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Annual dynamics of impervious surface in the Pearl River Delta, China, from 1988 to 2013, using time series Landsat imagery

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ABSTRACT

Information on impervious surface distribution and dynamics is useful for understanding urbanization and its impacts on hydrological cycle, water management, surface energy balances, urban heat island, and biodiversity. Numerous methods have been developed and successfully applied to estimate impervious surfaces. Previous methods of impervious surface estimation mainly focused on the spectral differences between impervious surfaces and other land covers. Moreover, the accuracy of estimation from single or multi-temporal images was often limited by the mixed pixel problem in coarse- or medium-resolution imagery or by the intra-class spectral variability problem in high resolution imagery. Time series satellite imagery provides potential to resolve the above problems as well as the spectral confusion with similar surface characteristics due to phenological change, inter-annual climatic variability, and long-term changes of vegetation. Since Landsat time series has a long record with an effective spatial resolution, this study aimed at estimating and mapping impervious surfaces by analyzing temporal spectral differences between impervious and pervious surfaces that were extracted from dense time series Landsat imagery. Specifically, this study developed an efficient method to extract annual impervious surfaces from time series Landsat data and applied it to the Pearl River Delta, southern China, from 1988 to 2013. The annual classification accuracy yielded from 71% to 91% for all classes, while the mapping accuracy of impervious surfaces ranged from 80.5% to 94.5%. Furthermore, it is found that the use of more than 50% of Scan Line Corrector (SLC)-off images after 2003 did not substantially reduced annual classification accuracy, which ranged from 78% to 91%. It is also worthy to note that more than 80% of classification accuracies were achieved in both 2002 and 2010 despite of more than 40% of cloud cover detected in these two years. These results suggested that the proposed method was effective and efficient in mapping impervious surfaces and detecting impervious surface changes by using temporal spectral differences from dense time series Landsat imagery. The value of full sampling was revealed for enhancing temporal resolution and identifying temporal differences between impervious and pervious surfaces in time series analysis.

1. Introduction

Impervious surfaces, as the most direct embodiment of urbanization, has a significant impact on biogeochemical cycles (Haustein, 2010; Chithra et al., 2015) and urban climate such as urban heat island (Weng et al., 2011; Deng and Wu, 2013). In recent years, numerous methods have been developed to estimate impervious surface at various spatial scales using satellite imagery. These methods included per-pixel and sub-pixel analysis from coarse or medium spatial resolution imagery, such as impervious surface indices analysis (Xu, 2010; Liu et al., 2013), spectral mixture analysis (Wu and Murray, 2003; Weng and Hu, 2008; Weng et al., 2008), machine learning (Hu and Weng, 2009), regression analysis (Bauer et al., 2008), image fusion between optical and SAR images (Zhang et al., 2014) and between DMSP–OLS Nighttime Light and MODIS Data (Shao and Liu, 2014). Improved spectral mixture analysis has been attempted to estimate impervious surfaces from high resolution imagery, such as IKONOS imagery

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(Wu, 2009; Lu and Weng, 2009). Similarly, Zhou and Wang (2008) used multiple agent segmentation and classification (MASC) to extract impervious surface area from digital orthophoto and QuickBird-2 imagery. Im et al. (2012) proposed a synthesis of WorldView-2, LiDAR data, and Landsat imagery to detect impervious surfaces. A comprehensive review of methods and techniques to estimate impervious surfaces can be found in Weng (2012).

Previous studies of impervious surface estimation from single or multi-temporal images mainly focused on the spectral differences between impervious surfaces and other land covers, but have been found ineffective to a certain degree due to the mixed pixel problem in the coarse or medium resolution imagery and the intra-class spectral variability problem in high resolution imagery. Schneider (2012) showed the advantages of temporal feature from time series data to resolve spectral confusion between land cover classes with similar characteristics. However, time series data at coarse resolution such as DMSP–OLS and MODIS has a limitation in mapping accuracy at the local to regional scales (Iiames and Lunetta, 2013). Landsat time series has the ability to retrieve impervious surfaces over long time scale due to its long record of continuous measurement at moderate spatial resolution and temporal frequency (Sexton et al., 2013a). Bhandari et al. (2012) showed that time series Landsat data was helpful in distinguishing vegetation change and impervious surface change due to phenological change, inter-annual climatic variability, and long-term change trends of vegetation. Several researches have demonstrated the value of time series Landsat imagery particularly for monitoring impervious surface dynamics in rapidly urbanizing areas (Gao et al., 2012; Sexton et al., 2013b; Li et al., 2015). Gao et al. (2012) used minimum distance map generated by spectral distance between each pixel from time series Landsat images to identify impervious surface. Sexton et al. (2013b) presented a signature extension method for dense time-series of Landsat TM images, which classified images based on intra-annual spectral indices to generate probabilistic maps. Li et al. (2015) provided a method of long term mapping of urban areas at an annual frequency using Landsat data, which focused on temporal consistency check after initial classification. However, existing studies using time series Landsat imagery paid main attention to the spectral differences between impervious and pervious surfaces, and/or used temporal consistency after classification instead of temporal characteristics before classification to improve estimation accuracy. Little attention has been paid to the differences in temporal spectral profile among various land covers that were derivable from a dense Landsat time series.

