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Integrating bottom-up classification and top-down feedback for improving urban land-cover and functional-zone mapping

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ABSTRACT

As two kinds of basic units of cities, land-cover objects and functional zones play different but totally important roles in urban mapping and studies. Recent several years have witnessed significant improvement in their classification methods, e.g. geographic object based image analysis (GEOBIA). However, these methods focus mainly on bottom-up classifications from visual features to semantic categories but they ignore top-down feedbacks which are capable of optimizing classification results. To resolve the issue, this study presents an iterative method which integrates bottom-up and top-down processes for land-cover and functional-zone classifications. First, hierarchical semantic cognition (HSC) is employed to make bottom-up classification for land covers and functional zones. The HSC is essentially a hierarchical Bayesian model which links visual features, land covers, spatial object patterns, and functional zones together with a hierarchical structure. Then, a top-down feedback method, inverse hierarchical semantic cognition (IHSC), is proposed to optimize the initial classification results. Finally, the two processes are carried out iteratively to generate more and more accurate results. To verify the effectiveness of this method, we conducted it in Beijing, China. Experimental results indicate that the method produces accurate classification results of land covers and functional zones, and improves their accuracies by 9.9% and 6.5% respectively. Accordingly, our method combines bottom-up classification and top-down feedback and can significantly improve land-cover and functional-zone mapping results, thus can be regarded as a novel paradigm of urban mapping.

1. Introduction

With the majority of the world's population living in cities, urban issues have attracted extensive attention worldwide (Matsuoka and Kaplan, 2008; Pickett and Zhou, 2015; Wen et al., 2016). Land covers and functional zones are two kinds of units of urban planning and investigations, and thus their maps are important for urban studies (Alberti et al., 2004; Haack et al., 1987; Zhang and Foody, 2001). Land covers refer to physical materials at the surface of the earth, and in cities they mainly include buildings, roads, soil, vegetation, and water (Fig. 1a–e), etc. On the other hand, functional zones categorize places where people undertake different socioeconomic activities (Zhang et al., 2018). They can be spatially aggregated by diverse land-cover objects, and their categories are semantically abstracted from land-use functions (Zhang et al., 2017), e.g., commercial zones, industrial zones, residential districts, shanty towns, campuses, and parks (Fig. 1f–k).

As shown in Fig. 2, land covers and functional zones in the urban area form a hierarchical structure: each urban area can be divided into different functional zones; while functional zones are composed of diverse land covers. The hierarchical structure is very important for connecting land covers with functional zones and also for recognizing their categories (Burnett and Blaschke, 2003). For functional-zone classification, land covers' semantics and spatial patterns are basic cues to identify functional-zone categories. For example, buildings, roads, vegetation, and soil make up the zone in Fig. 1(h), and based on their proportions and spatial patterns, the zone should be labeled as a residential district. This classification process uses low-level land covers to infer high-level functional-zone categories, so it is called "bottom-up classification". On the other hand, for land-cover classification, functional zones can provide local-context information, which complements object features in classifying land covers (Johnson and Xie, 2013; Zhang and Du, 2016). For example, the blue object circled in Fig. 1(i) can be a building or a patch of water considering its color and shape, but it should be the former when considering the functional zone, i.e., a shanty town. The cognition process, which uses the high-level information to calibrate land-cover categories at the low level, is called "top-down feedback". According to human cognition, the two processes of bottom-up classification and top-down feedback are carried out

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Fig. 1. Examples of urban land covers and functional zones in satellite images.

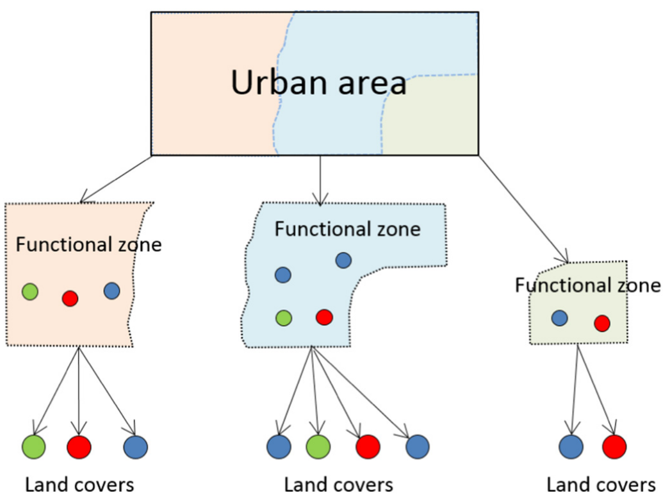

Fig. 2. Hierarchical structure between an urban area, functional zones and land covers.

