric detection ability [26]. To support this point of view, we calculated the ratio of the over-saturation area to the lit area for each provincial region from the DMSP-OLS data in 2010, and three regions, Beijing, Shanghai and Tianjin, were found to be in top three, with the ratio values of 13.82%, 13.41% and 4.93%, respectively. Because these three regions are highly over-saturated lit regions, the regression model significantly underestimated the GRP of the regions of Beijing, Shanghai and Tianjin, with relative errors of −54.6%, −67.9% and −35.6%, respectively, while the relative errors from the NPP-VIIRS estimation for Beijing, Shanghai and Tianjin were −40.6%, −17.9% and −5.0%, respectively (Table 4). Therefore, the GRP estimation can be improved significantly in the over-saturated regions when using the NPP-VIIRS data instead of the DMSP-OLS data. Second, while DMSP-OLS performs measurements around dusk or dawn, NPP-VIIRS performs measurements around midnight. Because human activities are often affected by time, the timing differences could have a big impact on sensors' capability to capture economic activities. Third, the onboard calibration on NPP-VIIRS, which is absent on DMSP-OLS, can also have a huge impact on data quality. The mechanism of the above three factors are primarily inferred, and more rigorous investigations should be taken to clarify them.

4. Discussion

Although there were several remotely sensed nighttime light sources of data [11,18,19], the only global source for economic modeling was the DMSP-OLS data, which is useful in mapping the spatial distribution of the economy. Nevertheless, the DMSP-OLS has severe limits in spatial resolution and radiometric detection range [22], which hinder accurate economic modeling. The optimal manner to observe the global nighttime light is by using the Nightsat Mission concept [27], which aims to develop a specific remote sensing satellite to comprehensively record the light at fine spatial, temporal, spectral and radiometric resolution. However, due to the high cost and technical requirements, the Nightsat Mission is only in the blueprint stage. Under this background, the NPP-VIIRS nighttime light imagery, a byproduct of the recently launched Suomi NPP satellite, is currently making great progress in acting as a bridge to the Nightsat mission from the DMSP satellites.

Historically, modeling China's regional economy using nighttime light imagery mainly takes prefecture and provincial level regions as material for analysis [13,17], and it is the first time to make the analysis in China's county level regions which is more valuable than those of the provincial and prefectural regions since the these regions are basic statistical units in China and their statistical data are more likely to have error. Like the previous work of modeling regional economy [13,14], the nighttime light data cannot model the regional economy as the unique source because the regression model should be set up with samples from economic data in the same country or region. Therefore, prior knowledge is needed when using the nighttime light in modeling regional economy.

Since the product of the global NPP-VIIRS nighttime light imagery was released by NOAA in 2013, there has been no published work related to the NPP-VIIRS nighttime light imagery, and this study is the first evaluation of NPP-VIIRS nighttime light imagery which proves the its stronger capacity in modeling regional economy than the DMSP-OLS nighttime light imagery.

5. Conclusion

The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi National Polar-orbiting Partnership (NPP) Satellite is a new generation sensor to record nighttime light, while this task was only assigned to the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) before 2011. As economic modeling is the a work that nighttime light imagery can efficiently deal with, this study made a first evaluation of the NPP-VIIRS nighttime light imagery by modeling China's regional economy in 31 provincial units and 393 county units.

Through regression analysis, the NPP-VIIRS data was found to exhibit a stronger capacity in modeling the regional economy compared with the nighttime light data acquired from the DMSP/F16 and DMSP/F18 satellites. Quantitatively, the total nighttime light (TNL) from NPP-VIIRS were found to exhibit R^2 values of 0.8699 and 0.8544 with the provincial GRP and county GRP, respectively, which are significantly stronger than the relationship (R^2 at 0.6923 and 0.7678 for F16 satellite and R^2 at 0.7056 and 0.6748 for F18 satellite) between the TNL from DMSP-OLS and GRP. And it is interesting find the TNL-GRP relationship can be significantly improved by discarding only two outliers in the regression analysis of the county level regions, making the R^2 values from 0.7678, 0.6748 and 0.8544 to 0.8513, 0.8011 and 0.9431 for DMSP-OLS/F16, DMSP-OLS/F18 and NPP-VIIRS, respectively. With this improvement, TNL from the NPP-VIIRS imagery can be used to predict the GRP in county level regions with 42.97% of them in high accuracy, while the rates of the DMSP-OLS/ F16 and DMSP-OLS/ F18 are 36.06% and 19.18%, respectively. All these results demonstrate that the NPP-VIIRS data is more powerful than the DMSP-OLS data in modeling regional economy.

