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The use of single-date MODIS imagery for estimating large-scale urban impervious surface fraction with spectral mixture analysis and machine learning techniques

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ABSTRACT

Urban impervious surface information is essential for urban and environmental applications at the regional/national scales. As a popular image processing technique, spectral mixture analysis (SMA) has rarely been applied to coarse-resolution imagery due to the difficulty of deriving endmember spectra using traditional endmember selection methods, particularly within heterogeneous urban environments. To address this problem, we derived endmember signatures through a least squares solution (LSS) technique with known abundances of sample pixels, and integrated these endmember signatures into SMA for mapping large-scale impervious surface fraction. In addition, with the same sample set, we carried out objective comparative analyses among SMA (i.e. fully constrained and unconstrained SMA) and machine learning (i.e. Cubist regression tree and Random Forests) techniques. Analysis of results suggests three major conclusions. First, with the extrapolated endmember spectra from stratified random training samples, the SMA approaches performed relatively well, as indicated by small MAE values. Second, Random Forests yields more reliable results than Cubist regression tree, and its accuracy is improved with increased sample sizes. Finally, comparative analyses suggest a tentative guide for selecting an optimal approach for large-scale fractional imperviousness estimation: unconstrained SMA might be a favorable option with a small number of samples, while Random Forests might be preferred if a large number of samples are available.

1. Introduction

Urban impervious surfaces generally refer to any impermeable materials found in urban areas, including rooftops, parking lots, sidewalks, drive ways, highways, etc. Knowledge of the amount and spatial distribution of impervious surfaces is important for urban and environmental applications, including watershed conservation and restoration, stream protection strategy analysis, and metropolitan master planning, etc. (Arnold and Gibbons, 1996). Because of their impermeable nature, impervious surfaces can bring a series of environmental impacts (Schueler, 1994, 2003, 2009). For example, the increase of impervious surfaces during the process of watershed urbanization may remarkably degrade ecosystem functions and stream hydrology, known as the "urban stream syndrome" with three major symptoms, e.g. hydrological changes, riverine physical alternation, and degradation of water quality (Paul and Meyer, 2001; Brabec et al., 2002; Meyer et al., 2005; Walsh et al., 2005). In addition, impervious surfaces could lead to the increase of surrounding air temperature, which accordingly affects urban microclimatology and human thermal comfort (Mahmoud, 2011; Ng et al., 2012). Therefore, as a key environment indicator, particularly a watershed metric for stream health analysis and watershed management, accurate and timely impervious surface information is essential for practical applications at the watershed/regional scale (Jantz et al., 2005; White and Greer, 2006; Chander et al., 2009).

To derive timely and accurate information of impervious surfaces, remote sensing imagery has been extensively employed (Wu and Murray, 2003; Deng and Wu, 2013). A traditional method is to adopt high- and medium-resolution remote sensing imagery, such as IKONOS (Goetz et al., 2003, 2004; Wu 2009), and Landsat Thematic Mapper (TM) or Enhanced Thematic Mapper Plus

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(ETM+) imagery (Yang et al., 2001, 2003a, 2003b; Homer et al., 2004). However, one scene of high- or medium-resolution imagery is hardly to cover a large region: each Landsat TM/ETM+ image only covers a ground area of approximately 180 × 180 km, and a much smaller area is covered by an IKONOS scene (Goetz et al., 2003; Chander et al., 2009). To cover the entire study area, a large volume of images acquired on different dates have to be mosaiced (Chander et al., 2009; Yang et al., 2012), which consequently brings a number of challenging problems such as between-image variations in atmospheric condition, solar illumination geometry and vegetation phenology, etc., and could further give rise to erroneous estimation of land cover fractions (Goetz et al., 2003; Chander et al., 2009). Correspondingly, multiple pre-processing steps, such as image selection, co-registration, geometrical correction, spectral index calculation (e.g. normalized difference vegetation index (NDVI) and the Tasseled Cap (TC) transformation, etc.), and imagery normalization, etc. (Huang et al., 2001, 2002; Homer et al., 2002, 2004; Powell et al., 2008; Fry et al., 2011), are required to ensure satisfactory image quality. These preprocessing steps, however, are extremely time consuming and labor intensive (DeFries et al., 1997; Yang et al., 2012).

