Computers, Environment and Urban Systems 52 (2015) 1–9

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

Remote sensing for urban planning and management: The use of window-independent context segmentation to extract urban features in Stockholm

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ARTICLE INFO

Article history:
Received 6 January 2012
Received in revised form 10 February 2015
Accepted 11 February 2015

Keywords:
Urban remote sensing
Segmentation
Spatial analysis
Urban planning and management
Feature extraction

ABSTRACT

The strategic scale of urban planning and management is concerned with the planning and monitoring of general land use in a city, such as different types of residential, industrial and commercial areas. Because of the poor results of standard per-pixel-based classification methods in urban areas, visual interpretation of remote sensing data is often preferred. This paper empirically tests the ability of a novel method, called window-independent context segmentation, to extract information that is useful at the strategic scale of urban planning and management. The method is implemented in a theoretical framework that is a response to Bibby and Shepherd's call for a new ontology in the application of geographic information systems and remote sensing to land use issues. In a case study using a SPOT5 satellite image of central Stockholm, the window-independent context segmentation method extracts urban features that correspond to the strategic scale of urban-planning and management and that differ in function and underlying planning theory and practice.

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1. Introduction

Because the majority of the world's population now lives in urban areas, there is an urgent need for tools that allow for efficient exploration of information on the composition and dynamics of urban agglomerations (United Nations, 2014). These tools are particularly important because processes in urban areas act as main drivers of global and local land change (Patino & Duque, 2013; Weng, 2012). Fortunately, the increase in the availability of remote sensing data, coupled with the continuous development of GIS software, has led to new possibilities of geographical analysis in the field of urban planning and management (UPM). Remote sensing has the potential to collect information over large areas repeatedly; thus, remote sensing is suitable for investigating and evaluating models and hypotheses and for constructing new theories to help policy-makers and professionals in the field of UPM (Patino & Duque, 2013; Rashed, Weeks, Stow, & Fugate, 2005). However, there is a gap between the progress of research communities and the practical application of the data and products by urban planners and decision-makers. Various efforts have been made to bridge this gap, such as the GEOURBAN consortium, which consists of researchers, planners and representatives from industry and showcases the possibilities for integrating remote sensing information into the UPM process (Chrysoulakis et al., 2014; Esch et al., 2013; Marconcini et al., 2013). Similarly, this paper aims to demonstrate how contextual segmentation can be used to extract information from satellite imagery for UPM professionals.

In a recent study, Sliuzas, Kuffer, and Masser (2010) argued that UPM operates on two spatial scales with different urban remote sensing requirements: local and strategic. The local scale is concerned with specific site planning and monitoring in which the recognition of objects, such as individual buildings, is important. Object-based image analysis (OBIA) is commonly used to classify buildings and other objects at the local scale. The strategic scale, however, is concerned with planning and monitoring of general land use (zoning) in cities; it involves different categories of urban land use and functions, such as different types of residential, industrial and commercial areas at an aggregated city-block scale. Because of the poor results of standard per-pixel-based classification methods in urban areas, visual interpretation of remote sensing data is often preferred at the strategic scale. In this paper, I build upon this distinction and argue that a newly developed method for contextual segmentation can be used for classifying remote sensing material that is useful at the strategic scale of UPM.

Although urban remote sensing is performed at both local and strategic scales, the scales require different data sources. Using Anderson, Hardy, Roach, and Witmer's (1976) scheme, the

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http://dx.doi.org/10.1016/j.compenvurbsys.2015.02.002
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classification of urban categories, such as residential and industrial (level II), which correspond to the strategic scale of UPM, requires a spatial resolution of ⩽20 m, while the classification of single-family units and apartments (level III), which correspond to the local scale of UPM, requires a resolution of ⩽5 m. Thus, urban remote sensing applications associated with the local scale of UPM have benefitted from the increased availability of high-resolution imagery, which has led to increased interest in spatial image analysis methods that combine spectral and spatial information for analysis and classification (Gao, 2009). An example of spatial image analysis is object-based image analysis (OBIA). OBIA has gained popularity since the early 2000s because of GIS users' growing need to extract meaningful objects from high-resolution remote sensing imagery. Hay and Castilla (2006) proposed that OBIA "…is a sub discipline of GIScience devoted to partitioning remote sensing (RS) imagery into meaningful image-objects…". The methodological origins of OBIA trace back to the 1970s, when it was nearly abandoned in favour of per-pixel-based classification (Gao, 2009 p. 421). Object-based classification is based on attributes that mimic the human interpretation of an image, including size, shape, texture and context (Bruce, 2008). In practice, these "meaningful image-objects" are built from patches of uniform tone and texture that are created by a segmentation routine. After the initial segmentation, the object can be constructed using different measurements of shape, texture, topology, heterogeneity and spatial relationships of the patches. Bhaskaran, Paramananda, and Ramnarayan (2010) used OBIA at the local scale of UPM through a combination of per-pixel-based and object-based methodologies to increase the classification accuracy of white roofs and vegetation (important factors for heat islands) in Queens and Brooklyn, New York.

