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Feasibility of a new-generation nighttime light data for estimating in-use steel stock of buildings and civil engineering infrastructures

Hanwei Liang[a,*], Liang Dong[a,b,c,*], Hiroki Tanikawa[d], Ning Zhang[e,f], Zhiqiu Gao[g], Xiao Luo[h]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disaster, School of Geography and Remote Sensing, Nanjing University of Information Science & Technology, Nanjing 210044, China
[b] CML, Leiden University, Leiden, The Netherlands
[c] Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), Onogawa 16-2, Tsukuba-City, Ibaraki 305-8506, Japan
[d] Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
[e] Department of Economics, Jinan University, Guangzhou, Guangdong 510632, China
[f] Institute of Resource, Environment and Sustainable Development, Jinan University, Guangzhou, Guangdong 510632, China
[g] State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
[h] College of Architecture and Urban Planning, Tongji University, No. 1239, Siping Road, Shanghai, PR China

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ABSTRACT

Regional scale estimation of in-use steel stock (IUSS) using satellite observation of nighttime lights (NTL) is essential for urban resource consumption management and resource recovery monitoring. S-NPP VIIRS (Suomi National Polar-orbiting Partnership's Visible Infrared Imaging Radiometer Suite) NTL product is newly released in 2013, which has enhancements in both spatial and radiometric resolutions compared with the DMSP-OLS (Defense Meteorological Satellite Program's Operational Linescan System) NTL products. To evaluate whether these enhancements can improve the estimations of IUSS of buildings (IUSSB) and civil engineering infrastructure (IUSSCE), the S-NPP VIIRS NTL products were used to estimate IUSSB and IUSSCE at both sub-national level of Japan and national level of world, and their performances were compared with those of using DMSP-OLS radiance calibrated (RC) NTL data. Our results indicate that the S-NPP VIIRS NTL data can offer more accurate estimates of IUSSB and IUSSCE (R^2 values of 0.952 and 0.909) than those of DMSP-OLS RC NTL (R^2 of 0.929 and 0.884) at prefectural level of Japan. Similar to DMSP-OLS RC NTL product, urban NTL of S-NPP VIIRS data has a stronger relationship with IUSSB, and IUSSCE was more closely related to total NTL. At national level, S-NPP VIIRS NTL also showed better estimations of IUSSB and IUSSCE. We confirmed that dividing the world into different regional groups is also required for estimating IUSSB and IUSSCE from S-NPP VIIRS NTL. For estimation of IUSSCE, two classifications including Asia region and Non-Asia region are appropriate when using S-NPP VIIRS NTL product, which is superior to DMSP-OLS RC NTL. For estimation of IUSSB, more classifications may be still required which is similar to DMSP-OLS RC NTL. Overall, our study indicated that S-NPP VIIRS data have greater capability in modeling IUSSB and IUSSCE than DMSP-OLS RC data. Our results are critical for ever-improvement of policy making on urban resource management.

1. Introduction

Along with the promotion of urbanization and industrialization, a large quantity of metal resources has been transferred from natural environment to human-built environment (Rauch, 2009). These in-use metal resources not only provide indispensable service for human socioeconomic activities, but also hold a high potential as secondary resource (Gordon et al., 2006). Steel is the most widely used metal on the Earth, which is used in various products in the society, e.g., buildings, railways, and pipelines. A full accounting of

Abbreviations: IUSS, in-use steel stock; IUSSB, in-use steel stock of buildings; IUSSCE, in-use steel stock of civil engineering infrastructure; NTL, nighttime lights; S-NPP VIIRS, Suomi National Polar-orbiting Partnership's Visible Infrared Imaging Radiometer Suite; DMSP-OLS, Defense Meteorological Satellite Program's Operational Linescan System; RC, radiance calibrated; NOAA/NGDC, National Oceanic and Atmospheric Administration's National Geophysical Data Center; MODIS, Moderate-resolution Imaging Spectroradiometer; DN, digital number.

* Corresponding authors.
E-mail addresses: liang.hanwei@nuist.edu.cn (H. Liang), dong0926@163.com (L. Dong).

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the physical magnitude of steel accumulation (also referred to as “in-use steel stock”) in the society is a prerequisite for improving the sustainable resource management and cross-boundary material recycling.

Traditionally, in-use steel stock (IUSS) is mainly calculated from statistical data by two approaches known as “top-down” and “bottom-up” (Müller, 2006). However, the applicability of these traditional methods is always limited. On one hand, statistical data is often only available at administrative region (e.g., country and province) and for certain time, which make it difficult to study the distribution of IUSS with high spatial and temporal resolution. On the other hand, calculating in-use steel stock using traditional approaches is time and labor consuming, because large amount of statistical data and complicated calculation are involved. Recently, satellite products of nighttime lights have raised interest of the scientific community in the field of environmental accounting such as material stock, electricity power consumption, and fossil fuel emissions, owing to their distinct merits of low cost, high spatial resolution, wide observation scope and high efficiency.

