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Automated mapping of impervious surfaces in urban and suburban areas: Linear spectral unmixing of high spatial resolution imagery

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ABSTRACT

Quantifying impervious surfaces in urban and suburban areas is a key step toward a sustainable urban planning and management strategy. With the availability of fine-scale remote sensing imagery, automated mapping of impervious surfaces has attracted growing attention. However, the vast majority of existing studies have selected pixel-based and object-based methods for impervious surface mapping, with few adopting sub-pixel analysis of high spatial resolution imagery. This research makes use of a vegetation-bright impervious-dark impervious linear spectral mixture model to characterize urban and suburban surface components. A WorldView-3 image acquired on May 9th, 2015 is analyzed for its potential in automated unmixing of meaningful surface materials for two urban subsets and one suburban subset in Toronto, ON, Canada. Given the wide distribution of shadows in urban areas, the linear spectral unmixing is implemented in non-shadowed and shadowed areas separately for the two urban subsets. The results indicate that the accuracy of impervious surface mapping in suburban areas reaches up to 86.99%, much higher than the accuracies in urban areas (80.03% and 79.67%). Despite its merits in mapping accuracy and automation, the application of our proposed vegetation-bright impervious-dark impervious model to map impervious surfaces is limited due to the absence of soil component. To further extend the operational transferability of our proposed method, especially for the areas where plenty of bare soils exist during urbanization or reclamation, it is still of great necessity to mask out bare soils by automated classification prior to the implementation of linear spectral unmixing.

1. Introduction

An impervious surface is usually defined as a type of surface material that does not allow water to penetrate through ground into soil. Examples include asphalt roads, highways, sidewalks, parking lots, and most widely-distributed building rooftops (Weng, 2012). As the process of urbanization has accelerated, particularly in developing countries, an increasing number of environmental managers and urban planners have concentrated their attention on the acquisition of impervious surface information, including area, spatial distribution, and the ratio of perviousness to imperviousness. This is because the amount of impervious surface can increase runoff amount, duration, and intensity in urban areas, and thus has a significant influence on urban hydrological cycles (Weng, 2001). An increase in runoff can also increase the probability of the transport of non-point source pollution, reducing water quality in drainages, streams, and even lakes (Hurd and Civco, 2004). Furthermore, an increase in impervious surface will result in the loss of green space, which can greatly impact urban micro-environments and micro-climates by changing heat fluxes into and out of urban areas (Yang et al., 2003).

Over the past two decades, the importance of and great need for impervious surface information have facilitated the technical development of impervious surface mapping. Conventional ground-based measurement and aerial photo interpretation are able to supply reliable impervious surface information, but are not time-efficient. With the advent of image processing techniques and enhanced computing capacities, researchers have been increasingly able to conduct automated impervious surface mapping for large study areas. However, most of these studies made use of low-medium spatial resolution remote sensing imagery to map urban impervious surfaces (Bauer et al., 2004; Carlson and Arthur, 2000; Carlson, 2004; Civco et al., 2002; Gillies et al., 2003; Yang et al., 2003), until the development of high spatial resolution imagery.

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Although high spatial resolution imagery offers rich spatial details for impervious surface mapping (Cablk and Minor, 2003; Goetz et al., 2003; Lu and Weng, 2009; Lu et al., 2011; Yang and Li, 2015), some new problems have arisen with this development. Most importantly, shadows commonly exist in high spatial resolution urban imagery, induced by high-rise buildings and low sun elevation (Yang et al., 2015). The abundance of shadows can obscure the distinction between impervious surfaces and vegetation in shadowed areas, due to the reduction or even total loss of spectral information. Unlike shadows, the reduced boundary effect is less obvious in high spatial resolution images, but still arise concerns. Although the increased spatial resolution is able to resolve most of urban features, a significant number of pixels are still likely to have mixed and indistinct boundaries(Yang et al., 2014). Reduced boundary effects can negatively impact the accuracy of impervious surface mapping, especially when impervious features are closely adjacent to vegetation (Wu and Murray, 2003). In addition, high within-class spectral variability always occurs in high spatial resolution imagery, and decreases the accuracy of image classification (Hsieh et al., 2001; Johansen et al., 2010). In order to suppress this effect, it is necessary to measure or digitize a sufficient number and variety of training samples for classifiers; however, this process is time-consuming and labor-intensive.