The good performance of the NPP-VIIRS data revealed by our analysis provides a quantitative foundation to use such imagery as data source for taking the economic census in the countries with low-quality statistical systems and countries where economic data is blocked to the outside. Consequently, such economic census data can help international community to provide humanitarian aid to the regions under economic crisis and humanitarian disasters.

Since NPP-VIIRS imagery is a recently emerging data source, all the released data is one scene of images acquired in 2012, which is insufficient to make a comprehensive evaluation. As the National Oceanic and Atmospheric Administration (NOAA) is working to produce more and higher quality NPP-VIIRS nighttime light imagery, future study can be taken on multi-temporal analysis of the imagery in many fields such as land cover mapping, change detection, energy consumption evaluation and fishing boats detection. Besides, more advanced technique should be developed to analyze this kind of imagery because of its higher spatial resolution than the traditional DMSP-OLS nighttime light imagery.

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Conflict of Interest

The authors declare no conflict of interest.

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Appendix

Table A1. The gross regional product (GRP) and total nighttime light (TNL) in the 393 county level regions. DMSP 2009 represents the DMSP-OLS data in 2009, DMSP 2010 represents the DMSP-OLS data in 2010 and NPP 2012 represents the NPP-VIIRS data in 2012.

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Shitai County	Anhui	1.09	1.26	600	3958	195
Yi County	Anhui	1.37	1.58	2726	6946	214
Jingde County	Anhui	1.67	2.04	1343	5168	279
Qimen County	Anhui	2.77	3.21	2588	11458	327
Jixi County	Anhui	2.80	3.34	4828	9565	778
Xiuning County	Anhui	3.52	4.14	7283	17780	863
Qingyang County	Anhui	3.54	4.35	9201	24772	1390
Yuexi County	Anhui	3.52	4.55	3200	10000	418
Jing County	Anhui	3.84	4.68	4529	14337	1422
Taihu County	Anhui	4.44	5.62	3105	13742	765
Wangjiang County	Anhui	4.46	5.72	9361	22784	1296
Langxi County	Anhui	4.45	5.74	11598	28641	3061
Jinzhai County	Anhui	5.12	6.02	5420	15400	1178
Hanshan County	Anhui	5.35	6.44	15371	33384	2638
Quanjiao County	Anhui	5.40	6.50	19509	39962	4224
Mingguang Municipality	Anhui	5.76	6.79	14242	29927	2431
Laian County	Anhui	5.78	6.99	20144	43873	3554
Dongzhi County	Anhui	5.65	7.02	9070	23760	1113
Jieshou Municipality	Anhui	5.96	7.26	13582	22460	2765
Tongling County	Anhui	5.75	7.46	26701	56953	6367
Qianshan County	Anhui	5.60	7.79	6320	21054	1194
Dangshan County	Anhui	6.53	7.89	20508	34040	2325
She County	Anhui	6.76	7.92	15457	30582	1318
Guzhen County	Anhui	6.63	8.17	10176	14789	1629
Funan County	Anhui	7.04	8.30	17354	39513	3362
Huoshan County	Anhui	6.68	8.35	10776	20434	1078
Fengyang County	Anhui	7.26	8.52	25633	50011	4068
Linquan County	Anhui	7.47	8.59	20005	43359	3308
Dingyuan County	Anhui	7.23	8.65	15208	43881	3366
He County	Anhui	7.27	8.72	29517	67510	4583
Si County	Anhui	7.36	8.78	10130	20544	1293
Wuhe County	Anhui	7.46	8.93	9257	17153	1314
Susong County	Anhui	7.09	9.08	7380	22338	1002

