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Urban landscape pattern analysis based on 3D landscape models

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ABSTRACT

Landscape ecology, urban landscape ecology in particular, has become one of the most promising subjects in geographical research. Among studies of urban planning, land cover change, sustainable development and so forth, more and more focus has been placed on understanding the spatial composition and structure of urban landscape. Recent research has proved that landscape patterns at the vertical directions exert important influence on specific ecological processes. As a result, it is of great importance to analyse comprehensive urban landscape patterns from a 3D perspective.

This paper proposes a framework on the realization and application of 3D landscape models. Due to its high resolution in both horizontal and vertical directions, airborne Lidar (Light detection and ranging) is an ideal tool to establish 3D landscape models. The use of 3D landscape models enables researchers to design proper 3D landscape metrics and analyse 3D urban landscape patterns. A case study was conducted to compare landscape patterns between two sites from both 2D and 3D perspectives. A set of 3D landscape metrics was employed and the results proved that vertical landscape patterns, which mainly feature the spatial structures and distribution of buildings and trees, were better understood based on 3D landscape models.

Introduction

Landscape patterns play a key role in ecological processes. Since landscape patterns can be understood from a diversity of perspectives, growing research emphasis is placed on designing appropriate methods to analyse and evaluate spatial patterns of different landscape types (Gao & Li., 2011; Su, Xiao, Jiang, & Zhang, 2012, Su, Xiao, & Zhang, 2012; Xiao et al., 2013; etc.)

Landscape patterns can be analysed with words, statistics, graphics and landscape metrics, which is the most wildly used approach to quantify landscape patterns. In the past decades, designing and interpreting landscape metrics have developed into an important research topic in landscape ecology. More than 100 landscape metrics have been coined (Forman & Godron, 1986; Gardner, Milne, Turner, & O'Neill, 1987; Ludwig, Bastin, Chewings, Eager, & Liedloff, 2007; McGarigal & Marks, 1995; O'Neill et al., 1988; Ong, 2003; Parrott, Proulx1, & Thibert-Plante, 2008; Ricotta et al., 2000; Riitters et al., 1995; Romme, 1982) and applied in urban ecology, landscape planning, monitoring of landscape changes, forest dynamics, ecological network planning and so forth. These studies have showed the practicality of using quantitative analysis to evaluate landscape ecological issues and some important landscape metrics, such as Patch Number, Mean Patch Area, Patch Density, Shannon Diversity Index and so on, have been well accepted as fundamental indicators of landscape configuration. In addition, some research (Herold, Couclelis, & Clarke, 2005; Lausch & Herzog, 2002; Šímová & Gdulová, 2012; Sundell-Turner & Rodewald, 2008) has been conducted to examine the performance of a diversity of metrics under different situations. Therefore, researchers can easily analyse landscape patterns in the horizontal direction with a systematic and mature methodology, including a set of well-accepted metrics and principles of selecting appropriate metrics.

Traditional 2D landscape models can be further improved for better landscape pattern analysis. As people may overlook, lacking quantitative information in the vertical direction can result in inaccurate or non-discriminatory description of landscape patterns. For instance, land cover percentage of building areas in a town centre may equal that in a metropolitan area whilst the building structure, height in particular, can differ substantially between the two landscape types. The situation also occurs in urban forests,

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which may have similar tree cover area but different tree heights. In addition to the height of urban features, terrain information, which is an important factor in some ecological processes (Chen, Liu, Lv, Feng, & Fu, 2008), should be included in landscape pattern analysis. Therefore, Chen et al. (2008) pointed out that understanding landscape models at multiple dimensions is a challenging yet significant trend, for future landscape ecology research.

Apart from landscape pattern analysis, 3D landscape models may also add special values to research on the interactions between landscape patterns and ecological processes. The role that 2D landscape patterns play in ecological progresses has been widely examined. Recently, how vertical landscape patterns may affect ecological progresses arouses growing interests of ecologists. Massive studies have been conducted and findings from these studies proved that height information of vegetation, trees, artificial structures and other features, has a significant influence on the abundance and diversity of birds (Flaspohler et al., 2010; Hodgkison, Hero, & Warnken, 2007; Kirk & Hobson, 2001; Santos, Telleria, Diaz, & Carbonell, 2006), occurrence and abundance of specific species (Levick & Rogers, 2008; Stewart et al., 2009), total species richness (Estrada, Damon, Hernández, Pinto, & Núñez, 2006; Reeder, Debinski, & Danielson, 2005), nest success (Shochat et al., 2005), rates of CO2 exchange (Petrone, Chahil, Macrae, & English, 2008), SOC (soil organic carbon) stock (Li, Wang, Endo, Zhao, & Kakubari., 2010), vegetation dynamics (Koniak & Noy-Meir, 2009), and nutrient enrichment (Craft, Krull, & Graham, 2007). Although previous research suggested correlations between vertical landscape patterns and a diversity of ecological processes, vertical landscape patterns discussed in most studies only refer to the mean height of landscape features. Based on high-resolution 3D landscape models, which feature detailed vertical patterns and height heterogeneity of landscape features, the research on the interactions between 3D landscape patterns and ecological processes can be further explored.

