International Journal of Applied Earth Observation and Geoinformation 50 (2016) 39–50

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

These lit areas are undeveloped: Delimiting China's urban extents from thresholded nighttime light imagery

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ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 19 February 2016
Accepted 27 February 2016
Available online 14 March 2016

Keywords:
Nighttime light imagery
Urban extents
China
Threshold
GDP per capita

ABSTRACT

Nighttime light imagery is a powerful tool to study urbanization because it can provide a uniform metric, lit area, to delimit urban extents. However, lit area is much larger than actual urban area, so thresholds of digital number (DN) values are usually needed to reduce the lit area. The threshold varies greatly among different regions, but at present it is still not very clear what factors impact the changes of the threshold. In this study, urban extent by province for China is mapped using official statistical data and four intercalibrated and geometrically corrected nighttime light images between 2004 and 2010. Lit area in the imagery for most provinces is at least 94% greater than the official amount of urban area. Regression analyses show a significant correlation between optimal thresholds and GDP per capita, and larger thresholds more commonly indicate higher economic level. Size and environmental condition may explain a province's threshold that is disproportionate to GDP. Findings indicate one threshold DN is not appropriate for multiple (adjacent) province urban extent mapping, and optimal thresholds for one year may be notably different than the next. Province-level derived thresholds are not appropriate for other geographic levels. Brightness of nighttime lights is an advantage over imagery that relies on daylight reflection, and decreases in brightness indicate faster growth in the horizontal direction than the vertical. A province's optimal threshold does not always maintain an increase with population and economic growth. In the economically developed eastern provinces, urban population densities decreased (and this is seen in the brightness data), while urban population increased.

1. Introduction

"In 1950, 30 percent of the world's population was urban, and by 2050, 66 percent of the world's population is projected to be urban" (United Nations, 2014).

Urbanization influences social and environmental systems across different geographic scales (Small et al., 2005; Imhoff et al., 1997). Rapid urban development leads to issues, such as housing shortages, employment pressures, natural resource depletion, environmental pollution, and ecological degradation (Travisi et al., 2010; Bart, 2010; Miller, 2012). Delimiting urban extents is important for understanding the rate of urbanization and the associated social and ecological issues. However, it is not a trivial task to map urban extents at large geographic scales. At present, geographical and environmental researchers use remote sensing as a tool to map urban extents over large areas (Schneider et al., 2010; Small et al., 2005; Zhou et al., 2015). The biggest challenge of using remotely sensed imagery based on daytime reflectance to delimit urban extents is the lack of a uniform administrative definition among countries/regions (Small et al., 2005). The Defense Meteorology Satellite Program's Operational Linescan System (DMSP-OLS) nighttime light imagery provides a uniform metric to monitor and analyze urban expansion by the physical measurement of lit area (Small et al., 2005). Yet, lit areas derived from nighttime light imagery cannot be used directly to delimit urban areas due to the blooming effect (Imhoff et al., 1997; Liu et al., 2012; Small et al., 2005). The blooming effect is a phenomenon in DMSP-OLS nighttime light imagery where urban peripheries are brightened by urban lights (Imhoff et al., 1997; Doll, 2008). Lit areas in original nighttime light imagery are larger than actual urban areas. Setting thresholds of DN values is often used to negate this issue. The thresholded method is to define a DN value on nighttime

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http://dx.doi.org/10.1016/j.jag.2016.02.011
0303-2434/