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Lingbi County	Anhui	7.81	9.17	8646	19198	2112
Lixin County	Anhui	8.13	9.49	15142	34196	2597
Shucheng County	Anhui	8.00	9.50	11946	26730	2211
Guangde County	Anhui	8.24	9.93	17685	46405	4182
Nanling County	Anhui	8.17	10.14	12162	31322	2905
Wuhu County	Anhui	8.05	10.30	20098	39535	4121
Lujiang County	Anhui	8.87	10.39	17414	47753	3881
Shou County	Anhui	9.34	10.69	11204	26681	2058
Fanchang County	Anhui	8.77	10.83	19200	42794	5279
Taihe County	Anhui	9.41	11.13	25007	48253	3836
Huaining County	Anhui	8.51	11.24	17650	46347	2930
Suixi County	Anhui	9.17	11.28	53721	93125	9143
Mengcheng County	Anhui	9.58	11.43	9971	23534	3422
Xiao County	Anhui	9.65	11.65	32039	56087	4444
Zongyang County	Anhui	9.30	12.05	11601	38071	1706
Yingshang County	Anhui	10.57	12.56	36005	65478	5193
Guoyang County	Anhui	10.58	12.80	20960	39524	3556
Ningguo Municipality	Anhui	10.68	13.01	12723	26474	2716
Tongcheng Municipality	Anhui	10.28	13.41	13763	33199	2403
Huaiyuan County	Anhui	11.19	13.56	20597	41501	3508
Huangshan Municipality	Anhui	12.28	14.08	26402	46573	2918
Huoqiu County	Anhui	11.43	14.29	20824	50157	3371
Tianchang Municipality	Anhui	11.71	14.70	33932	63225	4316
Xuancheng Municipality	Anhui	13.12	14.75	28843	64269	6570
Chaozhou Municipality	Anhui	14.06	15.49	26473	60916	5511
Chizhou Municipality	Anhui	12.67	15.93	29289	68075	5201
Changfeng County	Anhui	13.22	16.38	44547	92780	11225
Lu'an Municipality	Anhui	12.67	16.50	45404	92679	7632
Fengtai County	Anhui	14.71	17.20	31259	56319	4719
Chuzhou Municipality	Anhui	13.65	17.42	39095	67148	11717
Bozhou Municipality	Anhui	16.02	17.56	42206	78069	8010
Dangtu County	Anhui	14.93	18.94	38519	84967	10239
Wuwei County	Anhui	17.85	21.92	26172	79470	5742
Feidong County	Anhui	18.68	22.00	52264	95739	13586
Fuyang Municipality	Anhui	18.89	24.29	47526	85478	10732
Suuzhou Municipality	Anhui	21.52	24.65	51042	87029	11054
Feixi County	Anhui	21.46	27.48	58519	115414	21955
Anqing Municipality	Anhui	19.23	28.35	20434	37711	5004
Bengbu Municipality	Anhui	26.71	31.52	36650	55499	12621
Huaibei Municipality	Anhui	28.19	34.88	27697	34727	4770
Tongling Municipality	Anhui	28.61	39.21	8667	14596	2893
Huainan Municipality	Anhui	36.25	43.16	55452	97019	11547
Maanshan Municipality	Anhui	52.07	62.16	32907	51075	14471
Wuhu Municipality	Anhui	65.23	79.47	55272	96989	20943
Hefei Municipality	Anhui	159.15	192.04	75696	96792	37327
Songxi County	Fujian	2.05	2.39	2576	4437	324
Zhenghe County	Fujian	2.06	2.40	2570	7101	701

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB) 2009	GRP (Billion RMB) 2010	TNL DMSP 2009	TNL DMSP 2010	TNL NPP 2012
Zherong County	Fujian	2.28	2.71	2277	3022	303
Zhouning County	Fujian	2.29	2.72	3962	6793	792
Mingxi County	Fujian	2.66	3.18	2845	6474	553
Guangze County	Fujian	2.92	3.43	3030	6043	593
Pingnan County	Fujian	2.88	3.44	3071	4897	356
Shouning County	Fujian	3.00	3.63	3291	4200	282
Qingliu County	Fujian	3.51	4.25	4718	12014	905
Jianning County	Fujian	3.51	4.28	3733	7580	488
Huaan County	Fujian	3.58	4.33	9503	14047	1502
Taining County	Fujian	3.95	4.54	5216	12732	812
Shunchang County	Fujian	4.49	5.16	4763	7251	712
Jiangle County	Fujian	4.41	5.36	6845	14908	1199
Ninghua County	Fujian	4.81	5.88	4591	12680	1138
Pucheng County	Fujian	5.49	6.47	5395	9260	614
Wuyishan Municipality	Fujian	5.59	6.58	14713	24115	3306
Yongtai County	Fujian	6.16	7.30	8506	16439	1424
Yunxiao County	Fujian	5.83	7.33	12778	16822	3097
Wuping County	Fujian	6.16	7.42	10250	17016	1277
Dongshan County	Fujian	5.90	7.84	17326	25966	2005
Jianyang Municipality	Fujian	6.64	7.86	13000	22940	3814
Changtai County	Fujian	6.18	7.90	19932	35352	5983
Liancheng County	Fujian	6.24	7.95	15152	22482	2051
Gutian County	Fujian	6.92	8.19	11368	10998	1430
Minqing County	Fujian	7.38	8.43	10946	15165	1406
Datian County	Fujian	6.60	8.57	19737	27425	2586
Pinghe County	Fujian	7.25	8.77	15062	29275	2691
Changting County	Fujian	7.27	8.83	11065	21215	1820
Pingtan County	Fujian	7.36	8.97	6260	13157	2527
Xiapu County	Fujian	7.99	9.39	11008	16280	1873
Zhaoan County	Fujian	8.09	9.72	17645	29203	2365
Youxi County	Fujian	8.31	10.00	17224	20443	1743
Zhangping Municipality	Fujian	8.30	10.16	14054	24240	2142
Dehua County	Fujian	8.86	10.17	13105	19916	3126
Jian'ou Municipality	Fujian	8.72	10.32	13460	20129	1912
Luoyuan County	Fujian	7.89	10.39	17438	25783	3568
Sha County	Fujian	8.58	10.43	21883	29577	3097
Shaowu Municipality	Fujian	8.93	10.62	9286	16881	1775
Nanjing County	Fujian	8.95	10.72	20884	37403	2940
Yongding County	Fujian	9.46	11.10	23248	40901	3602
Shanghang County	Fujian	10.83	12.67	24797	41454	4025
Ningde Municipality	Fujian	10.84	12.68	17337	26348	5279
Fuding Municipality	Fujian	10.76	13.38	20452	39310	5972
Xianyou County	Fujian	11.94	13.98	27430	45824	5675
Zhangpu County	Fujian	12.56	15.00	38744	63326	6961
Yongchun County	Fujian	14.88	17.10	24363	37750	4914
Nanping Municipality	Fujian	15.27	17.64	26329	29903	3188
Fuan Municipality	Fujian	14.28	17.72	22684	31858	4381

