ISPRS Journal of Photogrammetry and Remote Sensing 65 (2010) 479–490

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

A pre-screened and normalized multiple endmember spectral mixture analysis for mapping impervious surface area in Lake Kasumigaura Basin, Japan

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ARTICLE INFO

Article history:
Received 26 October 2009
Received in revised form
15 June 2010
Accepted 24 June 2010
Available online 22 July 2010

Keywords:
Impervious surface area
Spectral mixture analysis
Endmember selection
Lake Kasumigaura Basin

ABSTRACT

The impervious surface area (ISA) has emerged not only as an indicator of the degree of urbanization, but also as a major indicator of environmental quality for drainage basin management. However, since almost all of the methods for estimating ISA have been developed for urban environments, it is questionable whether these methods can be successfully applied to drainage basins, such as those found in Japan, which usually have more complicated vegetation components (e.g. paddy field, plowed field and dense forest). This paper presents a pre-screened and normalized multiple endmember spectral mixture analysis (PNMESMA) method, which includes a new endmember selection strategy and an integration of the normalized spectral mixture analysis (NSMA) and multiple endmember spectral mixture analysis (MESMA), for estimating the ISA fraction in Lake Kasumigaura Basin, Japan. This new proposed method is superior to the previous methods in that the estimation error of the proposed method is much smaller than the previous SMA- or NSMA-based methods for drainage basin environments. The overall root mean square error was reduced to 5.2%, and no obvious underestimation or overestimation occurred for high or low ISA areas. Through the assessment of environmental quality in Lake Kasumigaura Basin using the ISA fraction, the results showed that the basin has been in the impacted category since 1987, and that in the two decades since, the environmental quality has continued to decline. If this decline continues, then Lake Kasumigaura Basin will fall into the degraded category by 2017.

1. Introduction

The Impervious Surface Area (ISA) is defined as an area consisting of constructed surfaces (roofs, roads, parking lots, driveways, sidewalks, and other surfaces) which prevent water from infiltrating into the soil. The ISA has emerged not only as an indicator of the degree of urbanization, but as a major indicator of environmental quality for drainage basin management (Arnold and Gibbons, 1996). Previous studies pointed out that the increase of ISA has changed the hydrological character (White and Greer, 2006; Xian et al., 2007) and heat balance (Kato and Yamaguchi, 2007; Yuan and Bauer, 2007) of drainage basins, put environmental pressure on the aquatic ecosystem (Alberti et al., 2007), and had other detrimental effects. A widely accepted scale for the impact of the ISA on drainage basins are: stressed if they contain 1%–10% ISA, impacted if they contain 10%–25% ISA and degraded if they contain more than 25% ISA (Arnold and Gibbons, 1996; Elvidge et al., 2007; Schueler, 1994). Therefore, it is essential to accurately estimate the ISA for effective management of drainage basins.

Remote sensing techniques, which have the inherent ability to provide spatial and temporal information about the Earth surface, may be the only viable way to effectively monitor large scale land use/cover change such as that around a drainage basin. However, accurately estimating the ISA from satellite data is still challenging because the ISA always results in spectral heterogeneity at scales comparable to sensor resolution, which limits the utility of conventional hard classification methods (Small, 2001). To solve the problem of spectral heterogeneity, a vegetation-impervious surface-soil model (V-I-S) was proposed for parameterizing the biophysical composition of urban environments (Ridd, 1995). In this model, a given pixel can be modeled by the fractions of vegetation, impervious surface and soil, based on spectral mixture analysis (SMA). On the basis of SMA and V-I-S models, many studies in which the ISA was estimated have been conducted in urban areas (Phinn et al., 2002; Powell et al., 2007; Rashed et al., 2005; Small and Lu, 2006; Wu and Murray, 2003).

The success of the application of SMA and V-I-S models for accurately estimating ISA fractions depends on the selection of the endmember components (Dennison and Roberts, 2003a,b). According to the V-I-S model, three endmembers, vegetation, impervious surface, and soil can be selected for the SMA. However, due to the complexity of spectral reflectance for ISA, more endmembers

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doi:10.1016/j.isprsjprs.2010.06.004

are required to explain more spectral variation, thereby increasing model fitness. For example, some applications in urban areas generally sub-classify impervious surfaces into two different endmembers, i.e. low albedo (e.g. asphalt) and high albedo (e.g. concrete) (Lu and Weng, 2006; Small, 2001; Wu and Murray, 2003). Vegetation and soil also show spectral complexities, with similar spectral shapes but different spectral magnitudes because of different leaf characteristics, canopy geometry, and leaf angle distributions for vegetation, and soil composition, grain size, and water content for soil (Matsushita and Fukushima, 2009; Wu, 2004; Dennison and Roberts, 2003a). However, too many endmembers make the mixture model not only sensitive to endmember selection, but also make it impossible to apply the model to multispectral imagery and thus potentially make the model inapplicable to most cases (Matsushita and Fukushima, 2009; Sabol et al., 1992; Wu and Murray, 2003). Wu (2004) proposed a normalized spectral mixture analysis (NSMA) to address the problems associated with spectral complexity (e.g. brightness variation and shade effect within each endmember). Lu and Weng (2006) developed another method by using the land surface temperature to remove non-impervious surfaces from the low albedo and high albedo estimations, which improved the accuracy of ISA estimation without any addition of endmember numbers. Powell et al. (2007) reported that multiple endmember spectral mixture analysis (MESMA), which allows the number and type of endmembers to vary from pixel to pixel, can also be used to address the problem of spectral variability. However, almost all of the SMA- or NSMA-based methods for estimating ISA have been developed for urban environments. Therefore, it is questionable whether these methods can also be successfully applied to an Asian drainage basin in which each endmember, particularly those for different vegetation species, has more complicated characteristics (Song, 2004, 2005).