As a result, high- and medium-resolution imagery may not be a viable option for mapping impervious surfaces at the regional or a larger scale (Lu and Weng, 2006; Knight and Voth, 2011; Lu et al., 2011). In contrast, coarse-resolution imagery, such as Advanced Very High Resolution Radiometer (AVHRR), and Moderate Resolution Imaging Spectroradiometer (MODIS), with a low spatial resolution and a large geographical coverage, could be more desirable (Lu and Weng, 2006; Weng, 2012). In particular, the 1–2 km resolution is preferable in global urban studies (Gamba and Herold, 2009; Weng, 2012). In addition to a coarse spatial resolution and a large-scene footprint, the high revisit frequency of coarse-resolution imagery is favorable for various applications (DeFries et al., 1998, 2000; Wardlow and Egbert, 2008; Shao and Lunetta, 2011, 2012). With generally daily observations, vegetation phenological cycle can be characterized effectively (Zhang et al., 2003; Weng, 2012), and consequently the anthropogenic impacts over a period can be examined. To quantify subpixel land cover information with multi-temporal images, temporal mixture analysis and machine learning techniques have been widely employed. Specifically, spectral unmixing has been carried out to estimate impervious surface distribution using time-series MODIS NDVI datasets (Shao and Lunetta, 2011; Knight and Voth, 2011; Yang et al., 2012). Further, with a series of spectral metrics as inputs, machine learning techniques have been applied to derive land cover abundances (Hansen et al., 2000, 2002, 2003). In spite of the inclusion of vegetation phonological information in multi-temporal images, between-image variations could still exist, which might in turn lead to uncertainty in the resultant fractional land covers.

Until now, spectral mixture analysis (SMA) has been rarely applied to a single-date coarse-resolution imagery to derive subpixel impervious surface information at the regional or a larger scale (Yang et al., 2012). The major difficulty lies in the selection of homogeneous land cover compositions (also termed endmembers). Particularly, it is difficult, and almost impossible, to select impervious surface endmembers in heterogeneous urban environments where pure impervious surface pixels are very rare (Lu et al., 2008, 2011). Therefore, with coarse-resolution imagery, it is impractical to adopt traditional endmember selection methods, such as selecting extreme pixels at the vertices of spectral feature spaces, with laboratory or/and in situ measurements, etc. In addition, although machine learning methods have been employed and reported in many studies, they cannot be objectively compared with SMA methods because of their completely different principles/mechanisms. In an attempt to solve these problems, this paper developed SMA and machine learning techniques to derive fractional land cover estimates using a single-date MODIS 1-km image. In particular, two specific objectives of this paper are: (1) to derive endmember spectra for SMA using a least squares solution (LSS) technique; and (2) to perform objective comparisons between SMA and machine learning techniques using the same sample datasets.

2. Materials and methods

2.1. Study area

We selected the States of Ohio and Virginia, USA as two study areas in our research (see Fig. 1). The purpose of adopting two different study areas is to explore whether consistent results can be achieved in different sites. Bordering Lake Erie, Ohio is located in the east of the Midwest region of the United States with a population of approximately 11.5 million in 2010. Covering a large geographical area of about 116,096 square km, Ohio possesses a wide variety of land use/cover types, such as developed lands including commercial, industrial, residential (ranging from low- and medium- to high-density), and civic (educational institutes, government services, and hospital, etc.), as well as undeveloped lands including forest lands (e.g. deciduous and evergreen forests), grasslands, pasture and cultivated lands, wetlands, and other open lands. Comparatively, Virginia is a state in the Mid-Atlantic region with obvious geographic variations. As part of the Chesapeake Bay watershed, the knowledge of impervious surfaces in Virginia is critical for the restoration of this important watershed (Jantz et al., 2005). With such large areas in both regions, it is highly necessary to adopt coarse-resolution imagery with a large-scene footprint, instead of a large collection of high- or medium-resolution images.

2.2. Data acquisition and pre-processing

To perform SMA and machine learning techniques, we employed a single-date 1-km MODIS Nadir BRDF Adjusted Reflectance (NBAR) (MCD43B4) image acquired on September 30, 2006. Three merits of the MODIS NBAR imagery include: (1) the preprocessed corrections of atmosphere and view angle, as well as reflectance standardization to a nadir view (Zhang et al., 2002, 2003); (2) comparative bands to those of Landsat TM/ETM+ imagery (Lobser and Cohen, 2007); and (3) the favorable resolution for regional/global urban studies (Gamba and Herold, 2009; Weng, 2012). With these advantages, MODIS NBAR imagery should meet the requirements of our research objectives. Besides, we collected the 2006 National Land Cover Dataset (NLCD) land cover and percent impervious surface area products as the training and testing datasets. For more detailed information of the model protocol, development and accuracy assessment of the 2006 NLCD datasets, readers can refer to relevant publications of U.S. Geological Survey (Yang et al., 2001; Homer et al., 2004; Nowak and Greenfield, 2010; Wickham et al., 2010; Xian et al., 2009; Xian and Homer, 2010, etc.). All remotely sensed data were reprojected to Universal Transverse Mercator (UTM) with zone 17 North and WGS84 datum. In addition to remote sensing imagery, urbanized area boundary data was collected to generate stratified random samples in rural and urban areas.

2.3. Sampling scheme and endmember signature derivation

Following Ridd's conceptual model of urban land cover compositions (1995), we adopted vegetation, impervious surface, and soil (V-I-S) as three target endmembers. Based on SMA theory, the abundance of each land cover can be derived through the inversion of the linear spectral mixing model with extracted endmember