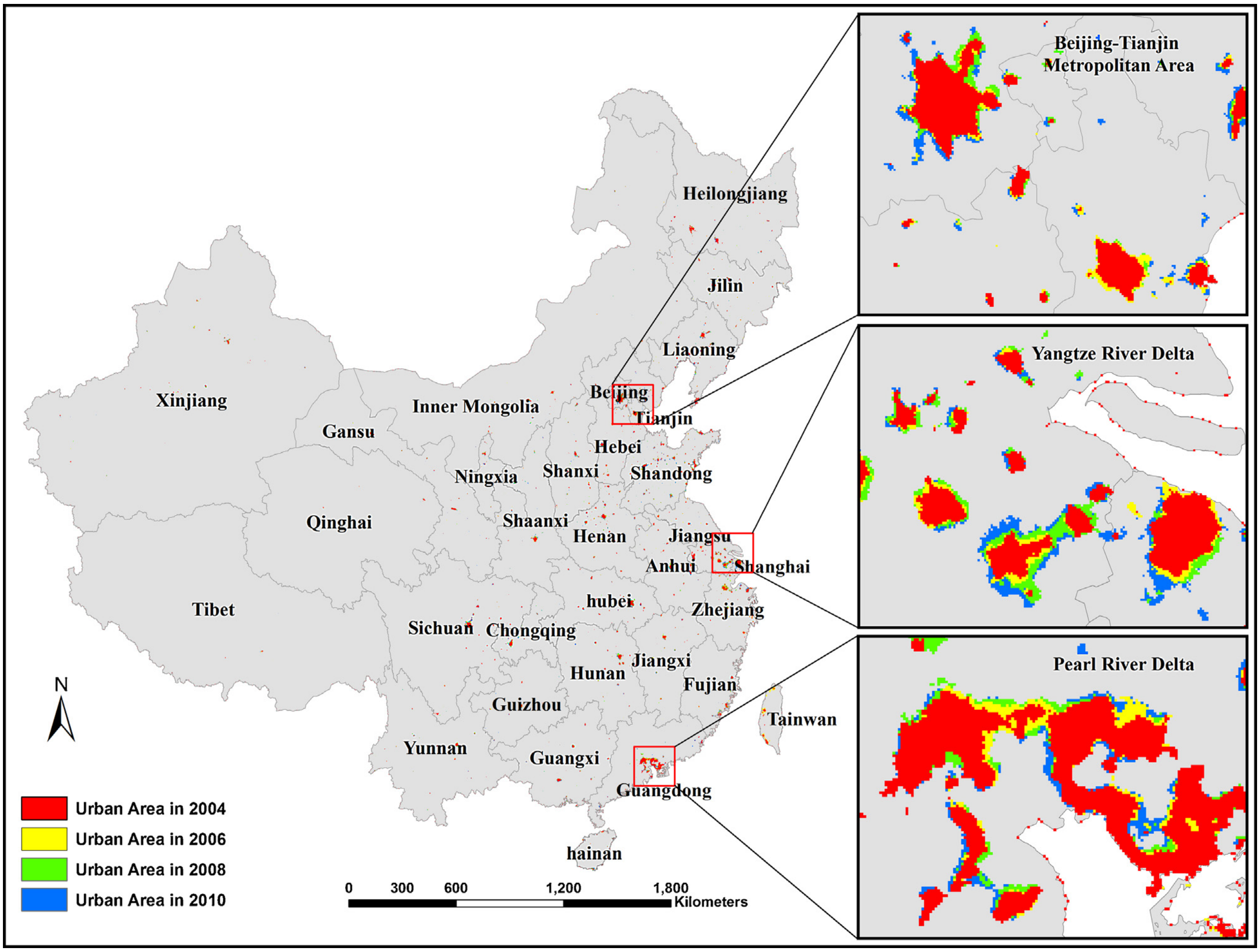

Fig. 1. Urban expansion in China derived from nighttime lights imagery from 2004 to 2010.

light imagery, which can attenuate the blooming effect and make the lit area more representative of the actual urban area.

In early nighttime light image products (i.e., frequency detection nighttime light images or percent-lighted images), reflection in the visible and near infrared was quantified at 2.7 km resolution using an algorithm for smoothing background disparities (Elvidge et al., 1997). The digital number (DN) of each pixel in this product represents the ratio of lighted observations to total cloud-free observations multiplied by 100. Imhoff et al. (1997) analyzed a dataset of 231 orbital swaths between the Fall of 1994 and the Spring of 1995 and ultimately calculated 89 as the best threshold value to negate blooming and map urban extents for the United States (U.S.). Small et al. (2005) found that although a relatively large DN-value threshold did minimize blooming areas, on a global scale, too large a number of small settlements were masked simultaneously. Consequently, Small et al. (2005) selected 14 and 10 as threshold of DN values to extract global urban areas from 1992 to 1993 and 1994 to 1995 frequency detection nighttime light image products, respectively. Currently, annual stable light image products are more widely used as the background noises of ephemeral events are removed. They are annual composites and cover a longer time extent (1992 to 2013). Sutton et al. (2007, 2010) selected 30 and 11 as threshold DN values to delimit urban extents for U.S. and Australia, respectively. Zhao et al. (2012) selected 10 as a threshold to remove blooming areas from lit areas for China. These studies reveal that optimal thresholds for accurately delimiting urban extents vary from place to place.

Since the economic reform in 1978, China experienced exceptional economic growth and unprecedented urbanization (Chen, 2007; Liu et al., 2012; Liu, 2010). The rapid urbanization led to a number of serious social and environmental problems and consequently the attention of geographers and environmentalists (Chen, 2007; Liu et al., 2012; Liu, 2010). China's economic growth and urbanization is spatially imbalanced (Fujita and Hu, 2001; Keng, 2006). Previous stable light imagery studies find a single threshold does not extract Chinese urban extents accurately from nighttime light imagery (Liu et al., 2012; Xiao et al., 2014; Yu et al., 2014). Consequently, Liu et al. (2012); Xiao et al. (2014); Yu et al. (2014) divided China into regions. Each region includes a few provinces and was given a uniform threshold because the provinces are spatially adjacent and supposedly have similar economic development characteristics. However, there is no study to test whether such divisions are reliable and whether economic level really influences threshold variation.

The objectives of this study are to explore: (1) divided China into regions. Each region includes a few provinces and was given a uniform threshold because the provinces are spatially adjacent and supposedly have similar economic development characteristics. However, there is no study to test whether such divisions are reliable and whether economic level really influences threshold variation.

The objectives of this study are to explore: (1) optimal thresholds to extract Chinese urban areas from nighttime light imagery, (2) the dominant land cover type(s) in lit area, (3) the factors that impact variations in optimal thresholds for different provinces and