ISPRS Journal of Photogrammetry and Remote Sensing 88 (2014) 80–90

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Mapping the human footprint from satellite measurements in Japan

Fan Yang [a], Bunkei Matsushita [a,*], Wei Yang [b], Takehiko Fukushima [a]

[a] Graduate School of Life and Environmental Science, University of Tsukuba, 1-1-1, Tennoudai, Tsukuba, Ibaraki 305-8572, Japan
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100857, China

ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 25 November 2013
Accepted 26 November 2013
Available online 21 December 2013

Keywords:
Human footprint
Impervious surface
Cropland
Temporal mixture analysis
MODIS
NDVI time series

ABSTRACT

Due to increasing global urbanization and climate change, the quantification of "human footprints" has become an urgent goal in the fields of biodiversity conservation and regional environment management. A human footprint is defined as the impact of a particular human activity on the Earth's surface, which can be represented mainly by impervious surfaces (related to industry and urbanization) and cropland (related to agriculture). Here we present a method called sorted temporal mixture analysis with post-classification (STMAP) for mapping impervious surfaces and cropland simultaneously at the subpixel level to fill the demand for precise human footprint information on a national scale. The STMAP method applies a four-endmember sorted temporal mixture analysis to provide the initial fractions of evergreen forests, deciduous forests, cropland, and impervious surfaces as a first step. Endmembers are selected from the sorted temporal profiles of the MODIS-normalized difference vegetation index (NDVI), as guided by a principal component analysis. The yearly maximum land surface temperatures and averaged stable nighttime light are then statistically analyzed to provide the thresholds for post-classification to further separate cropland from deciduous forest and bare land from impervious surface. As the four outputs of STMAP, the fractions of forest, cropland, impervious surfaces and bare land are derived. We used the reference maps of impervious surfaces and cropland obtained from the Landsat/TM and ALOS precise land-use/land-cover map at the subpixel level to evaluate the performance of the proposed method, respectively. Historical satellite images with high spatial resolution were used to further evaluate the cropland results derived with the STMAP method. The results showed that the STMAP method has promising accuracy for estimating impervious surfaces and cropland in Japan. The root mean square errors obtained with the STMAP method were 6.3% for the estimation of impervious surfaces and 9.8% for the estimation of cropland. Our findings can extend the applications of remote sensing technologies in ecological research and environment management on a large scale.

1. Introduction

Two of the core issues in ecology are the conservation of biodiversity and the improvement of ecosystem services in the context of global climate change (Dawson et al., 2011). With the global population exceeding 7 billion, massive human activity has become a leading driver affecting the ecosystem. There are few studies focusing on the quantitative impact assessment of human activity as it affects biodiversity on a regional scale, although scientists have already realized the key role human activity plays in ecosystems (Loreau et al., 2001). One reason may be that the estimation of human activity on a regional scale is one of the biggest challenges that ecological scientists are facing.

Satellite remote sensing techniques, which have the inherent ability to monitor spatial and temporal information on the Earth's surface, may provide the means by which to effectively analyze the impact of human activity on ecosystems on a regional scale (Kerr and Ostrovsky, 2003). Human footprints, defined as the impressions of human activity on the Earth's surface, can be analyzed using satellite images. Previous studies on urban remote sensing and agricultural remote sensing have built a scientific basis for quantifying human footprints.

An impervious surface (or an artificial surface) is a major human footprint made on the Earth's surface during the urbanization process (Irwin and Bockstael, 2007; Sutton et al., 2009). The quantification of impervious surfaces is one of the most widely examined topics in urban remote sensing (Weng, 2012), because impervious surface coverage is not only an indicator of the degree of urbanization, but also a major indicator of the impact of urbanization on water resources and the natural ecosystem (Arnold and Gibbons, 1996; Schueler, 1994). An impervious surface generally results in spectral heterogeneity on a scale comparable to the sensors' spatial resolution, which limits the utility of conventional

---

* Corresponding author. Tel./fax: +81 29 853 7190.
E-mail address: matsushita.bunkei.gn@u.tsukuba.ac.jp (B. Matsushita).

0924-2716/$ - see front matter © 2013 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS) Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.isprsjprs.2013.11.020

hard classification methods (Small, 2001). Therefore, many unmixing methods based on spectral information have been developed to overcome this limitation.

The most typical method is the spectral mixture analysis (SMA) based on the Vegetation–Impervious–Soil (V–I–S) model (Ridd, 1995). In the V–I–S model-based SMA, there are several endmembers (pure materials) which represent the land cover type, i.e., vegetation, areas of impervious surface, and soil. Wu and Murray (2003) succeeded in extracting the impervious surface fraction by using the data for the vegetation, impervious surface (low albedo and high albedo), and soil endmembers. Lu and Weng (2006) improved this method by adding the information of land surface temperature to filter out the bare soil with high albedo. Normalization (Wu, 2004) and a multiple-endmember solution (Powell et al., 2007) were also applied to enhance the SMA method by reducing the endmember variability.

In addition to SMA, there are other solutions that were developed to estimate impervious surfaces on an urban or drainage basin scale, such as considering impervious surfaces as a complement of the vegetation distribution (e.g., Bauer et al., 2007; Carlson and Arthur, 2000), or calculating impervious surfaces using a regression approach (e.g., Elvidge et al., 2007), an artificial neural network (ANN; e.g., Weng and Hu, 2008; Hu and Weng, 2009), or an object-based image analysis (OBIA; e.g., Benz et al., 2004; Hu and Weng, 2010; Hu and Weng, 2011). More details are provided in the review by Weng (2012). However, on the national or regional scale, the methods used are still inadequate to accurately determine the amounts of impervious surface, due to the fact that low temporal resolution (16-day) and small swath width (185 km) of Landsat-style data limit the frequency of updating (Xian and Homer, 2010).