With the rapid development of 3D observation technology, it is feasible to add vertical structures to 2D landscape models. For example, some local governments or companies have launched online 3D city maps. The real challenge lies in comprehensively understanding landscape patterns based on these 3D models. With a well-developed framework and methodology of 2D landscape ecology, 2D landscape patterns can be easily understood by adopting a set of 2D landscape metrics. By contrast, although some researchers (Blaschke, Tiede, & Heurich, 2004; Hou & Walz, 2013; Rogers, Cooper, McKenzie, & McCann, 2012; Zhang, Coillie, Clercq, Ou, & Wulf, 2013; etc.) employed specific 3D metrics to understand certain aspects of 3D landscape patterns, the number and diversity of 3D metrics are very limited to meet the requirements of comprehensive 3D landscape pattern analysis. In addition, since these 3D metrics were mainly intended for specific landscape types or ecological processes, many of them cannot be generalized to other study sites for pattern analysis and comparison.

To better understand 3D landscape patterns, this paper briefly introduces feasible methodologies and data sources that can be used for building 3D landscape models and then proposes a theoretical framework, based on which researchers can make use of the information from 3D models for specific research fields. A case study is included to examine the performance of 3D landscape metrics in revealing vertical landscape pattern characteristics.

Methodology

Establishing 3D landscape models

Amongst the development in relevant disciplines, airborne Lidar (Light detection and ranging) may be the most ideal tool for adding vertical information to current 2D landscape models. Airborne Lidar is an emerging technology that obtains elevation information of surface targets by calculating the time of flight taken for laser pulses travel between a LiDAR sensor and a target scene. Due to its high resolution in both the horizontal and vertical direction, airborne Lidar data can provide 3D landscape models with classified land cover types, as well as height information of each urban feature.

To date, many efficient methods (Axelsson, 2000; Bartels et al., 2010; Chen, Devereux, Gao, & Amable, 2012; Kraus & Pfeifer, 2001; Lohmann, 2002; Sohn & Dowman, 2002; Vosselman, 2000; Wack & Wimmer, 2002; etc.) have been designed to generate DTMs (Digital Terrain Models) and calculate the height of urban features. In addition to the vertical attribute, airborne Lidar data can also be used for land cover classification, another indispensable procedure for building 3D landscape models. Studies (Antonarakis, Richards, & Brasington, 2008; Brennan & Webster, 2006; Chen & Gao, 2014; Johansen, Arroyo, Armston, Phinn, & Witte, 2010. etc) have been conducted to classify land cover types using airborne Lidar data and achieved satisfactory results. In addition, Lidar data can be integrated with other data sources, such as multi-spectral images (Bork & Su, 2007; Rottensteiner, Trinder, Clode, & Kubik, 2005), hyperspectral data (Csatho, Schenk, Shin, & Seo, 2003), high resolution imagery (Chen, Su, Li, & Sun, 2009; Hill & Thomson, 2005; Ke, Quackenbush, & Im, 2010; Lee & Shan, 2003) and so forth, to further enhance classification accuracy. As a result, airborne Lidar data can support 3D landscape modelling with all necessary elements. With growing availability and decreasing cost, airborne Lidar data is an efficient and feasible tool for landscape ecologists.

If airborne Lidar data is not available due to policy or financial constraints, it is still possible to establish 3D landscape models with some alternative approaches, such as ground-based or vehicle-based Lidar, on-site survey and so forth. Compared with airborne Lidar data, these alternatives for establishing 3D landscape models can also provide researchers with reliable high-resolution 3D data sources. On one hand, these methods are highly time and resource consuming, and thus can usually cover comparatively small study areas. As a result, they are not suitable for large-scale surveying and modelling. On the other hand, due to its overhead angle, airborne Lidar systems can only obtain height information without detailed understory structure of trees and buildings. Therefore, 3D landscape models established using airborne Lidar data are not sufficient for some specific projects concerning the patterns of underpasses or understory structure of trees. In this case, the potential combination of airborne Lidar data and ground or vehicle-based Lidar data enables researchers to establish 3D landscape models with more detailed understory structures.

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With additional information of the object height (or referred to as nDSM, normalized Digital Surface Model), 3D landscape models can be employed to better distinguish pattern differences between landscapes using a set of properly selected 2D landscape metrics and well-designed 3D landscape metrics. On one hand, some generally applicable 3D landscape metrics can be applied as fundamental indicators of landscape configurations. Those metrics that analyse the fundamental patterns of buildings, trees and the entire landscape (E.g. Area Weighted Mean Building Height, Highest Patch Indices, Height Deviation Between Buildings, Ratio of Mean Building Height to Mean Tree Height, Ratio of Mean Buildings Area to Mean Building Height and so forth) have the potential to be applied to other study sites. On the other hand, researchers can also coin specific 3D landscape metrics according to different research objectives. If a research project focuses on the visual green effects in