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Landscape metrics for three-dimensional urban building pattern recognition

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ABSTRACT

Understanding how landscape pattern determines population or ecosystem dynamics is crucial for managing our landscapes. Urban areas are becoming increasingly dominant social-ecological systems, so it is important to understand patterns of urbanization. Most studies of urban landscape pattern examine land-use maps in two dimensions because the acquisition of 3-dimensional information is difficult. We used Brista software based on Quickbird images and aerial photos to interpret the height of buildings, thus incorporating a 3-dimensional approach. We estimated the feasibility and accuracy of this approach. A total of 164,345 buildings in the Liaoning central urban agglomeration of China, which included seven cities, were measured. Twelve landscape metrics were proposed or chosen to describe the urban landscape patterns in 2- and 3-dimensional scales. The ecological and social meaning of landscape metrics were analyzed with multiple correlation analysis. The results showed that classification accuracy compared with field surveys was 87.6%, which means this method for interpreting building height was acceptable. The metrics effectively reflected the urban architecture in relation to number of buildings, area, height, 3-D shape and diversity aspects. We were able to describe the urban characteristics of each city with these metrics. The metrics also captured ecological and social meanings. The proposed landscape metrics provided a new method for urban landscape analysis in three dimensions.

1. Introduction

Understanding how landscape pattern determines population or ecosystem dynamics is crucial for managing our landscapes (Kareiva & Wennergren, 1995). Landscape metrics were proposed to describe landscape pattern and to further exploring linkages with processes (Krummel, Gardner, Sugihara, O'Neill, & Coleman, 1987; O'Neill et al., 1988). Numerous landscape metrics have been developed since the 1980s (Lausch et al., 2015; Turner, 2005). Software has been developed to streamline the calculation of landscape metrics (Mcgarigal, 1995). Landscape metrics are usually calculated using land-use/cover or landscape category maps, which are projected in 2-D from real topography. These methods for landscape pattern analysis are not designed to include topography as a pattern-shaping factor.

Ecological research provides ample evidence that topography can exert a significant influence on the processes shaping broad-scale landscape vegetation patterns. There is also an increasing body of knowledge on how topography influences the frequency, spread, extent, and distribution of natural disturbances such as fire, pathogens, and geomorphic events across the landscape (Butler & Walsh, 1994; Hadley, 1994; Knight, 1987; Romme & Knight, 1981). Some researchers have tried to analyze pattern and dynamics in landscapes with surface landscape metrics; (Dorner, Lertzman, & Fall 2002; McGarigal, Tagil, & Cushman, 2009; Wu, Wei, & Lv, 2012; Zhang, Van Coillie, De Clercq, Ou, & De Wulf, 2013), and distribution of natural disturbances across the landscape (Kellogg, McKenzie, Peterson, & Hessl, 2008; Moniem & Holland, 2013; Rogers, Cooper, McKenzie, & McCann, 2012; Zhang et al., 2013).

Landscape ecology research could help quantify the effect of topography on different aspects of landscape pattern. Unfortunately, the theoretical framework of landscape ecology to date does not provide a well-developed methodology for analyzing pattern and dynamics in landscapes with strong topography, or, more generally speaking, landscapes with a strong underlying physiographic structure. New methods are required to address research questions arising from the interplay between the physical terrain and ecosystem dynamics (Dorner et al., 2002).

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Most of the surface landscape pattern studies choose natural landscapes with strong topography (Wu et al., 2012). The urban landscape is one of the most complex and spatial heterogeneous surface landscapes. Urban buildings form a highly suitable study area on which to test landscape pattern analysis methods and to study the relationship between landscape pattern and process. However, few studies have focused on the urban architecture landscape due to the difficulty of data acquisition.

Three-dimensional data on architecture can be obtained by three methods: original building plans, field surveys and remote sensing (RS) technology. Original building plans contain detailed information, but spatial information is usually absent and difficult to collect. Height and location information can be obtained through field surveys; however, these are time-consuming. RS technology makes it possible to interpret architectural characteristics in 3-D relatively quickly. Various RS data sources have been used for extracting information on urban buildings, such as aerial images (Suveg & Vosselman, 2002), Light Detection And Ranging (LIDAR) data (Alexander, Smith-Voysey, Jarvis, & Tansey, 2009; Awrangjeb, Ravanbakhsh, & Fraser, 2010; Yu, Liu, Wu, Hu, & Zhang, 2010), high-resolution satellite imagery (Jinliang & Xiaohua, 2009; Khosravi, Momeni, & Rahnemoonfar, 2014; Mayer, 1999; Sumer & Turker, 2013), synthetic aperture radar (SAR) images (Ok, 2013; Soergel, Michaelsen, Thiele, Cadario, & Thoennessen, 2009; Tupin & Roux, 2003) and point cloud data based on Unmanned Aerial Vehicles (UAV)(Erginer & Altug, 2012; Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013; Rosnell & Honkavaara, 2012). LIDAR data, SAR images and point cloud data are the most appropriate for extracting building information. However, the data are not always available in large scale study, especially in the developing countries, because of discontinuous data-collection periods and high prices.