To estimate the impervious surface on a national scale, Yang et al. (2012b) developed a sorted temporal mixture analysis (STMA) by using rearranged temporal profiles of the normalized difference vegetation index (NDVI) to unmix the pixels. Similar to other methods, one remaining problem with the STMA in the Yang et al. (2012b) study was that impervious surface and bare land could not be distinguished due to the similarity between the temporal profiles of those two land cover types. On the other hand, as an advantage of STMA, the cropland fraction can also be estimated simultaneously, which extends the possible applications of STMA to the field of agricultural remote sensing.

Agriculture is one of the most important human enterprises on the Earth's surface (Vitousek et al., 1997). In remote sensing, an agricultural human footprint can be quantitatively described as cropland. The precise estimation of cropland is a central topic of agricultural remote sensing in studies of food security (Lobell et al., 2008) and the global carbon and nitrogen cycle (Robertson et al., 2000). It is difficult to quantify cropland versus other vegetation types by using Landsat-style images, because of the limitations caused by spectral similarity and low temporal resolution.

Instead, satellite images with high temporal resolution are widely used to analyze cropland spatially (Brown et al., 2012; Moran et al., 1997; Quarmby et al., 1992; Sakamoto et al., 2005), since those images can capture the identical phenology of cropland despite their low spatial resolution (250 m to 1 km). Therefore, to overcome the spatial resolution limitation of such images, researchers apply unmixing to precisely extract the fraction information of cropland at the subpixel level (Lobell and Asner, 2004; Oleson et al., 1995; Ozdogan, 2010).

Unfortunately, when unmixing is applied to high-temporal-resolution images on the national or regional scale, the phenological profiles of the same vegetation in different geographic locations can shift along the time axis due to the climatic conditions. This problem was not prominent in previous studies that focused on local croplands (De Jong et al., 2011; Lobell and Asner, 2004; Oleson et al., 1995; Ozdogan, 2010; Verbesselt et al., 2010). STMA solves this problem through a sorting process (i.e., the rearrangement of NDVI temporal profiles from minimum to maximum according to the values of NDVI) and has proven to be effective to reduce the endmember variability (Yang et al., 2012b).

As a follow-up study, Yang et al. (2012a) tested the STMA to quantify the subpixel land covers by using supervised endmembers, and they reported an underestimation of cropland, caused mainly by the similarity between the temporal profiles of deciduous forest and cropland. Consequently, there remains a need for an efficient method that can precisely estimate both impervious surface and cropland, both of which represent the human footprint.

To fill the demand for precise impervious surface and cropland products on a national scale, we present an STMA with post-classification (STMAP) method for mapping remotely detectable human activities (i.e., impervious surface and cropland areas) in Japan. This method contains a four-endmember STMA model and a post-classification process that regroups the fractions to improve the accuracy. In Section 2, the required datasets are described. STMA is extended to a four-endmember model (evergreen forest, deciduous forest, cropland and impervious surface) in Section 3.1. In Section 3.2, a post-classification process using the yearly maximum land surface temperature and stable nighttime light regroups the initial fractions into forest, cropland, impervious surface and bare land at the subpixel level. The accuracy of the impervious surface and cropland estimates by STMAP are assessed by comparing them to the local reference data in Japan (Section 3.3). The fraction maps for impervious surface and cropland are shown and evaluated in Section 4. In Section 5, we discuss the results and implications, and present the general conclusion of this study.

2. Data processing

There are three types of satellite images included as inputs to be examined by the new method. The first type is the NDVI temporal profile from MODIS (the Moderate Resolution Imaging Spectroradiometer), which provides temporal information about the land surface. The second is the land surface temperature (LST) from MODIS, which is used in post-classification as a filter for impervious surface and cropland. The third type of satellite image is nighttime light from DMSP-OLS (the U. S. Air Force's Defense Meteorological Satellite Program–Operational Linescan System), which is also used in post-classification as a filter for impervious surface. The final result identifying impervious surface is assessed using three reference maps of impervious surface made from Landsat images, and cropland is assessed according to the ALOS precise land-use/land-cover map (ALOS LULC map, 2013) in Japan, produced by the Earth Observation Research Center (EORC) of the Japan Aerospace Exploration Agency (JAXA).

The MODIS 16-day vegetation index (VI) products (MOD13Q1; spatial resolution: 250 m) covering the four main islands of Japan (tile numbers: h27v04, h28v04, h28v05 and h29v05; Fig. 1) in 2001, 2006, and 2011 were downloaded from NASA's Earth Observing System Data and Information System (EOSDIS). The nadir-adjusted NDVI temporal profiles (23 elements in total for one year) with pixel reliability were extracted. The NDVI temporal profiles were further smoothed to improve the data quality by using a Savitzky-Golay filter-based method (Chen et al., 2004). This method is based on the assumptions that the NDVI temporal profiles follow the phenology of vegetation, and that clouds or poor atmospheric conditions usually depress NDVI values. This method has been proved to be effective to smooth out noise in NDVI temporal profiles, specifically the noise caused by cloud contamination and atmospheric variability (Chen et al., 2004).