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Prior-knowledge-based spectral mixture analysis for impervious surface mapping

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ABSTRACT

In this study, we developed a prior-knowledge-based spectral mixture analysis (PKSMA) to map impervious surfaces by using endmembers derived separately for high- and low-density urban regions. First, an urban area was categorized into high- and low-density urban areas, using a multi-step classification method. Next, in high-density urban areas that were assumed to have only vegetation and impervious surfaces (ISs), the vegetation–impervious model (V–I) was used in a spectral mixture analysis (SMA) with three endmembers: vegetation, high albedo, and low albedo. In low-density urban areas, the vegetation–impervious–soil model (V–I–S) was used in an SMA analysis with four endmembers: high albedo, low albedo, soil, and vegetation. The fraction of IS with high and low albedo in each pixel was combined to produce the final IS map. The root mean-square error (RMSE) of the IS map produced using PKSMA was about 11.0%, compared to 14.52% only using four-endmember SMA. Particularly in high-density urban areas, PKSMA (RMSE = 6.47%) showed better performance than four-endmember (15.91%). The results indicate that PKSMA can improve IS mapping compared to traditional SMA by using appropriately selected endmembers and is particularly strong in high-density urban areas.

1. Introduction

Impervious surfaces (ISs) are those through which water cannot infiltrate to reach the soil. Anthropogenic ISs include roads, driveways, sidewalks, parking lots, and rooftops (Arnold and Gibbons, 1996; Slonecker et al., 2001). The spatial distribution of ISs has important impacts on natural phenomena such as surface runoff and urban temperature change (e.g., the urban heat island effect) and is also closely related to socio-economic factors, such as population density and social conditions (Weng, 2011; Weng and Lu, 2008; Wu, 2004; Wu and Murray, 2003; Zhang et al., 2012; Zhou and Wang, 2007, 2008). Therefore, timely and accurate information regarding the distribution of urban ISs is critical in urban management.

Remote sensing is an important tool in regional IS mapping because of its speediness and large coverage (Lu and Weng, 2006; Wu and Murray, 2003). The vegetation–impervious surface–soil (V–I–S) model was first proposed for the mapping of ISs by Ridd to parameterize the biophysical composition of the urban environment and urbanization level (Ridd, 1995). This model has been extensively applied in urban IS mapping using remotely sensed data (Hu and Weng, 2009; Lu et al., 2011; Lu and Weng, 2004, 2006; Weng and Hu, 2008; Wu, 2004; Yang et al., 2010, 2012). Among these studies, the spectral mixture analysis (SMA) method has been widely used because of its advantages in dealing with mixed pixels (Lu and Weng, 2004, 2006; Small and Lu, 2006; Weng, 2011; Weng and Hu, 2008; Weng and Lu, 2008; Wu and Murray, 2003; Wu, 2004).

Selecting appropriate endmembers is crucial for IS mapping when using the SMA method (Lu and Weng, 2006). The endmember selection approaches used in previous SMA studies can be categorized into three types: IS endmembers selected directly from remotely sensed data, four-endmember SMA models, and multi-endmember SMA models. In the first category, the IS endmember is extracted directly from remote sensing data, such as data for rooftops, and imported into the SMA model to obtain the IS abundance value (Ji and Jensen, 1999; Lu and Weng, 2004; Phinn et al., 2002). However, a pure IS endmember cannot be acquired directly from a remotely sensed image. One reason for this is that some types of IS, such as concrete rooftops painted in different colors and bituminous pavement, are highly heterogeneous. Furthermore, it is difficult to identify large and uniform IS types from remotely