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Yongan Municipality	Fujian	14.99	18.28	22729	39269	3614
Lianjiang County	Fujian	15.78	18.85	25709	40090	5978
Sanming Municipality	Fujian	18.69	22.75	23057	33285	4147
Minhou County	Fujian	19.69	23.85	45480	81670	12996
Changle Municipality	Fujian	25.47	30.31	40017	64114	11062
Anxi County	Fujian	24.90	30.60	46147	77389	7589
Zhangzhou Municipality	Fujian	29.98	34.90	18013	26673	5252
Longhai Municipality	Fujian	29.48	36.55	88742	128540	18143
Shishi Municipality	Fujian	32.53	37.02	30541	33853	10607
Huian County	Fujian	34.45	39.94	58138	81808	10128
Longyan Municipality	Fujian	34.23	40.97	45677	71967	8818
Fuqing Municipality	Fujian	41.14	47.74	61439	107343	12364
Nan'an Municipality	Fujian	41.34	48.23	97952	151295	23615
Putian Municipality	Fujian	57.20	71.05	100083	143903	24093
Quanzhou Municipality	Fujian	70.36	82.59	68031	87346	21784
Jinjiang Municipality	Fujian	79.89	90.89	116079	136841	28985
Fuuzhou Municipality	Fujian	132.80	154.36	79436	106963	34064
Xiamen Municipality	Fujian	173.72	206.01	171921	208384	66025
Nan'ao County	Guangdong	0.80	0.95	2053	3438	271
LianshanZhuang&Yao A.C.	Guangdong	1.38	1.71	3808	5376	563
LiannanYao A.C.	Guangdong	1.48	1.89	3851	6484	622
Xinfeng County	Guangdong	2.62	3.06	5890	9579	666
Luhe County	Guangdong	2.64	3.21	8331	16157	1097
Shixing County	Guangdong	2.86	3.42	7151	10970	970
Pingyuan County	Guangdong	2.91	3.52	9918	16670	1446
RuyuanYao A.C.	Guangdong	3.34	3.87	8071	11714	1120
Heping County	Guangdong	3.50	3.97	8794	13144	1287
Wengyuan County	Guangdong	3.58	4.05	10671	14777	1133
Jiaoling County	Guangdong	3.61	4.30	11194	17606	1122
Yun'an County	Guangdong	3.79	4.42	14272	22749	1483
Dapu County	Guangdong	3.90	4.46	12271	28393	1785
Fengshun County	Guangdong	4.95	5.87	12113	28000	2004
Yu'nan County	Guangdong	5.18	5.88	22662	34245	2386
Dongyuan County	Guangdong	5.11	5.95	23459	37628	3410
Nanxiong Municipality	Guangdong	4.74	6.03	6400	11116	737
Renhua County	Guangdong	5.18	6.29	7477	11576	878
Zijin County	Guangdong	5.47	6.32	20356	32027	2133
Yangshan County	Guangdong	5.04	6.37	11789	19837	1667
Lechang Municipality	Guangdong	5.59	6.48	10661	17425	1815
Deqing County	Guangdong	5.07	6.59	15473	22372	1698
Lianping County	Guangdong	5.94	6.80	11521	16186	1095
Longmen County	Guangdong	5.74	6.88	21708	38343	2708
Wuhua County	Guangdong	5.94	7.05	19332	38003	2229
Fengkai County	Guangdong	5.64	7.06	18450	22212	1581
Guangning County	Guangdong	6.01	7.10	18770	26164	1819
Xuwen County	Guangdong	6.54	7.78	14399	26499	1632
Yangxi County	Guangdong	7.21	8.74	18865	32697	3273

