Remote Sensing of Environment 137 (2013) 184–197

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

# Support vector regression and synthetically mixed training data for quantifying urban land cover

Akpona Okujeni [a,*], Sebastian van der Linden [a], Laurent Tits [b], Ben Somers [c], Patrick Hostert [a]

[a] Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[b] Department of Biosystems, M3-BIORES, Katholieke Universiteit Leuven, W. de Croylaan 34, BE-3001 Leuven, Belgium
[c] Department Earth and Environmental Sciences, Division Forest, Nature and Landscape Research, Katholieke Universiteit Leuven, Celestijnenlaan 200E - bus 2411, B-3001 Leuven, Belgium

ARTICLE INFO

*Article history:*
Received 16 October 2012
Received in revised form 24 April 2013
Accepted 9 June 2013
Available online 19 July 2013

*Keywords:*
Support vector regression
Support vector machines
MESMA
Unmixing
Hyperspectral
Imaging spectroscopy
Urban
Berlin

ABSTRACT

Exploiting imaging spectrometer data with machine learning algorithms has been demonstrated to be an excellent choice for mapping ecologically meaningful land cover categories in spectrally complex urban environments. However, the potential of kernel-based regression techniques for quantitatively analyzing urban composition has not yet been fully explored. To a great extent, this can be explained by difficulties in deriving quantitative training information that reliably represents pairs of spectral signatures with associated land cover fractions needed for empirical modeling. In this paper we present an approach to circumvent this limitation by combining support vector regression (SVR) with synthetically mixed training data to map sub-pixel fractions of single urban land cover categories of interest. This approach was tested on Hyperspectral Mapper (HyMap) data acquired over Berlin, Germany. Fraction estimates were validated with extensive manual mappings and compared to fractions derived from multiple endmember spectral mixture analysis (MESMA). Our regression results demonstrate that the sets of multiple mixtures yielded high accuracies for quantitative estimates for four spectrally complex urban land cover types, i.e., fractions of impervious rooftops and pavements, as well as grass- and tree-covered areas. Despite the extrapolation uncertainty of SVR, which resulted in fraction values below 0% and above 100%, physically meaningful model outputs were reported for a clear majority of pixels, and visual inspection underpinned the quality of produced fraction maps. Statistical accuracy assessment with detailed reference information for 92 urban blocks showed linear relations with $R^2$ values of 0.86, 0.58, 0.81 and 0.85 for the four categories, respectively. Mean absolute errors (MAE) ranged from 6.4 to 12.8% and block-wise sums of the four individually modeled category fractions were always around 100%. Results of MESMA followed similar trends, but with slightly lower accuracies. Our findings demonstrate that the combination of SVR and synthetically mixed training data enable the use of empirical regression for sub-pixel mapping. Thus, the strengths of kernel-based approaches for quantifying urban land cover from imaging spectrometer data can be well utilized. Remaining uncertainties and limitations were related to the known phenomena of spectral similarity or ambiguity of urban materials, the spectral deficiencies in shaded areas, or the dependency on comprehensive and representative spectral libraries. Therefore, the suggested workflow constitutes a new flexible and extendable universal modeling approach to map land cover fractions.

## 1. Introduction

Research on the structure and functioning of cities is of great importance, particularly considering the rates of current and projected global urbanization (Alberti, 2005; Grimm et al., 2008; Pickett et al., 2011). Detailed descriptions of urban surface properties, i.e., beyond the broad differentiation of “urban land” and “non-urban environments”, are crucial for developing a more thorough understanding of the integrated human–natural ecosystem (Cadenasso, Pickett, & Schwarz, 2007). The spatial distribution, abundances and conditions of different impervious, pervious and vegetation cover types, for example, directly influence processes related to urban climate (Chudnovsky, Ben-Dor, & Saaroni, 2004; Gluch, Quattrochi, & Luvall, 2006), hydrology (Arnold & Gibbons, 1996; Pauleit & Duhme, 2000) or biodiversity (Blair, 1996; McKinney, 2002).