The objectives of this study are: (1) to develop a new NSMA-based method that can accurately estimate ISA in a drainage basin with the Lake Kasumigaura Basin as a case study; (2) to show the performance of the proposed method by comparing it with several previous methods, and (3) to assess the environmental quality of the Lake Kasumigaura Basin and explore its twenty-year changes using the ISA as an indicator. In the method development process, two main problems were considered. One is the vegetation endmember selection, which takes into account the vegetation diversity; the other is to overcome the flaws existing in the original SMA- or NSMA-based methods, which lead to underestimation in high ISA areas or overestimation in low ISA areas.

2. Study area

The Lake Kasumigaura Basin is located in the eastern part of the Kanto Plain of Japan, and covers an area of about 2157 km^2 (Fig. 1). The population of the Lake Kasumigaura Basin was approximately 1 million in 2000. With a surface area of 220 km^2 and an average depth of 4 m, the lake is the second largest in Japan. The climate of the area is similar to other regions on the Pacific side of Japan with an annual average air temperature of about 14 °C and an annual precipitation of 1250 mm.

The dominant landscapes in the Lake Kasumigaura Basin are paddy fields (25.8%), forests (22.7%), plowed fields (21.2%), and water (10.6%) (Matsushita et al., 2006). The traditional industries in this area are agriculture, livestock management, and fishery production. However, many new industrial plants have been constructed, and industrial shipments from the area continue to rise every year. Since the study area is only 60 km from Tokyo, there has been a rapid rise in the number of residents, recreational facilities, and resort areas in recent years, which has caused rapid changes in the landscape structure in the past decades. From 1979 to 1996, human-modified landscapes, such as artificial fields and golf courses, increased rapidly, while forests and croplands rapidly decreased (Fukushima et al., 2007). Increased patch (landscape element) numbers, Shannon's diversity, and decreased mean patch area have indicated that the Lake Kasumigaura Basin has become more fragmented and heterogeneous (Matsushita et al., 2006). With the completion of a new railroad linking Tsukuba and the Akihabara area of Tokyo in 2005, this trend is likely to persist as the population in the Lake Kasumigaura Basin continues to increase.

3. Image pre-processing

Four scenes of cloud-free or little cloud contaminated Landsat-5 TM images (Row 107/Path 35) were collected for the Lake Kasumigaura Basin. These images were acquired on July 24, 1987, July 19, 1999, July 11, 2000, and August 16, 2007. All images were geometrically corrected to UTM (Universal Transverse Mercator) projection (Zone 54N; Spheroid: GRS1980; Datum: JGD2000). The GSI Digital Map 25 000 (Geographical Survey Institute, Japan, 1:25000, published in 2002) was used as the reference image for geometric correction. A first order polynomial model was applied for the rectification with the nearest neighbor resampling method. The root mean square errors were less than 0.1 pixels (3 m) for all satellite images.

Relative radiometric normalization by automatic scattergram-controlled regression (ASCR) was carried out to compensate for the radiometric divergence present in images acquired under different illumination, atmospheric, or sensor conditions (Elvidge et al., 1995; Yuan and Elvidge, 1996). The image collected on July 24, 1987 was set as a reference image because it was cloud-free and taken under a good sensor condition. After the relative radiometric normalization, the rescaling gain, bias (Chander et al., 2007) and parameters (Chander and Markham, 2003) for the image acquired on July 24, 1987 were applied to all images to convert digital numbers (DNs) to top-of-the-atmosphere (TOA) reflectance.

Since the images collected on July 19, 1999 and July 11, 2000 contained some cloud coverage in the study area, a cloud mask was first made for the image acquired on July 11, 2000, and then the clear corresponding pixels in the image acquired on July 19, 1999 were used to replace the clouded pixels in the image acquired on July 11, 2000. Finally, the images acquired on July 24, 1987 and August 16, 2007, together with the composited image mainly based on the image acquired on July 11, 2000, were used to investigate ISA distribution in 1987, 2000 and 2007. A water mask was made by the unsupervised classification method (Wu and Murray, 2003), and water pixels in the study area were then removed using this water mask before the ISA estimation.

4. Development of a new NSMA-based method for estimating ISA in a drainage basin

4.1. Spectral mixture analysis (SMA) and normalized spectral mixture analysis (NSMA)

A linear spectral mixture analysis model was adopted in this study. For a given pixel, the reflectance for each band b (R_b) in the Landsat-5 TM image can be written as:

$$R_b = \sum_{j=1}^{N} f_j R_{j,b} + e_b \quad (1)$$

$$\sum_{j=1}^{N} f_j = 1, \quad f_j \geq 0 \quad (2)$$

where N is the number of endmembers (i.e. spectrally 'pure' materials), f_j is the fraction of endmember j, $R_{j,b}$ is the reflectance of