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Yunfu Municipality	Guangdong	7.60	8.86	29787	41835	4433
Longchuan County	Guangdong	7.71	8.89	14022	20700	1768
Luoding Municipality	Guangdong	7.90	9.06	16638	24275	2663
Enping Municipality	Guangdong	8.15	9.33	31348	46356	3483
Xingning Municipality	Guangdong	8.25	9.90	26741	39538	2657
Lianzhou Municipality	Guangdong	8.37	10.70	11688	17765	1971
Wuchuan Municipality	Guangdong	9.00	10.80	27646	43625	4237
Fogang County	Guangdong	9.37	11.44	28759	41852	3499
Chaozhou Municipality	Guangdong	10.78	11.49	76370	100636	11172
Jiexi County	Guangdong	9.72	11.83	19141	33417	2047
Xinxing County	Guangdong	9.99	11.87	21010	34459	3001
Huaiji County	Guangdong	9.58	11.91	18304	27930	2381
Huilai County	Guangdong	10.34	12.82	23854	40573	3769
Leizhou Municipality	Guangdong	10.64	12.83	20978	48281	2743
Mei County	Guangdong	10.79	12.85	30562	47950	3979
Yangdong County	Guangdong	10.54	12.99	36190	56185	6005
Shanwei Municipality	Guangdong	11.73	13.01	20541	29957	2172
Meizhou Municipality	Guangdong	11.58	13.34	16853	20712	2879
Raoping County	Guangdong	11.41	13.35	28849	45790	3959
Lufeng Municipality	Guangdong	11.53	13.72	37179	58702	5403
Suixi County	Guangdong	11.65	13.91	43086	76667	5513
Haifeng County	Guangdong	13.24	15.29	39775	60143	5569
Heyuan Municipality	Guangdong	12.83	15.59	34851	45734	5851
Sihui Municipality	Guangdong	17.90	16.06	48263	63726	7002
Heshan Municipality	Guangdong	14.36	16.17	48717	71479	6508
Yangchun Municipality	Guangdong	14.62	17.84	38393	56037	6186
Lianjiang Municipality	Guangdong	15.43	18.28	31526	65026	7094
Conghua Municipality	Guangdong	15.60	18.73	55067	78032	7090
Qingxin County	Guangdong	15.19	20.06	40751	68103	6482
Kaiping Municipality	Guangdong	16.81	20.11	42475	66046	5932
Xinyi Municipality	Guangdong	17.45	20.59	11930	15958	1010
Yingde Municipality	Guangdong	15.96	20.89	47561	76056	9607
Dianbai County	Guangdong	17.87	21.27	48352	68477	9222
Gaoyao Municipality	Guangdong	17.04	21.52	67775	98782	10623
Huazhou Municipality	Guangdong	19.14	22.77	22671	40060	3466
Jieyang Municipality	Guangdong	18.60	23.01	31729	36078	6065
Taishan Municipality	Guangdong	19.30	23.10	63438	107565	8929
Jiedong County	Guangdong	18.43	23.16	46547	70353	8449
Huidong County	Guangdong	21.66	25.05	63030	89077	8628
Yangjiang Municipality	Guangdong	20.36	25.42	29563	39818	8396
Gaozhou Municipality	Guangdong	24.16	27.84	28684	40325	2962
Boluo County	Guangdong	25.27	29.48	118718	160817	14087
Puning Municipality	Guangdong	24.28	30.12	57220	98232	10248
Chaoan County	Guangdong	27.05	31.40	17962	19697	3277
Shaoguan Municipality	Guangdong	29.32	34.06	72417	86389	10796
Qingyuan Municipality	Guangdong	31.37	35.81	86498	104861	15808
Zhaoqing Municipality	Guangdong	32.53	38.45	41911	55683	10670