Data from municipal authorities provide detailed information on urban surface characteristics at the scale of urban blocks, a preferred spatial unit for urban management purposes or urban environmental studies (Heiden et al., 2012; Pauleit & Duhme, 2000). Data collections are, however, often based on cost- and time-intensive field surveys and are subject to irregular updates. In this context, remote sensing constitutes a supplemental technique to derive information on the physical composition of urban areas (Jensen & Cowen, 1999; Maktav, Erbek, & Jurgens, 2005; Miller & Small, 2003).

---

* Corresponding author. Tel.: +49 30 2093 6905; fax: +49 30 2093 6848.
*E-mail address:* akpona.okujeni@geo.hu-berlin.de (A. Okujeni).

0034-4257/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.06.007

Data acquired by various multispectral spaceborne sensors, which range from very high to moderate spatial resolution and high acquisition frequency, have been applied for mapping urban land cover (Myint, Gober, Brazel, Grossman-Clarke, & Weng, 2011; Powell, Roberts, Dennison, & Hess, 2007; Rashed, Weeks, Roberts, Rogan, & Powell, 2003; Thomas, Hendrix, & Congalton, 2003). Many studies followed the V–I–S model by Ridd (1995), a framework used to universally characterize three major urban surface components, i.e., "vegetation", "impervious surfaces" and "soil". However, the coarse spectral resolution of multispectral data often limits the accurate distinction of different impervious, pervious and vegetation surface cover types (Herold, Gardner, & Roberts, 2003; Myint et al., 2011; Small & Lu, 2006). Therefore, Small (2004) and Small and Lu (2006) proposed the substrate vegetation dark surface (SVD) model, which characterizes the urban environment by biophysical surface reflectance properties rather than by land cover types. Nevertheless, linking spectral with thematic information remains desirable, especially when high resolution spectral information is available. Other studies overcame some of the limitations of multispectral data by analyzing high-resolution images with object-based strategies (Myint et al., 2011; Shackelford & Davis, 2003; Thomas et al., 2003). Still others use complex multi-sensor and multi-temporal approaches that extend the spectral feature space or take advantage of information beyond the spectral domain (Griffiths, Hostert, Gruebner, & van der Linden, 2010; Taubenböck et al., 2012). Even when employing such fusion approaches we need to better understand the opportunities and limitations of high resolution spectral data.

The increasing availability of imaging spectrometer data from urban areas has allowed for a more detailed mapping of thematic surface properties on a purely spectral basis. Several studies have demonstrated the great potential of continuous spectral information for fine-scale classifications, including various man-made materials and vegetation species (Franke, Roberts, Halligan, & Menz, 2009; Herold et al., 2003). Other studies have included rather broad-scale classifications when considering ecologically meaningful sub-categories, e.g., impervious rooftops and pavements, pervious soils, and grass- and tree-covered areas (Roessner, Segl, Heiden, & Kaufmann, 2001; van der Linden & Hostert, 2009). Thus far such investigations have been more experimental in nature because currently available high quality data sets are almost exclusively constrained to airborne acquisitions with limited spatial coverage and temporal frequency. This is likely to change with the advent of new hyperspectral satellite missions, e.g., the German Environmental Mapping and Analysis Program (EnMAP; Stuffler et al., 2007; Stuffler et al., 2009) or the Hyperspectral Infrared Imager (HyspIRI; National Research Council, 2007; Roberts, Quattrochi, Hulley, Hook, & Green, 2012). Such systems will provide imaging spectrometer data of a large spatial extent on a timely and frequent basis, which will open up new opportunities for urban remote sensing applications (Heldens, Heiden, Esch, Stein, & Mueller, 2011). Ground sampling distances (GSDs) in the range of 30 to 60 m will, however, complicate studies, especially in spatially heterogeneous environments. Robust analysis approaches with universal applicability and best possible transferability on data of coarser spatial resolution will be needed to best utilize imagery acquired by future spaceborne imaging spectrometers.