alternately or even synchronously (Cohen, 2000), so that human beings can accurately recognize land covers and functional zones.

However, existing land-cover and functional-zone classifications focus mainly on bottom-up approaches, but they ignore top-down feedbacks. For land-cover classifications, many techniques have been developed during the past decades, and they mainly fall into two types: per-pixel and object-based classifications (Myint et al., 2011). In the early stage, per-pixel classifications were popular, and many classifiers were developed, such as artificial neural network (ANN; Yoshida and Omatu, 1994), decision trees (Friedl and Brodley, 1997), k-nearest neighbors (Franco-Lopez et al., 2001), support vector machine (SVM; Pal and Mather, 2005), and random forest (Pal, 2005). These methods are skilled at classifying land covers with low-resolution satellite images based on spectral features (Heydari and Mountrakis, 2018), but weak in dealing with very-high-resolution (VHR) images where land covers are heterogeneous and have substantial discontinuities in the visual cues (Farabet et al., 2013).To resolve this issue, object-based methods were proposed. They first segment images into homogeneous objects, then extract object features, and finally classify these objects based on features (Blaschke, 2010). Object-based methods achieve significant improvements for land-cover classifications with VHR images, as they can reduce heterogeneities of pixel spectrums and extract more complete land covers. Actually, both per-pixel and object-based classifications are based on bottom-up mechanism, as they use only low-level features to obtain high-level categories. However, they ignore top-down feedbacks to further improve classification results.

For functional-zone classification, it is usually implemented by scene-based classification with VHR satellite images, where functional zones are represented by image scenes (Boutell et al., 2004; Farahzadeh et al., 2015). Scene classification came from 2002 and developed rapidly in the recent ten years. In the early stage, scenes were characterized by visual features, e.g., spectral, textural, and geometrical features, and classified by traditional classifiers, such as ANN and SVM (Payne and Singh, 2005; Serrano et al., 2002; Yan et al., 2003; Zhang et al., 2015). These methods are effective to deal with simple scenes with unique visual indicators, but not to classify heterogeneous scenes with diverse kinds of objects and non-stationary visual features (Kontschieder et al., 2014; Lienou et al., 2010; Zhang and Du, 2015). To resolve this issue, topic models were presented and widely used, including probabilistic latent semantic analysis (pLSA) and latent Dirichlet allocation (LDA) (Bosch et al., 2006; Cao and Fei-Fei, 2007). They employed object features and categories to generate potential semantics for scene classification. However, these scene classification methods, not to mention of traditional classifiers or topic models, totally depend on low-level information and belong to bottom-up classifications (Serrano et al., 2004), whose results are often influenced by the inaccurate low-level information. Accordingly, top-down feedbacks should be considered to optimize land covers and further improve functional-zone classification results.

As demonstrated above, the widely used classification methods of land covers and functional zones are totally bottom-up, and ignore top-down feedback. This strategy is inconsistent with human cognition. Accordingly, we want to present a novel paradigm to integrate both bottom-up classification and top-down feedback for classifying land covers and functional zones simultaneously. To achieve this purpose, two issues should be resolved: 1) how to establish a hierarchical structure to link land covers and functional zones, and 2) how to conduct the bottom-up classification and top-down feedback with the hierarchical structure.

For the first issue, Yao et al. (2016) used random forests, a hierarchical classifier, to link land covers and functional zones together and measure their mapping relationships. However, the method ignores visual features and spatial object patterns which are basic cues for recognizing land covers and functional zones. To resolve this problem, we proposed a four-level structure, i.e., hierarchical semantic cognition