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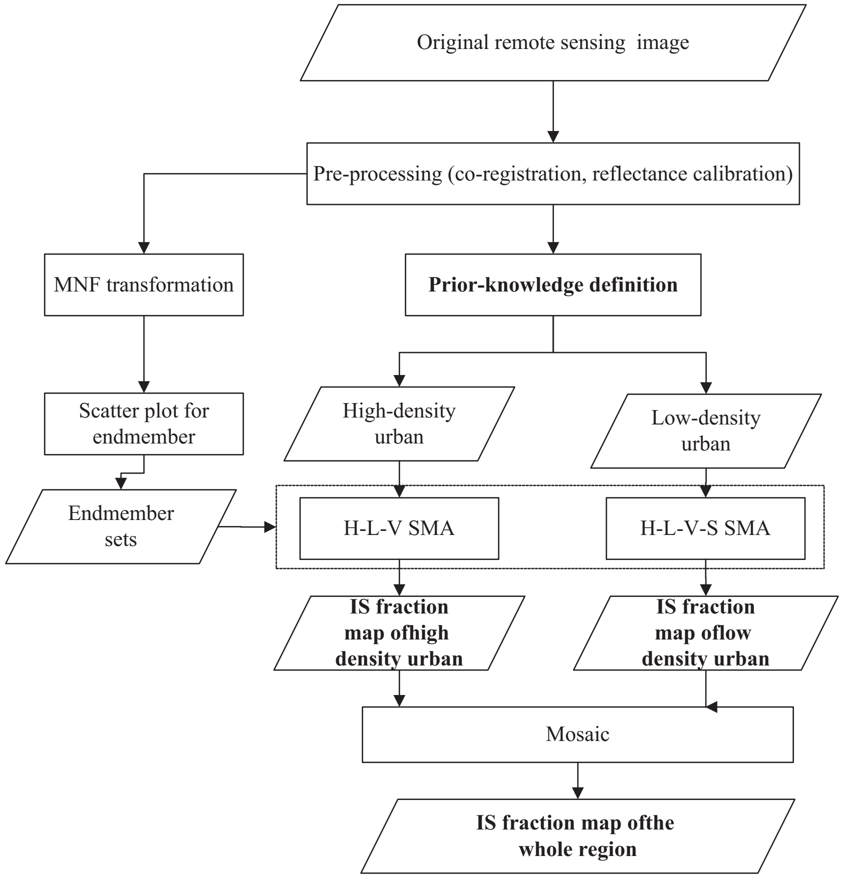

Fig. 1. Flowchart of the PKSMA method.

sensed images with low or moderate spatial resolutions (Wu and Murray, 2003). To solve this problem, a four-endmember SMA model was proposed for IS mapping using the indirect IS endmember (Wu and Murray, 2003). In this method, four endmembers (high albedo, low albedo, vegetation, and soil) were defined and used in an SMA model. Wu and Murray (2003) found that IS abundance could be obtained by combining the fraction of high and low albedo abundances. Lu and Weng (2006) explored the four-endmember SMA method for the extraction of IS information from Landsat Enhanced Thematic Mapper (TM) data and used land surface temperature to eliminate the effect of mixture with other land cover types.

Previous studies have shown that the abundance of ISs tends to be overestimated in low-density urban areas but underestimated in high-density urban areas when using a four-endmember SMA (Weng, 2011). In addition, the fixed characteristics of the endmembers that are assumed in the four-endmember SMA model are not able to fully represent the mixed pixels because the components of land cover comprising the mixed pixels vary in complex urban landscapes. For example, in urban transitional areas, some pixels may be composed of three land cover components, (vegetation, soil and IS). In contrast, in highly developed urban cores, especially in metropolises, soil is rare and mixed pixels may be composed of two endmembers: vegetation and IS (Roberts et al., 1998; Somers et al., 2011; Weng and Hu, 2008). The multi-endmember SMA (MESMA) method was developed (Roberts et al., 1998; Somers et al., 2009, 2011; Song, 2005) to minimize residuals and effectively resolve the problem of spectral variability in endmembers by adjusting the endmember combinations (Dennison and Roberts, 2003; Franke et al., 2009; Powell et al., 2007; Roberts et al., 1998). The feasibility of IS mapping using MESMA has been proven by comprehensive comparisons of different combinations of selected endmembers (Rashed et al., 2003), demonstrating its potential in addressing the issues of spectral variation in endmembers. Powell et al. (2007) presented a MESMA methodology in which a Landsat+ image was used to build a specific spectral library based on generalized categories of urban materials: vegetation, soil, IS, and water. In total 1137 two-, three-, and four-endmember models for each pixel were generated for IS mapping. Almost 97% of the pixels within the image were modeled within a 2.5% root-mean-square error constraint. Yang et al. (2010) incorporated 15 models using Landsat 5 images for IS mapping and analyzed the advantages of MESMA over the traditional SMA method. However, because of the assumed minimum system error residual, the MESMA model, which lacks a physical basis for explaining the components of mixed pixels, is only mathematically optimal and cannot physically describe the components of mixed pixels. Furthermore, building the complex endmember library and determining the optimal model iteratively can be very difficult and limits the practical applicability of MESMA for IS mapping.

In this study we developed a prior-knowledge-based SMA (PKSMA) for IS mapping, particularly for mixed pixels with prior information. The prior knowledge was acquired by classifying the whole urban region into high- and low-density urban areas. In high-density urban areas, a high albedo–low albedo–vegetation SMA (H–L–V SMA) model was used, whereas in low-density urban regions, a high albedo–low albedo–vegetation–soil SMA (H–L–V–S SMA) model was adopted. In Section 2, we describe the PKSMA method in detail. In Section 3, the study area and data sets are described, followed by the experiments and results in Section 4. The conclusions are presented in Section 5.