Since 1992, two types of global nighttime lights (NTL) products have been provided by the Defense Meteorological Satellite Programs’ Operational Linescan System (DMSP-OLS). One is the DMSP-OLS stable NTL product, which records annual average composites of stable NTL from the cloud-free segments of individual orbits spanning 1992–2012. This product has good performance for extracting the extent of human settlements due to its stable light signal (Elvidge et al., 2007a; Henderson et al., 2003; Liu et al., 2012). Meanwhile, its long-term data availability facilitates the modeling long-term variation of socioeconomic indicators from NTL (Cao et al., 2014; Wu et al., 2013). However, the quantitative application of this product is impacted by the limited 6-bit data quantification which causes over-saturated DNs in urban cores. Another type of NTL product is the DMSP-OLS radiance calibrated (RC) NTL, which provides non-saturated radiance values for several discontinuous years such as 1996, 1999, 2000, 2003, 2006, and 2010. DMSP-OLS RC NTL product is a better estimator of several socioeconomic indicators than DMSP-OLS stable NTL product, because it is free of over-saturation problem in urban cores (Elvidge et al., 2007b; Ghosh et al., 2009; Letu et al., 2012). In recent years, DMSP-OLS RC NTL product has been widely applied to estimate electric power (Letu et al., 2014), CO_2 emissions (Ghosh et al., 2010; Letu et al., 2014), in-use stocks of metals such as copper and aluminum (Rauch, 2009; Takahashi et al., 2009, 2010) for certain years. Hsu et al. (2011, 2013) showed that DMSP-OLS RC NTL is also a good estimator for in-use steel stock of buildings and civil engineering infrastructure at prefecture and national levels. Based on the DMSP-OLS RC NTL imageries in 2006 and 2010, Hattori et al. (2013) monitored the dynamic change of national in-use steel stock in buildings and civil engineering infrastructure.

At the beginning of 2013, a new global monthly NTL composite is published by the National Oceanic and Atmospheric Administration’s National Geophysical Data Center (NOAA/NGDC) of the United States. The new NTL product is detected by the Visible Infrared Imaging Radiometer Suite (VIIRS) which is equipped with the Suomi National Polar-orbiting Partnership (S-NPP) satellite on October 2011. The new S-NPP VIIRS NTL product has several improvements compared with the DMSP-OLS NTL products. First, the spatial resolution of the DMSP-OLS NTL products is 30 arc-seconds ($\sim$1 km), while it has been improved to 15 arc-seconds ($\sim$500 m) in S-NPP VIIRS NTL product. Furthermore, the data quantification of S-NPP VIIRS NTL product has been improved to 14-bit with a wider radiometric detection range, which effectively overcomes the over-saturation problem of the DMSP-OLS NTL products in urban cores. In addition, the in-flight calibration is available for S-NPP VIIRS NTL, which ensures a direct comparison between NTL imageries obtained by the VIIRS sensor but onboard different satellites; and this is also significant for quantitatively monitoring the temporal change of socioeconomic indicators.

Some researchers have reported that S-NPP VIIRS NTL product is a good proxy for extracting urban built-up areas (Shi et al., 2014a) and for modeling some socioeconomic indicators such as gross domestic/regional products (Li et al., 2013; Ma et al., 2014; Shi et al., 2014b), electricity power consumption (Ma et al., 2014; Shi et al., 2014b), and human population (Ma et al., 2014). However, the performance of S-NPP VIIRS NTL in estimation of IUSS has not been examined yet. More importantly, although S-NPP VIIRS NTL product has advantages on spatial resolution and quantification over DMSP-OLS NTL products, it is still not clear whether the estimation of IUSS using S-NPP VIIRS NTL would be superior to that using DMSP-OLS NTL. Therefore, in order to better derive IUSS from various satellite observations of NTL, it is desirable to evaluate the performance of S-NPP VIIRS NTL product for estimating the IUSS, and compared with that using DMSP-OLS NTL products which have been well documented. In addition, the scale of IUSS is still unknown in many developing countries due to lack of statistical data. It is preferable to derive the in-use steel stock in these countries with the aid of S-NPP VIIRS NTL product.

Toward this end, this study first evaluated the potential of S-NPP VIIRS NTL data for estimating in-use steel stock of buildings (IUSSB) and civil engineering infrastructure (IUSSCE) at the sub-national level of Japan. The reminder of this study is structured as follows: Section 2 provides a description of the database, the data preprocessing procedure, and linear regression methods used in this study. Section 3 compares the estimations of IUSS using S-NPP VIIRS NTL data and DMSP-OLS RC NTL data at both sub-national level of Japan and the national level of world. Section 4 discusses the potential factors responsible for the similarity and differences between S-NPP VIIRS NTL and DMSP-OLS RC NTL for estimating IUSS between S-NPP VIIRS NTL based on a land cover map. Finally, this study is concluded in Section 5.

2. Data and methodology

2.1. In-used steel stock database

At the national level, time-series dataset of IUSSB and IUSSCE for 41 countries/regions was originally published by Hatayama et al. (2010) for the period of 1980–2005, and then it has been updated to the year 2010 by Hattori et al. (2013) (Fig. 1). The IUSSB and IUSSCE in this dataset were calculated from statistical data using the top-down approach (available at http://dx.doi.org/10.1016/j.resconrec.2013.11.007). In brief, this approach first computes the steel inflow of each major end use (i.e., building, railways, roads, and water pipes) in a defined boundary (i.e., country) over a certain period of time, which is also referred to as the steel consumption. The steel outflow is determined by the steel inflow and the lifetime distribution of each steel-containing product. The magnitude of in-use steel stock in each major steel-containing product was then estimated as the gap of steel inflow and outflow (Müller, 2006).

At the sub-national level, Tanikawa et al. (2015) and Fishman et al. (2015) compiled a long-term (1945–2010) in-use steel stock dataset for 47 prefectures of Japan. This dataset comprises IUSSB and IUSSCE that were calculated from statistical data using the bottom-up approach. This approach directly quantified the in-use steel stock by multiplying the quantity of each steel-containing product (i.e., building railways, roads, and water pipes) with its relevant steel intensity. The steel intensity is determined by the weight of steel per physical unit of product (Müller, 2006).