At the strategic scale, the use of per-pixel-based methods for spectrally classifying remote sensing images in urban areas using medium-resolution imagery is challenging because of the high spectral variability in urban materials and because a specific spectral signature might appear in a number of different contexts in the urban landscape. Consequently, classification reliability has been lower in urban areas than in rural settings (Bhaskaran et al., 2010; Donnay, Barnsley, & Longley, 2001; Gao, 2009; Herold, Roberts, Gardner, & Dennison, 2004; Longley, 2002; Schöpfer, Lang, & Strobl, 2010).

Even when the accuracy concerns of per-pixel-based classifications in urban areas are addressed, professionals in the urban field, excluding landscape ecologists, tend to be less interested in the resulting distribution of land cover. Although the classified data that per-pixel-based methods deliver are valid, they do not address the strategic problems and issues associated with urban settings. This is particularly true in the social sciences, where information on the spatial and structural properties and different indicators of social and economic functions is more important than that in other fields. Thus, the specific contextual arrangements, rather than the individual pixel spectral characteristics, typically define urban features (Donnay et al., 2001; Longley, 2002).

Although several difficulties remain, important methodological breakthroughs have been made in the traditional fields of study for urban remote sensing applications (Gatrell & Jensen, 2008), including land use and land cover (LULC) change (Chen, Chang, Yu, & Huang, 2009; Tan, Lim, Matjafri, & Abdullah, 2010; Turan, Kadiogullari, & Gunlu, 2010; Wentz, Nelson, Rahman, Stefanov, & Roy, 2008; Yang, Ma, Du, & Yang, 2010), monitoring urbanisation (Coskun, Alganci, & Usta, 2008; Schneider, Friedl, & Potere, 2010; Thapa & Murayama, 2011) and monitoring urban heat islands (Li, Wang, Wang, Ma, & Zhang, 2009; Rajasekar & Weng, 2009).

In a recent contribution, Nielsen and Alhqvist (2014) claimed that context-based segmentation methods can be used to identify strategic-scale UPM categories from satellite imagery. Using a novel method for information extraction called window-independent context segmentation (WICS) on a SPOT4 scene from 2009 with a 10×10 spatial resolution, covering Columbus, Ohio. Nielsen and Alhqvist (2014) extracted three urban area categories that corresponded to the strategic scale of UPM: industrial/commercial and two residential categories, with mean construction years of 1955 and 1980, respectively; the overall accuracy was 73%.

WICS is reminiscent of segmentation routines because it produces image 'segments' but differs in its use of geographical distances between classes. WICS also shares the aforementioned goals of OBIA, but it does not require pre-segmentation. Instead, WICS uses the spectral information in each individual pixel as the building block for the classification.

In this paper, the WICS method is applied to a SPOT5 scene that covers central Stockholm, Sweden, with the aim of determining whether the method can identify information that is useful at the strategic scale of UPM.

2. Data and methodology

An interesting aspect of spatial image analysis and OBIA in remote sensing is the theoretical consequences, which require further study. I suggest a theoretical framework that is a response to Bibby and Shepherd's (2000) call for a new ontology in the application of GIS and remote sensing to land use issues. In their examination of the ontology of remote sensing and GIS, Bibby and Shepherd (2000) claimed that the philosopher Julius Moravcsik's (1975) fourfold view of the meaning of objects has been conflated to only the *Formal* dimension in GIS, or "…physical attributes that distinguish one kind from another" (Bibby & Shepherd, 2000 p. 584). The other three dimensions are the *Constitutive* (the composition of things), the *Telic* (the function and purpose), and the *Agentive* (the processes that produce things). These dimensions are of interest to a wide range of users of remote sensing data, particularly those within the social sciences and UPM.

Spatial image analysis in the form of OBIA can incorporate the *Constitutive* dimension into the already inherent *Formal* dimension (physical attributes that discern one thing from another, i.e., electro-magnetic reflection), and the combination reflects aspects of the *Telic* dimension, which is of interest to the strategic scale of UPM.

The main theoretical motivation behind using WICS in urban analysis is the principle that the local configuration (the *Constitutive* dimension) of materials with different spectral signatures, such as asphalt, grass or concrete (the *Formal* dimension), can be considered a visual fingerprint of function, planning and use (the *Telic* dimension). Extracting these fingerprints requires going beyond the scale of the individual building and field of grass and aggregating them into generalised concepts, such as classes of the built environment.

The WICS procedure comprises four steps (Fig. 1). Step 1 reduces the input data, for example, a multispectral satellite image, to a manageable size. This reduction could be performed through supervised or unsupervised spectral classification. Data reduction is necessary because the next step constitutes calculating distances between different pixels based on the spectral classes to which they belong.

Step 2 consists of calculating the nearest-neighbour distance to all of the spectral classes for each individual pixel in the image. These distances are then used to create a contextual feature vector in the next step. A distance threshold can be applied to limit the effect of extreme values.

Step 3 creates a contextual feature vector for each pixel in the image. A contextual feature vector consists of the geographical nearest-neighbour distance from a specific pixel to pixels of all

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