Several approaches for extracting building characteristics with high-resolution aerial and satellite images have been proposed, such as human–computer interaction (Gülch, 1997; Heuel & Nevatia, 1995), matching of grouping-based stereo images (Mohan & Nevatia, 1989), 3-D-interpretation of mono images using shadows (Shufelt, 1996), building extraction from digital surface models (Weidner, 1997), matching of primitives in multi-images (Henricsson, 1998), and monoplotting methods (Mikhail, Bethel, & McGlone, 2001, p. 215).

Monoplotting is a photogrammetric procedure that enables 3-D feature extraction of objects from single images where an underlying digital elevation model (DEM) representing the bare earth excluding vegetation and buildings is available (Mikhail et al., 2001, p. 215). Satellite image data from IKONOS and QuickBird can be used for mapping in monoplotting methods. The monoplotting technique has shown that a height extraction accuracy of 0.9 m can be achieved with a single ground control point using the Rational Polynomial Coefficients (RPC, a sensor orientation model) bundle adjustment from IKONOS or QuickBird images (Fraser & Yamakawa, 2004).

Our specific objectives were to: (1) test the accuracy of architecture height measurements with high-resolution satellite imagery (HRSI) and the Brista software; (2) build metrics to describe 3-D spatial patterns and check their validity; and (3) analyze the urban architecture characteristics of seven cities in the Liaoning central urban agglomeration.

2. Materials and methods

2.1. Study area

The study area (40°01′-43°29′N, 122°11′-125°46′E) is located in Liaoning Province, Northeast China, with an area of 6.5×10^4 km^2, constituting 44.5% of the total area of Liaoning Province. The study area lies in the transition zone between a branch of the Changbai Mountains and the flood plain of the Liao River in China. The eastern part of the watershed consists of low hills, while the middle and western parts are located on an alluvial plain. The seven study cities in the Liaoning central urban agglomeration were Shenyang, Anshan, Benxi, Fushun, Liaoyang, Tieling and Yinkou (Fig. 1). Shenyang is the central city, and the capital of Liaoning Province. The population of the study area was 21.7 million in 2014. With the growth of population and industry, the urban proportion of the study area has increased continuously. At same time, many area with low buildings have been replaced with high-rise architecture.

2.2. Data

QuickBird images (cell size of 0.61 m) of the seven cities were collected in 2013 (Table 1). The 3-D architectural data of the study area were extracted from the QuickBird images using the software package Brista. Brista was developed by the University of Melbourne and supports the photogrammetric processing of HRSI data and monoplotting functions. Monoplotting is a semi-automated approach for 3-D reconstruction from satellite images.

The software package Brista was developed by the Department of Geomatics at the University of Melbourne, and at the Cooperative Research Centre for Spatial Information for extracting 3-D information based on HRSI data with both RPC bundle adjustment and monoplotting functions via visual interpretation (Willneff, Poon, & Fraser, 2005). The Brista software has the characteristics of a low need for professional knowledge, simple operation, high extraction accuracy and easy data access.

After defining the bias-free sensor orientation, accurate 3-D information can be extracted from HRSI via Brista's monoplotting function. The monoplotter solves the planimetric position via least-squares estimation with the final height determined through interpolation from the DEM. To calculate the 3-D position of a point, an initial height value (e.g., the average of the maximum and minimum heights in the DEM) is required to determine a preliminary planimetric position. From this position, a new height value is interpolated from the DEM. Iterations terminate when the position is below a certain convergence limit. The detailed interpretation steps for 3-D architectural data for each building, including the building outline and height, can be found in Willneff et al. (2005). A total of 66,978, 34,686, 19,563, 26,166, 15,597, 10,379, and 19,021 buildings were measured for Shenyang, Anshan, Benxi, Fushun, Liaoyang, Tieling and Yinkou, respectively. The height for each building was extracted from Quickbird images and Brista software. The height of each story for residential buildings is 2.8 m in China. We could not distinguish building type, so the number of stories took the integer of building height divided 2.8 due to first floor of some buildings were higher than 2.8 m. The accuracy of interpretation based on very high resolution satellite imagery can be estimated with cartographic maps 1:1000 or 1:500 (Freire et al., 2014). Due to the absence of the cartographic maps in study area, the actual heights of 815 different buildings across the seven cities were measured in 2013 using a LaserCraft Contour XLRic for accuracy estimation. The overall mean height deviation was 1.02 m. The mean building height was 9.13 m. The aggregated accuracy was 88.82%, which was suitable for 3-D urban pattern recognition. The accuracies in Shenyang, Anshan, Benxi, Fushun, Liaoyang, Tieling and Yinkou were 90.03%, 88.62%, 89.34%, 88.06%, 89.33%, 88.09% and 88.76%, respectively.

2.3. Metrics

Twelve metrics were selected (Table 2), which reflected aspects of the number of buildings and number of high buildings, area