In order to cope with the abundance of shadows in high spatial resolution imagery, many studies have made use of hierarchical classification approaches to map impervious surfaces in non-shadowed and shadowed areas, respectively (De Roeck et al., 2009; Yang and Li, 2015). In comparison with traditional pixel-based methods, object-based image analysis (OBIA) has been shown to be superior (Hu and Weng, 2011; Lu et al., 2011; Yuan and Bauer, 2006; Zhou and Wang, 2008) at impervious surface mapping because it is able to overcome the problem of within-class spectral variability. Nevertheless, the uncertainty introduced by the segmentation process can complicate the procedure of impervious surface mapping. Additionally, the problem of reduced boundary effects has not been solved, and is still dependent upon segmentation quality. In recent years, attempts have been made to utilize sub-pixel methods, most commonly linear spectral unmixing, as a solution to mixed-boundary pixels and within-class spectral variability in mapping impervious surfaces using high spatial resolution imagery (Lu and Weng, 2009; Wu, 2009). It has been widely accepted that linear spectral unmixing is preferable for low-medium spatial resolution imagery (Lu and Weng, 2006; Phinn et al., 2002; Van de Voorde et al., 2009; Weng et al., 2008; Weng et al., 2009; Wu and Murray, 2003), due to the larger number of mixed pixels and higher spectral resolutions. Small (Small, 2003) and Yang et al. (Yang et al., 2014) indicated that high spatial resolution imagery demonstrates a self-consistent basis, also known as spectral mixing space, for the description of urban surface materials. Specifically, Yang et al. (Yang et al., 2014) pointed out that the vegetation-high albedo-low albedo model is more suitable for linear spectral mixing of high resolution urban imagery than the vegetation-impervious-soil model (Ridd, 1995), which is commonly used for low-medium spatial resolution imagery. Compared to dark spectral features in low-medium resolution imagery, urban impervious surfaces are separated into bright and dark surface materials with the increasing spatial resolution. Meanwhile, bare soils become more spectrally similar to bright surfaces, thus are categorized as high albedo surfaces (Yang et al., 2014). Therefore, the traditional vegetation-impervious-soil model is not able to differentiate urban impervious surfaces and bare soils from high spatial resolution imagery. By contrast, the vegetation-high albedo-low albedo model has the capacity of characterizing urban surface materials, and can be further simplified to vegetation-bright impervious-dark impervious for urban areas where bare soils do not exist.

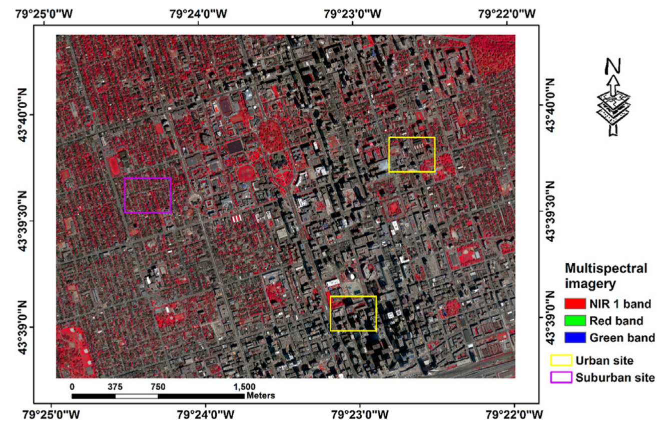

Fig. 1. WorldView-3 multispectral imagery of the study area (NIR 1, red, and green bands as R, G, B). Yellow and purple rectangles represent the two urban subsets and one suburban subset, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this paper, we implement the vegetation-bright impervious-dark impervious model for linear spectral unmixing of high spatial resolution imagery to automatically map impervious surfaces in urban areas. Although the linear spectral unmixing method has the advantage in dealing with the problems of mixed boundary pixels and within-class spectral variability, we have also adopted the hierarchical strategy to avoid the confusion between dark impervious surfaces and shaded features. In other words, linear spectral unmixing is implemented in non-shadowed and shadowed areas separately, and then merged for impervious surface mapping.

2. Methodology

2.1. Study area and data

Our study area was located in Toronto, Southern Ontario, Canada. The WorldView-3 satellite data used for this study were collected on May 9th, 2015. The data contained eight multispectral bands (i.e., coastal, blue, green, yellow, red, red edge, near infrared 1 (NIR 1), and near infrared 2 (NIR 2)), with 2 m spatial resolution and a panchromatic band with 0.5 m spatial resolution. In this study, we clipped a 4×3 km area of the original multispectral imagery of 2000×1500 pixels for impervious surface mapping (Fig. 1). This study area encompassed downtown Toronto and its surrounding suburban areas, and the absence of bare soils in these areas made them optimal for enabling the vegetation-bright impervious-dark impervious model for mapping impervious surfaces. Specifically, the downtown area is a typical urban mosaic of street trees, grass fields, and many high-rise buildings, leading to an abundance of shadows. On the other hand, the surrounding suburban areas are occupied by myriad low-rise residential houses, so shadows rarely exist. Therefore, we further selected two urban subsets (yellow rectangles in Fig. 1) and one suburban subset (purple rectangle in Fig. 1), each composed of 200×150 pixels, in order to compare the results of impervious surface mapping in different types of urban mosaics. Furthermore, the original multispectral and panchromatic imagery were fused by the Gram–Schmidt procedure in the ENVI software package (Laben and Brower, 2000) to produce eight-band pan-sharpened multispectral imagery with 0.5 m spatial resolution for the quantitative assessment of linear spectral unmixing results.

2.2. Methods

As the spectral features of urban surface materials in non-shadowed areas differ remarkably from those in shadowed areas,