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Mining the regularity of landscape-structure heterogeneity to improve urban land-cover mapping

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ABSTRACT

The availability of remote sensing images of various resolutions has enabled the incorporation of landscape structures in land-cover mapping. Despite the effectiveness of landscape metrics in quantifying landscape structures, they are inadequate in characterizing three elements: spatial neighborhoods, spatial dependencies, and semantic dependencies. Moreover, methods for mining the regularity of landscape-structure heterogeneity (i.e., spatial variations in landscape structures) are still limited, particularly for applications in urban land-cover mapping. This study hence proposes a novel approach with the aims to (1) characterize landscape structures considering the above three elements; (2) mine the regularity of landscape-structure heterogeneity; and (3) apply landscape-structure information as contexts to improve urban land-cover mapping. To achieve the first aim, landscape-structure features including pair-wise spatial relationships and neighborhood-based landscape metrics are defined. To accomplish the second aim, a clustering technique and a landscape infographic are used to cluster landscape structures and visualize landscape-structure types, respectively. Finally, a hierarchical classifier based on the feedforward multi-layer perceptron is developed for the third aim. Experiments are conducted in a heterogeneous urban environment in Beijing, China. The results show that the proposed approach, which considers 34 landscape-structure features and 19 landscape-structure types, achieves a classification accuracy improvement of 6.43% compared with the approaches without considering landscape-structure information. This study therefore demonstrates the effectiveness of incorporating landscape-structure features and landscape-structure types in improving urban land-cover mapping.

1. Introduction

Landscape is a heterogeneous land area containing a mosaic of natural and man-made entities (Ndubisi, 2014). Landscape structure analysis studies the composition of land-cover entities and their spatial arrangements with the aim to discover meaningful regularity from landscape mosaics (Chen et al., 2008). As this regularity contains useful information of the processes from which the landscape emerges, quantifying landscape structures has been considered as fundamental in studies of ecological functioning and landscape change (Fu et al., 2011; Schröder and Seppelt, 2006).

Landscape structure analysis commonly describes landscape composition and configuration on categorical maps using metrics. A series of landscape metrics have been developed (Chen et al., 2008; McGarigal and Marks, 1995) to effectively characterize landscape structures. With the availability of remote sensing images of various resolutions, landscape metrics have been utilized in many research topics, including but not limited to, assessing land-use and land-cover change (Herold et al., 2002), examining the interplay between landscape structures and ecological functions (Du et al., 2016), and quantifying ecosystem services (Estoque and Murayama, 2013).

Despite the effectiveness of landscape metrics, the use of them has at least two limitations. First, the values of landscape metrics, especially calculated at local scales, are closely related to the sizes and shapes of spatial neighborhoods, which refer to local spatial extents of landscapes relative to the whole area. As land-cover entities exhibit spatial and semantic dependencies in landscapes, which vary greatly over spatial neighborhoods with different sizes and shapes, it is imperative to define spatial neighborhoods appropriately. To address this issue, prior studies have employed two approaches. A moving window is most commonly applied over land-cover maps (Díaz-Varela et al., 2016; Gaucherel, 2007), where the results of landscape metrics are summarized in the central pixel of the window to construct a new metric map. Another approach subdivides a map into a grid with equal-size blocks

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(Niesterowicz and Stepinski, 2016; Yang et al., 2014). Nevertheless, the two approaches take groups of contiguous pixels as neighborhoods, while overlooking the fact that ecological processes do not occur in fixed boundaries. Besides, moving windows and blocks often have regular shapes, limited in adapting to the variations of geographic environments with arbitrary shapes. Accordingly, the use of these approaches with landscape metrics is incapable of making geographic sense.

The second limitation of landscape metrics is that, although they characterize different attributes of landscape structures, such as area, edge, shape, contrast, aggregation, and diversity, none of metrics can capture spatial and semantic dependencies simultaneously (Ahlqvist and Shortridge, 2010). On the one hand, the area, edge and shape metrics only describe the geometric characteristics of individual patches. On the other hand, though the contrast and aggregation metrics measure the relationships between multiple patches, they are oversimplified in both spatial and semantic dimensions (Ahlqvist and Shortridge, 2010). That is to say, in spatial dimension, metrics such as Contagion Index (CONT) and Percentage of Like Adjacencies (PLADJ) simply express adjacent relationships in a binary fashion to determine whether pixels/patches are adjacent or not. As for semantic dimension, most aggregation metrics (e.g., PLADJ, Aggregation Index (AI)) only separate between the same and different classes (i.e., whether two adjacent pixels/patches are of identical class). Even though some contrast metrics (e.g., Contrast-Weighted Edge Density (CWED)) incorporate a weight matrix to measure the differences of class pairs, careful consideration should be given to the weights as they affect the results greatly. Nevertheless, empirical basis for establishing a weighting scheme is still lacking. The oversimplification in spatial and semantic dimensions of the traditional metrics has thus caused ambiguity in quantifying landscape structures (Zhang and Atkinson, 2016) such that some landscape metrics may have the same numerical values for completely different landscape structures. A new measure that fully considers spatial neighborhoods, spatial dependencies, and semantic dependencies of land-cover entities is therefore desirable to better quantify landscape structures (hereafter landscape-structure features, and Appendix A lists the terminologies used in this study).

