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Stratified spectral mixture analysis of medium resolution imagery for impervious surface mapping

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ABSTRACT

Linear spectral mixture analysis (LSMA) is widely employed in impervious surface estimation, especially for estimating impervious surface abundance in medium spatial resolution images. However, it suffers from a difficulty in endmember selection due to within-class spectral variability and the variation in the number and the type of endmember classes contained from pixel to pixel, which may lead to over or under estimation of impervious surface. Stratification is considered as a promising process to address the problem. This paper presents a stratified spectral mixture analysis in spectral domain (Sp_SSMA) for impervious surface mapping. It categorizes the entire data into three groups based on the Combinational Build-up Index (CBI), the intensity component in the color space and the Normalized Difference Vegetation Index (NDVI) values. A suitable endmember model is developed for each group to accommodate the spectral variation from group to group. The unmixing into the associated subset (or full set) of endmembers in each group can make the unmixing adaptive to the types of endmember classes that each pixel actually contains. Results indicate that the Sp_SSMA method achieves a better performance than full-set-endmember SMA and prior-knowledge-based spectral mixture analysis (PKSMA) in terms of R, RMSE and SE.

1. Introduction

Impervious surface is defined as any area consisting of constructed surface which water cannot infiltrate to reach the soil (Yang et al., 2010; Weng, 2012), such as roads, roofs, and parking lots. It not only serves as a key indicator of the degree of urbanization, but also affects in the micro-ecosystem change (Wang et al., 2015). The increasing replacement of nature landscape by impervious surface leads to the change of hydrological character (White and Greer, 2006; Xian et al., 2007; Du et al., 2015), the generation of heat island effects (Kato and Yamaguchi, 2007; Yuan and Bauer, 2007; Coseo and Larsen, 2014), deterioration in water quality (Conway, 2007) and other detrimental effects. Therefore, it is essential to monitoring impervious surface distribution timely and accurately to ensure urban development is sustainable (Wu and Murray, 2005; Du and Du, 2014).

Remote sensing technology has become an important method, and may be the only viable way, to effectively extract impervious surface due to its high efficiency and low cost with large coverage (Yang et al., 2010; Lu and Weng, 2006). Various studies have been conducted for impervious surface mapping, with images from a large range of satellite sensors and a variety of data sources, including MODIS images with coarse spatial resolution (Yang and Lunetta, 2011; Deng and Wu, 2013b), Landsat TM/ETM+ and ASTER imagery (Hu and Weng, 2009; Sexton et al., 2013) with moderate spatial resolution, and IKONOS and QuickBird data (Lu and Weng, 2009; Zhou and Wang, 2008) with high spatial resolution. In addition to the optical remote sensing data, some other types' data, such as nighttime photography (Kotarba and Aleksandrowicz, 2016), Synthetic Aperture Radar (SAR) imagery (Zhang et al., 2016, 2014b) and open social data (Hu et al., 2016), have also been studied on their application to impervious surface estimation in recent years. Among them, medium spatial resolution images might be a better choice for the urban impervious surface mapping, because they provide a good trade-off among coverage, price, and quality.

However, due to the heterogeneity of urban land covers and the limitation in spatial resolution, the presence of mixed pixels has been recognized as a major problem in the analysis of medium spatial resolution images (Weng, 2012). Several unmixing methods have then been applied for impervious surface extraction, including linear spectral mixture analysis (LSMA) (Weng et al., 2009; Hu and Weng, 2008;

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Yang and He, 2017), artificial neural network (ANN) (Mohapatra and Wu, 2008), regression analysis (Yang et al., 2003; Yang and Liu, 2005; Kaspersen et al., 2015) and regression trees (Huang and Townshend, 2003; Deng and Wu, 2013b). Yet LSMA is still the most popular approach due to its simplicity and physically-based description of the fractions of different land covers (Small and Milesi, 2013; Burazerovic et al., 2013).

While LSMA and LSMA based methods are easy to use in estimating impervious surface, several problems still exist. It has been found that impervious surface tends to be overestimated in the areas with small amounts of impervious surface, but is underestimated in the areas with large amounts of impervious surface (Weng, 2012; Lu and Weng, 2006). The similarity in spectral properties between impervious and pervious surface, especially impervious surface and soil, can be one of the main reasons for underestimation in urban area and overestimation in pervious area. Another problem is the difficulty in selecting endmembers due to within-class spectral variability (Foody et al., 1997). It should be noted that the differences in type, geometry and illumination etc. lead to the huge differences in term of spectral characteristics of impervious surface. Therefore, using one endmember to represent all types of impervious surfaces is often found problematic (Weng et al., 2008). The performance of LSMA can also be reduced if every pixel in the image is unmixed into a fix set of endmembers, where some pixels may only contain a subset of endmembers.