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB) 2009	GRP (Billion RMB) 2010	TNL DMSP 2009	TNL DMSP 2010	TNL NPP 2012
Maoming Municipality	Guangdong	44.51	56.73	32469	48799	7973
Zengcheng Municipality	Guangdong	57.25	68.16	129535	176085	20933
Zhanjiang Municipality	Guangdong	62.39	76.91	71797	100806	22033
Jiangmen Municipality	Guangdong	76.84	88.38	158420	210843	24661
Huizhou Municipality	Guangdong	88.83	113.05	226298	275805	39995
Shaotou Municipality	Guangdong	102.79	119.95	204871	258243	35836
Zhuhai Municipality	Guangdong	103.87	120.86	159386	202466	30467
ZhongShan Municipality	Guangdong	156.64	185.07	308903	342023	63758
Dongguan Municipality	Guangdong	376.39	424.65	528739	543842	120807
Foshan Municipality	Guangdong	482.09	565.15	588483	640247	128858
Shenzhen Municipality	Guangdong	820.13	958.15	384745	400431	121564
Guangzhou Municipality	Guangdong	840.97	987.94	577226	630177	147401
Zixi County	Jiangxi	1.41	1.65	1546	4028	331
Tonggu County	Jiangxi	1.58	2.00	1858	6542	404
Guangchang County	Jiangxi	1.60	2.02	3485	5975	345
Jing'an County	Jiangxi	1.87	2.23	3539	7518	591
Shicheng County	Jiangxi	2.05	2.30	4609	9233	595
Yihuang County	Jiangxi	2.24	2.71	2875	6113	150
Quannan County	Jiangxi	2.37	2.71	3919	7235	335
Shangyou County	Jiangxi	2.48	2.77	3622	5413	306
Lianhua County	Jiangxi	2.34	2.81	1882	4151	195
Le'an County	Jiangxi	2.48	2.89	2048	4746	189
Xiajiang County	Jiangxi	2.36	2.90	1764	7142	551
Anyuan County	Jiangxi	2.64	2.96	3861	8076	390
Xunwu County	Jiangxi	2.59	3.07	4790	14035	841
Jinggangshan Municipality	Jiangxi	2.55	3.11	4899	8839	906
Dingnan County	Jiangxi	2.75	3.11	5455	9823	781
Lichuan County	Jiangxi	2.57	3.12	3402	7475	285
Wan'an County	Jiangxi	2.63	3.29	2009	4855	174
Xingzi County	Jiangxi	2.27	3.34	6906	16653	828
Jinxi County	Jiangxi	3.08	3.62	5547	10762	893
Dean County	Jiangxi	2.74	3.73	5734	14662	887
Pengze County	Jiangxi	3.11	3.77	4479	14116	753
Chongyi County	Jiangxi	3.19	3.82	2439	3957	289
Huichang County	Jiangxi	3.60	4.25	5079	13797	1088
Hengfeng County	Jiangxi	3.66	4.49	4072	8008	671
Duchang County	Jiangxi	3.60	4.50	4577	13222	731
Yiyang County	Jiangxi	3.60	4.51	8164	14768	901
Yujiang County	Jiangxi	3.29	4.52	9800	18754	974
Yongxin County	Jiangxi	3.79	4.62	2669	6500	243
Jiujiang County	Jiangxi	3.76	4.64	11242	30527	2096
Wuyuan County	Jiangxi	4.15	4.77	7105	19674	1591
Wuning County	Jiangxi	4.23	5.09	2771	15158	630
Wannian County	Jiangxi	4.24	5.10	7032	13266	671
Yifeng County	Jiangxi	4.06	5.10	4642	16919	995
Yanshan County	Jiangxi	4.39	5.18	10549	19105	1234
Anyi County	Jiangxi	4.50	5.28	6928	14280	612

