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Impervious surface extraction in urban areas from high spatial resolution imagery using linear spectral unmixing

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ABSTRACT

Impervious surface, as an important indicator of urbanization assessment, plays a significant role in analyzing the climate, environment and hydrologic cycle in urban areas. Impervious surface extraction in urban areas from satellite imagery attracts growing attention in many applications. Recently, the increasing availability of high spatial resolution satellite imagery provides new opportunities for impervious surface extraction at a fine scale. However, impervious surface like asphalt roads, parking lots, and sidewalks is often obscured by tree canopies, which can remarkably underestimate impervious surface area in urban areas. In order to overcome this problem, this study adopts linear spectral unmixing to detect impervious surface information through tree canopies, and further incorporates with object-based classification to mitigate the negative effects of tree canopy obscurity when extracting impervious surface from high spatial resolution imagery. The performance of the proposed impervious surface extraction method is investigated by a subset of QuickBird imagery in Beijing urban areas. Results demonstrate that the proposed method effectively reduces impervious surface underestimation in urban areas by 11.20%, and more accurate impervious surface extraction and mapping can assist government policy makers for timely monitoring of urban hydrological environment.

1. Introduction

With rapid urbanization in the past decades, more and more land surface is covered by urban built-up areas. One of the most obvious physical evidences for urban growth is an increasing area of impervious surface (Jensen and Cowen, 1999). Impervious surface where water cannot infiltrate through the ground, including building rooftops, asphalt roads, highways, parking lots, and sidewalks, directly affects the amount of runoff to streams and lakes and non-point source pollution even water quality (Dougherty et al., 2004). Therefore, impervious surface distribution becomes an important indicator for monitoring urban hydrological environment (Choi and Ball, 2002; Shuster et al., 2005; Zhou et al., 2010).

In recent years, new satellite-based sensors promise to transform traditional impervious surface mapping that has either relied on expensive ground-based measurements or less accurate interpretation of aerial photography. Particularly, the increasing availability of high spatial resolution satellite imagery, such as IKONOS, QuickBird, GeoEye, and WorldView, has offered new opportunities for impervious surface extraction in urban areas at a fine scale (i.e., under 5 m) (Cablk and Minor, 2003; Goetz et al., 2003; Lu et al., 2011; Lu and Weng, 2009; Yuan and Bauer, 2006). Besides, more and more studies prefer the object-based image analysis in contrast with the pixel-based methods because the object-based methods perform better with less “salt and pepper” noises in high spatial resolution imagery (Laliberte et al., 2004; Zhou and Troy, 2008). Since land covers in

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shadow areas show different spectral features from those in non-shadow areas, it is more preferable to separately extract impervious surface from shadow and non-shadow areas, hereafter namely hierarchical impervious surface extraction (De Roeck et al., 2009; Li et al., 2011).

Impervious surface including asphalt roads, parking lots, and sidewalks is often obscured by tree canopies, which can remarkably underestimate impervious surface area in urban areas (Van der Linden and Hostert, 2009). Nevertheless, tree canopies, especially along the street, are not completely occlusive so some impervious surface (e.g., asphalt roads) information can be detected through tree canopies in high spatial resolution imagery. The pixels containing impervious surface information are very likely mixed with the spectral features of tree canopies. Conventionally, linear spectral unmixing is commonly used for impervious surface mapping in medium-low resolution or hyperspectral imagery (Deng et al., 2012; Van de Voorde et al., 2009; Weng et al., 2009). However, both Small (2003) and Yang et al. (2014) found that the inversion of a simple three-component linear mixture model is able to produce stable, consistent estimates of endmember fractions for each pixel even in high spatial resolution imagery. Despite not so many mixed pixels in high spatial resolution imagery, the vegetation-high albedo-low albedo model can provide a widely applicable physical characterization of impervious surface in urban areas. Thus, this study chose to adopt linear spectral unmixing to detect impervious surface information through tree canopies from high spatial resolution imagery.

2. Study area and experimental data

Beijing urban area, China was selected as the study area. Land cover types in the study area include vegetation cover such as trees and grassland, and impervious surfaces such as sidewalks and asphalt roadways.

QuickBird imagery of Beijing urban area, acquired on Sep. 30 of 2003 (off-nadir viewing angle: 9.3 degrees) was used in the study. The QuickBird imagery contains four multispectral bands with the spatial resolution of 2.44 m (blue, green, red, and near infrared band) and a panchromatic band with the spatial resolution of 0.61 m. Moreover, the multispectral and panchromatic images were fused to produce a pan-sharpened multispectral image with the pixel size of 0.61 m as the reference imagery. Specifically, the image fusion was carried out using the Gram–Schmidt procedure (Laben and Brower, 2000) implemented in the ENVI software package. A subset of the multispectral image of 918 × 923 pixels was adopted in this experiment (Fig. 1), corresponding with the reference imagery of 3672 × 3692 pixels.

3. Methods

The proposed impervious surface extraction method included two main parts, that is linear spectral unmixing and object-based classification. In terms of linear spectral unmixing, both Simple Endmember Spectral Mixture Analysis (SESMA) and Multiple Endmember Spectral Mixture Analysis (MESMA) models were implemented and quantitatively compared for impervious surface information detection through tree canopies. Hierarchical object-based classification was then conducted for impervious surface extraction in shadow and non-shadow areas, respectively. Further, the final impervious surface map was derived by the appropriate extension of the detected impervious surface information through tree canopies based on the object-based classification result. At last, the mapping accuracy of impervious surface was quantified by the reference impervious surface map. Detailed procedures are demonstrated as Fig. 2.

3.1. Linear spectral unmixing

3.1.1. Shadow restoration

Since most of impervious asphalt roads in urban areas are absorptive at optical wavelengths (Herold and Roberts, 2005; Herold et al., 2004), shadow restoration is of great necessity prior to linear spectral unmixing because it is able to reduce spectral confusion between shadow areas and low albedo land covers in non-shadow areas (e.g., asphalt roads). In lieu of the commonly applied histogram threshold method (Chen et al., 2007; Dare, 2005; Zhou et al., 2009), this study made use of object-based classification to identify the shadow areas over the entire imagery, which was also the first step of the following object-based classification.

A linear-correlation correction approach was thereafter utilized for shadow restoration. Several previous studies proved that it outperformed other shadow restoration techniques, such as Gamma correction and histogram matching (Dare, 2005; Sarabandi et al., 2004; Yang et al., 2015). The linear-correlation correction method hypothesizes that the signals recoded in shadow areas still provide enough useful information for restoration although they are relatively weak. Specifically, it assumes a linear relation between the digital number (DN) values of shadow areas and those of non-shadow areas, which can be expressed as (Chen et al., 2007; Sarabandi et al., 2004; Zhou et al., 2009)

$$y = \frac{S_y}{S_x}(x - x_m) + y_m \tag{1}$$

where x and y are the original and output DN values of shadow pixels, S_x and S_y are the standard deviation of shadow and non-shadow areas while x_m and y_m are the mean values of shadow and non-shadow areas.

3.1.2. Endmember selection

Since vegetation and impervious surface are two of the primary land covers in urban areas, the endmember classes of vegetation, high albedo, and low albedo impervious surface can provide a useful physical description of urban areas (Small, 2003). As such, this study also used these three endmember classes for linear spectral unmixing.

In the MESMA model, too large number of endmembers in one class may result in significant challenges in interpretation and computation. So several endmember