Stratification is considered as a promising process to solve these problems. In (Lu and Weng, 2004), stratification of a whole scene into subareas with similar landscape structures is suggested to improve impervious surface mapping. Several studies (Wu and Murray, 2003; Zhang et al., 2014a; Small, 2001; Somers et al., 2009) have attempted to employ different endmember class sets for urban and rural areas. However, the endmembers sets applied to each subarea are extracted from the entire image scene. The weakness of this treatment is the spectral variability in different subsets is not considered. The endmembers, which are selected at the extreme of an n-dimensional scatter plot of the entire image may be less representative as the pure pixels in each subset (Deng and Wu, 2013a). The current methods stratify a remote sensed image into urban and rural areas through spatial information, such as texture and road density information (Zhang et al., 2014a; Liu and Yang, 2013). The overlooked the spectral information would result in mis-estimation of land cover abundances.

In this study, we address the above mentioned problems and propose a stratified spectral mixture analysis in spectral domain (Sp_SSMA) for impervious surface mapping. We clipped an image data set into three groups to reduce the within class variability in each subgroup based on three spectral character components, namely Combinational Build-up Index (CBI) (Sun et al., 2015), Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) and color intensity. Then, endmembers are selected from each group independently rather than from the entire image to cope with the within class variability. An endmember set with different types and numbers is applied in each group to make it more adaptive. Impervious surface fractions are estimated by LSMA and the results of the three subgroups are combined to produce a complete map.

The remainder of this article is structured as follows. The second section presents the methodology of Sp_SSMA, including the stratification, the selection of endmembers and the procedures for deriving impervious surface abundance. The third section introduces the study areas and remotely sensed data, including data preprocessing. The comparative results and discussions are reported in Section 4. Finally, conclusions are provided in Section 5.

2. Methodology

Based on the definition, impervious surface is a unifying theme. However it consists of a number of artificial features which have different spectral profiles in general. Fig. 1(a) illustrates the mean spectral values of different impervious surface and other major land cover classes based on the pure pixels selected from a Landsat TM image. It indicates that not only impervious surfaces consist of different structures, colors, and materials, vegetation and soil also show great spectral differences within each of them. Fig. 1(b) is the corresponding grouped scatter points of the sampled pixels in the feature space composed by the first two components of minimum noise fraction (MNF1and MNF2). We can see that the pure pixels are not always located at the extremes of the scatter plot as it supposed to be theoretically, due to the within-class variation of a land cover type. It also indicates the spectral variability within several classes as well as the spectral confusion among several land covers, especially between urban impervious surfaces and bare soil.

Therefore, simply extracting a single set of endmembers from the vertices in an n-dimensional scatter plot of an entire scene, like the treatment in (Powell et al., 2007), is potentially less reliable because they cannot account for the considerable within-class variability (Rashed et al., 2003; Roessner et al., 2001). The similarity of spectral characteristics between impervious and pervious surface, especially bare soil, also prevent the SMA-based methods from achieving a promising result.

To tackle this problem, we develop a stratified spectral unmixing method in spectral domain (Sp_SSMA). Three spectral feature components, CBI, intensity component of intensity-hue-saturation (IHS) and NDVI, are utilized to partition the entire data into three groups, named Group 1, Group 2 and Group 3. Each group is processed independently, including endmember extraction and spectral unmixing, to minimize the within class spectral variability and the confusion between some urban features and non-impervious land covers. The major steps in Sp_SSMA are described in Fig. 2.

2.1. Stratification

2.1.1. CBI calculation

CBI is a feature-extraction based spectral impervious surface index. It reduces the original multi-/hyper-bands into three thematic-oriented features. They are the first component of a principal component analysis (PC1), Normalized Difference Water Index (NDWI) (Gao, 1996) and Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), to represent high albedo, low albedo and vegetation respectively. The features are calculated using the following equations (Sun et al., 2015):

$$CBI=\frac{(PC1_{nor}+NDWI_{nor})/2\text{-}SAVI_{nor}}{(PC1_{nor}+NDWI_{nor})/2+SAVI_{nor}} \tag{1}$$

with

$$SAVI=\frac{(\rho_{NIR}\text{-}\rho_{RED})(1+L)}{\rho_{NIR}\text{-}\rho_{RED}+L} \tag{2}$$

$$NDWI=\frac{\rho_{GREEN}-\rho_{NIR}}{\rho_{GREEN}+\rho_{NIR}} \tag{3}$$

where ρ_{GREEN}, ρ_{RED}, ρ_{NIR} represent the reflectance value of GREEN, NIR and SWIR bands, respectively. L is a correction factor ranging from 0 to l. In this study, 0.5 is taken to form a vegetation image. $PC1_{nor}$, $SAVI_{nor}$ and $NDWI_{nor}$ are the normalized PC1, SAVI and NDWI respectively.

In CBI, impervious surfaces are highlighted with positive values, vegetation is represented with negative values while bare soil and mixed land cover types are associated with numerical values about zero. Qualitative and quantitative assessments of accuracy analysis, separability between impervious surface and soil at different spatial and spectral resolutions as well as comparison with other indices indicate that CBI is a promising and reliable urban landscape index for mapping impervious surface areas (Sun et al., 2015).

2.1.2. I calculation

The IHS color space can be regarded as a two-dimensional color