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Chongren County	Jiangxi	4.54	5.38	2196	7510	371
Nancheng County	Jiangxi	4.42	5.41	7532	12846	692
Xin'gan County	Jiangxi	4.35	5.42	4527	9037	294
Fuliang County	Jiangxi	4.60	5.43	13099	26935	1547
Nanfeng County	Jiangxi	4.53	5.43	7043	11131	587
Suichuan County	Jiangxi	4.50	5.45	3225	7566	501
Dayu County	Jiangxi	5.25	5.69	6305	10177	623
Wanzai County	Jiangxi	4.70	5.76	3741	8227	423
Jishui County	Jiangxi	4.88	6.00	4122	9062	374
Longnan County	Jiangxi	5.13	6.01	9617	17828	1138
Xiushui County	Jiangxi	5.05	6.13	3485	13112	930
Fengxin County	Jiangxi	5.16	6.28	8855	17928	945
Ruichang Municipality	Jiangxi	5.21	6.29	7693	17180	1568
Yongxiu County	Jiangxi	5.43	6.33	11132	31008	1551
Hukou County	Jiangxi	4.82	6.43	6897	16283	1497
Ruijin Municipality	Jiangxi	5.40	6.51	14468	23857	2332
Yongfeng County	Jiangxi	5.25	6.51	2143	7675	578
Yugan County	Jiangxi	5.56	6.57	10342	17045	888
Anfu County	Jiangxi	5.34	6.60	3605	8939	415
Yushan County	Jiangxi	5.27	6.76	10191	22308	1489
Dongxiang County	Jiangxi	5.69	7.03	6708	16345	1193
Shanggao County	Jiangxi	5.94	7.11	7244	20562	1299
Luxi County	Jiangxi	5.96	7.31	2649	7626	523
Ji'an County	Jiangxi	5.92	7.40	6644	16870	1352
Gan County	Jiangxi	6.24	7.46	8908	15620	1438
Xingguo County	Jiangxi	6.48	7.55	8258	12458	681
Taihe County	Jiangxi	6.29	7.64	5932	12746	871
Ningdu County	Jiangxi	6.43	7.65	11172	12139	727
Poyang County	Jiangxi	6.74	8.03	14947	32500	1681
Xinfeng County	Jiangxi	7.06	8.40	9514	16072	947
Nankang Municipality	Jiangxi	7.41	8.49	21806	35909	2598
Shangrao County	Jiangxi	6.69	8.72	22328	44378	4282
Yudu County	Jiangxi	7.43	8.95	7342	13867	1142
Dexing Municipality	Jiangxi	7.71	9.07	16312	33223	2297
Yingtan Municipality	Jiangxi	6.56	9.17	10005	13941	2163
Shangli County	Jiangxi	8.02	9.89	6254	17415	1013
Fenyi County	Jiangxi	8.02	10.10	5246	15759	1135
Ji'an Municipality	Jiangxi	9.06	10.83	19590	33020	4055
Gao'an Municipality	Jiangxi	9.27	11.25	12617	36253	2484
Shangrao Municipality	Jiangxi	9.55	11.54	7490	10354	2344
Yichun Municipality	Jiangxi	9.89	11.62	14335	38463	3289
Leping Municipality	Jiangxi	12.19	14.34	14164	26411	1758
Guangfeng County	Jiangxi	12.80	15.10	11024	15890	1149
Zhangshu Municipality	Jiangxi	11.80	15.21	9563	22448	2022
Jinxian County	Jiangxi	14.32	16.52	14227	25356	1474
Xinjian County	Jiangxi	14.75	17.52	40679	71023	9311
Fuzhou Municipality	Jiangxi	17.13	20.35	26907	43987	4226

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB) 2009	GRP (Billion RMB) 2010	TNL DMSP 2009	TNL DMSP 2010	TNL NPP 2012
Guixi Municipality	Jiangxi	15.48	20.58	18772	28958	3099
Ganzhou Municipality	Jiangxi	18.35	20.91	30439	40155	7244
Fengcheng Municipality	Jiangxi	20.05	24.09	30459	56365	4652
Jingdezhen Municipality	Jiangxi	19.61	26.38	18471	28061	3411
Nanchang County	Jiangxi	25.53	30.60	57717	87257	10148
Pingxiang Municipality	Jiangxi	26.10	32.03	16906	32202	2747
Jiujiang Municipality	Jiangxi	39.03	47.08	27771	47149	6168
Xinyu Municipality	Jiangxi	40.39	53.02	32904	64539	6765
Nanchang Municipality	Jiangxi	124.65	150.10	52770	72453	15290
JingningShe A.C.	Zhejiang	2.29	2.68	4180	5656	435
Qingyuan County	Zhejiang	2.63	3.17	3398	4735	326
Yunhe County	Zhejiang	2.80	3.35	5809	8944	990
Dongtou County	Zhejiang	3.00	3.44	2278	4129	613
Taishun County	Zhejiang	3.41	3.98	6076	9417	781
Wencheng County	Zhejiang	3.52	4.05	8324	14685	1684
Songyang County	Zhejiang	3.90	4.75	10180	15556	1662
Pan'an County	Zhejiang	4.07	4.82	6247	12479	1050
Suichang County	Zhejiang	4.87	5.77	7558	14742	1349
Shengsi County	Zhejiang	5.34	5.89	3544	4791	1115
Longquan Municipality	Zhejiang	5.16	6.26	10406	13074	1288
Kaihua County	Zhejiang	5.91	7.02	10055	17518	1740
Changshan County	Zhejiang	6.20	7.55	12293	23418	2209
Xianju County	Zhejiang	8.40	10.10	15757	30330	2580
Sanmen County	Zhejiang	8.89	10.66	20153	32937	3036
Jinyun County	Zhejiang	9.11	11.22	17004	26917	2420
Qingtian County	Zhejiang	9.42	11.43	18743	33025	3177
Chun'an County	Zhejiang	10.07	11.75	13738	27233	2126
Longyou County	Zhejiang	9.77	11.83	15369	32657	2728
Tiantai County	Zhejiang	10.07	11.86	19741	33465	3406
Daishan County	Zhejiang	10.24	12.81	9050	17440	1797
Wuyi County	Zhejiang	10.80	12.96	19530	35590	3640
Pujiang County	Zhejiang	11.08	13.16	19795	37288	3410
Jiangshan Municipality	Zhejiang	14.11	17.02	20167	38761	2876
Lishui Municipality	Zhejiang	14.39	17.52	30283	48378	7021
Lanxi Municipality	Zhejiang	14.74	18.03	24391	44645	4390
Jiande Municipality	Zhejiang	16.22	18.96	25266	49904	3865
Anji County	Zhejiang	15.90	19.01	32444	65835	6482
Tonglu County	Zhejiang	16.73	19.79	27372	49787	6646
Pingyang County	Zhejiang	17.39	20.26	26927	49809	6336
Yongjia County	Zhejiang	17.62	20.51	33419	55645	5501
Xinchang County	Zhejiang	18.73	21.51	20065	33023	4450
Fenghua Municipality	Zhejiang	19.39	22.51	32874	63007	6300
Haiyan County	Zhejiang	21.02	23.83	30902	57629	6106
Deqing County	Zhejiang	20.33	24.02	38101	75838	7020
Cangnan County	Zhejiang	21.72	25.48	35920	61188	8842
Xiangshan County	Zhejiang	23.61	27.17	29780	55327	7088
Shengzhou Municipality	Zhejiang	23.17	27.34	34342	60169	4537