Despite this promising development, using imaging spectrometer data for urban applications remains a challenge. The high number of materials, their varying conditions, as well as the surfaces' anisotropic reflectance behavior lead to vast spectral diversity. As a consequence, different spectral phenomena such as high within-class variability of individual materials, complex multi-modal class compositions, and high inter-class similarity or ambiguity complicate urban land cover assessments (Heiden, Segl, Roessner, & Kaufmann, 2007; Herold, Roberts, Gardner, & Dennison, 2004; Herold, Schiefer, Hostert, & Roberts, 2006; Schiefer, Hostert, & Damm, 2006). This complexity is further aggravated by the high amount of spectrally mixed pixels typical for urban remote sensing data. The extent of spectral mixing, i.e., the number of mixed pixels and the abundance of different materials contributing to the mixed signal, strongly depends on the fine-scale spatial patterns of different urban objects, and on the GSD of the respective sensor (Small & Lu, 2006).

Spectrally mixed signatures produce inaccuracies in per-pixel classification approaches, which assign each pixel to a discrete urban land cover category (Powell et al., 2007; Small, 2001). This applies even to investigations on airborne or high resolution spaceborne remote sensing data of 4 m GSD (Small, 2003; van der Linden, Janz, Waske, Eiden, & Hostert, 2007). Hence, quantitative mapping of urban land cover components constitutes an alternative concept that becomes particularly relevant once coarser resolution spaceborne imaging spectrometer data becomes available. In general, quantitative approaches account for sub-pixel mixing by transforming reflectance measurements of individual pixels into both physically meaningful quantities of surface fractions and thematically meaningful land cover types. Multiple endmember spectral mixture analysis (MESMA; Roberts et al., 1998) is probably the most commonly used technique to systematically decompose mixed pixels into fractional abundances of distinct spectrally pure endmembers (EMs). Within-class spectral variability is accounted for by using an extensive iterative procedure with multiple linear mixture models (Somers, Asner, Tits, & Coppin, 2011). In the context of imaging spectrometry of urban areas, MESMA was successfully used to quantify thematically detailed land cover types or to derive material-oriented fraction maps (Franke et al., 2009; Roberts et al., 2012).

Support vector machines (SVMs) have received increasing attention in the remote sensing community; SVMs are supervised, non-parametric statistical learning techniques designed to solve classification and regression problems (Schölkopf & Smola, 2002; Vapnik, 1995). A recent review of implementations and applications of SVMs was provided by Mountrakis, Im, and Ogole (2011). As applied to remote sensing data, SVMs have shown great capabilities to model complex multi-modal, nonlinear data distributions in high-dimensional spectral feature spaces (Huang, Davis, & Townshend, 2002; Melgani & Bruzzone, 2004; Pal & Mather, 2006). Thus far, the advantage of kernel-based support vector classification (SVC) for a per-pixel-based mapping of spectrally complex urban land cover categories from imaging spectrometer data has been demonstrated (Tuia & Camps-Valls, 2011; van der Linden et al., 2007; Waske, van der Linden, Benediktsson, Rabe, & Hostert, 2010). However, the potential of kernel-based support vector regression (SVR) as a quantitative technique for analyzing the complex hyperdimensional urban feature space with high spectral and spatial heterogeneity has not yet been fully explored. Given a set of adequate training samples, SVR allows us to estimate a continuous output variable, such as sub-pixel fractions of a single land cover category. To date, most studies have used SVR for predicting biophysical/chemical plant parameters by relating spectral information to in situ samples (Camps-Valls, Bruzzone, Rojo-Alvarez, & Melgani, 2006; Tuia, Verrelst, Alonso, Perez-Cruz, & Camps-Valls, 2011; Verrelst et al., 2012). Few studies have adopted SVR to quantify fractions of broad urban categories in 30 m multispectral satellite imagery using reference information from very high resolution land cover maps (Esch et al., 2009; Walton, 2008). This latter approach fully relies on the availability of very accurately co-registered, very high resolution reference. Often such data – and especially accuracy – is not given when high resolution imagery from spatially heterogeneous environments is used as input, e.g., for airborne line scanner data from urban areas. Moreover, reliable sub-pixel fractions cannot be labeled in the data itself or mapped in the field. These difficulties in finding reliable quantitative training information explain the lack of studies that use regression techniques for sub-pixel mapping. To the best of our knowledge, no investigations have been carried out where SVR was used together with imaging spectrometer data to derive sub-pixel fraction maps of spectrally complex urban land cover categories.