In addition, vast efforts have been devoted to examining landscape heterogeneity (i.e., the variability and complexity of landscape composition and configuration in a broader context) because of its essential influences in ecosystem functioning. For instance, Ali et al. (2014) quantified the spatiotemporal aspects of landscape heterogeneity through a landscape heterogeneity mapping approach. Díaz-Varela et al. (2016) analyzed the trends of landscape heterogeneity at multiple spatial scales with a novel metric. Indeed, although landscape structures vary spatially (Partington and Cardille, 2013), some of them have similar characteristics, which can be generalized and represented into different groups. Little attention, however, has been paid to mining such spatial regularity of landscape heterogeneity (i.e., the generalized characteristics of similar landscape structures). As the diverse biophysical conditions in ecosystems lead to the spatial variations of how and to what extent the landscape structures affect ecological functions (Li et al., 2017), it is necessary to identify typical landscape-structure groups (i.e., landscape-structure types) based on such regularity. This allows the heterogeneous effects of landscape structures on the ecological functions to be explored, such as land surface temperature (LST) (Zhou and Wang, 2011), species richness (Redon et al., 2014) and soil erosion (Zhang et al., 2017). Therefore, this study operationalizes landscape heterogeneity as the spatial variations of landscape structures (hereafter landscape-structure heterogeneity). Note that, as a measure of landscape composition and configuration, landscape-structure features also own heterogeneity because the computed values vary over different sizes of spatial neighborhoods and different spatial and semantic dependencies of land-cover entities. Consequently, landscape-structure features can be further utilized to mine the regularity of landscape-structure heterogeneity through a clustering technique and a landscape infographic proposed by this study. The mining process will lead to several interpretable and visualized landscape-structure types.

The availability of very-high-resolution (VHR) images (Shen et al., 2015; Shen et al., 2016) offers opportunities for urban land-cover mapping at fine resolution, but the classification accuracy is often unsatisfactory due to the large intra-class spectral heterogeneity and small inter-class spectral variability (Johnson and Xie, 2013). Therefore, considering the dependencies between target and its neighbors in the VHR images is necessary because they can serve as contextual information to reduce the classification ambiguity. Existing context-enabled classification approaches, i.e., random field models (Moser and Serpico, 2013; Tarabalka et al., 2010) and multi-level dependency models (Hermosilla et al., 2012; Johnson and Xie, 2013) are, however, limited in measuring such dependencies. Random field models only measure the spatial dependencies between adjacent pixels/objects in a binary fashion, while multi-level dependency models generally consider the geometry, spectrum and compositions of higher levels, but ignore the configuration information.

Moreover, prior studies assumed that individual and contextual features play the same role in the classification. Indeed, two types of features should be treated differently, as opposed to equally during the classification, as the lower-level individual features are employed in the early classification stage for finding basic composition information, while the higher-level contextual features are used in the later stage for determining the final classes (Qiao et al., 2015). Nevertheless, none of existing classifiers (e.g., support vector machine and artificial neural network (ANN)) distinguish their roles in classification tasks. This study thus develops a hierarchical classifier based on a feedforward multilayer perceptron (MLP) for its capability of handling nonlinear complex relationship and incorporating different types of data into analyses (Benediktsson and Sveinsson, 1997). As a kind of ANN, MLP consists of the input, the hidden and the output layers. Conventionally, each neuron in the input layer corresponds to a specific feature and is treated with no bias in the training and predicting processes. Because object and landscape-structure features should be employed at different levels, the traditional MLP may not be directly adaptable.

To address the aforementioned issues, a novel approach is hence proposed. Specifically, this study aims to (1) characterize landscape structures considering spatial neighborhoods, spatial dependencies and semantic dependencies of land-cover entities; (2) mine the regularity of landscape-structure heterogeneity; and (3) improve urban land-cover mapping of VHR images with the incorporation of landscape-structure information (i.e., landscape-structure features and landscape-structure types). The contributions of this study are at least twofold. First, this study is the first attempt to mine the regularity of landscape-structure heterogeneity. Second, this study improves the accuracy of urban land-cover mapping by incorporating object and landscape-structure features at different levels into a novel hierarchical classifier.

2. Methodology

The proposed approach consists of four steps: (1) generating initial land-cover maps; (2) defining landscape-structure features; (3) mining the regularity of landscape-structure heterogeneity; and (4) optimizing initial maps with a hierarchical classifier (Fig. 1). A Worldview-2 image covering a typical urban area in Beijing, China is used to assess the performance of the approach. Initial classification of VHR images is first carried out to provide basic land-cover maps. Then the extracted landscape-structure information helps improve the accuracy of the initial maps. The subsequent sections provide details on each step.

2.1. Generating initial land-cover maps

This step is not restricted to a specific classification method as long as the urban land-cover maps reach an acceptable accuracy. The object-based method is used here because it proves to be more adaptable than