Table A1. *Cont.*

County Name	Province	GRP (Billion RMB)		TNL		
		2009	2010	DMSP 2009	DMSP 2010	NPP 2012
Jiashan County	Zhejiang	22.64	27.61	36047	68991	6407
Ninghai County	Zhejiang	23.62	27.87	38738	67634	6931
Changxing County	Zhejiang	24.04	28.39	51645	95127	10249
Dongyang Municipality	Zhejiang	24.40	28.69	51462	85429	13501
Lin'an Municipality	Zhejiang	23.50	28.77	27757	53683	5031
Yuhuan County	Zhejiang	24.48	30.82	27406	41567	6498
Yongkang Municipality	Zhejiang	26.09	31.05	37850	62849	6883
Quzhou Municipality	Zhejiang	26.48	32.62	38721	69603	6272
Linhai Municipality	Zhejiang	27.70	32.80	67354	101233	9949
Pinghu Municipality	Zhejiang	28.37	34.05	42615	79440	10226
Jinhua Municipality	Zhejiang	34.05	40.30	54954	95908	12331
Tongxiang Municipality	Zhejiang	34.03	40.93	50329	96246	10185
Fuyang Municipality	Zhejiang	35.25	41.57	50951	100689	12054
Shangyu Municipality	Zhejiang	36.82	43.63	57164	96220	11564
Haining Municipality	Zhejiang	37.53	45.58	57769	103112	10130
Zhoushan Municipality	Zhejiang	37.95	45.65	50891	98634	12725
Ruian Municipality	Zhejiang	38.28	45.72	59828	90356	15623
Shaoxing Municipality	Zhejiang	40.76	46.67	10638	15166	4355
Leqing Municipality	Zhejiang	42.35	49.58	57076	92612	11524
Yuyao Municipality	Zhejiang	48.92	56.79	84664	148997	23042
Jiaxing Municipality	Zhejiang	48.22	57.82	86150	146412	16040
Wenling Municipality	Zhejiang	50.20	58.15	69597	104369	15206
Huzhou Municipality	Zhejiang	50.61	59.64	86924	155486	18378
Yiwu Municipality	Zhejiang	52.38	61.99	83731	120519	28499
Zhuji Municipality	Zhejiang	52.77	62.15	73386	125610	11760
Cixi Municipality	Zhejiang	62.49	75.74	97703	165870	31900
Shaoxing County	Zhejiang	65.58	77.61	93368	152755	25479
Taaizhou Municipality	Zhejiang	72.93	85.28	94652	134089	24225
Wenzhou Municipality	Zhejiang	105.43	119.63	78065	103949	30137
Ningbo Municipality	Zhejiang	254.90	306.22	224290	359909	93111
Hangzhou Municipality	Zhejiang	406.99	474.08	361647	552131	131346