In this study, we aimed at analyzing temporal spectral differences between impervious and pervious surfaces and improving mapping accuracy of impervious surfaces by developing a dense Landsat time series for the Pearl River Delta, southern China, from 1988 to 2013. The delta is located in the humid subtropical region, where the majority of days during a year are cloudy. Moreover, abundant rains often create variable source areas on the ground with seasonal changes in the area of water bodies (Zhang et al., 2012). These issues may not have been encountered when studying in a relatively dry temperate zone as with the most previous studies. With solving these issues in mind, our procedure was designed as follows: First, in order to build better temporal spectral profiles for ground features, both gap filling and smoothing methods were employed to handle missing data/cloudy pixels problem. Next, the temporal characteristics of each land cover were identified with Land Surface Temperature (LST), Biophysical Composition Index (BCI), and Normalized Difference Vegetation Index (NDVI). Then, the temporal differences between impervious and pervious surfaces in these biophysical variables were assessed by time series similarity measures. Finally, a decision tree classifier was applied to extract impervious surfaces based on annual distance maps that were derived based on the temporal differences between training samples and testing samples.

2. Methodology

This study intended to quantify the spatiotemporal patterns of impervious surfaces using dense time series Landsat images through the following analytical steps (Fig. 1): First, time series Landsat images were registered in the same projection and converted to surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). Then, clouds and shadows were masked and removed. Next, time series LST, BCI, and NDVI images were extracted from the time series Landsat imagery. For each series of LST, BCI, and NDVI imagery, gap filling (Garcia, 2010; Wang et al., 2012) and smoothing processes were applied to fill up missing values. After that, LST, BCI, and NDVI temporal features for each pixel were obtained. Then, time series similarity measures were used to calculate the differences in temporal spectral signature between impervious and pervious surfaces based on selected consistent training samples. Annual distance maps were generated by using equally-weighted time series similarity measures. Finally, the C4.5 decision tree algorithm (Quinlan, 2014) was employed to classify the distance maps. Temporal filtering was then developed to correct illogical errors in land cover transitions.

2.1. Study area

China has experienced rapid urbanization with its reform process since the 1980s. The Pearl River Delta, as an economically important region of China, was selected as the study area due to its dramatic urbanization in the past 26 years. It is located between 21°–23°N and 111°–115°E, and has a subtropical climate with an annual mean temperature of 21–23 °C and annual precipitation of 1500–2500 mm. However, the delta exhibits a dry season, from October to April, and a wet season, from May to September. Economically, the delta experienced a double-digit growth in annual gross domestic product (GDP) from 1980 to 2000. Since the new century, it has continued to experience strong economic growth with an average annual GDP growth up to 15% between 2000 and 2007; but, from 2008 to 2013, the GDP growth slowed down to below 10% facing several difficulties including reduction in

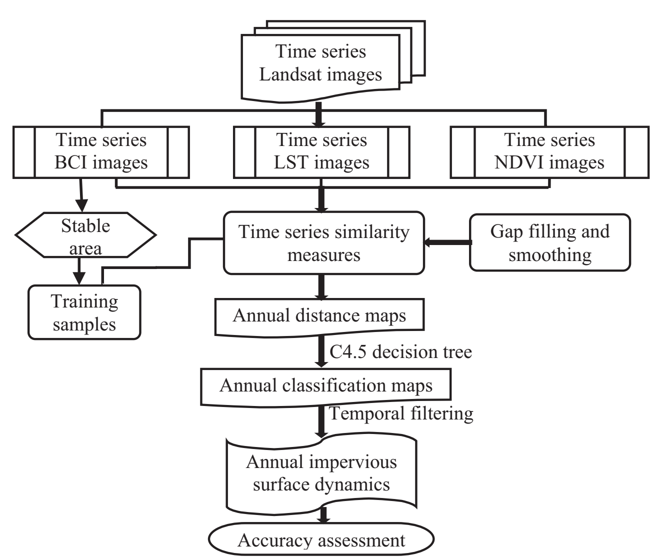

Fig. 1. Procedures for mapping impervious surface dynamics using time series Landsat imagery.