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A multivariate analysis integrating ecological, socioeconomic and physical characteristics to investigate urban forest cover and plant diversity in Beijing, China

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ABSTRACT

Understanding the factors driving the variation in urban green space and plant communities in heterogeneous urban landscapes is crucial for maintaining biodiversity and important ecosystem services. In this study, we used a combination of field surveys, remote sensing, census data and spatial analysis to investigate the interrelationships among geographical and social-economic variables across 328 different urban structural units (USUs) and how they may influence the distributions of urban forest cover, plant diversity and abundance, within the central urban area of Beijing, China. We found that the urban green space coverage varied substantially across different types of USUs, with higher in agricultural lands ($N = 15$), parks ($N = 46$) and lowest in utility zones ($N = 36$). The amount of urban green space within USUs declines exponentially with the distance to urban center. Our study suggested that geographical, social and economic factors were closely related with each other in urban ecological systems, and have important impacts on urban forest coverage and abundance. The percentage of forest as well as high and low density urban areas were mainly responsible for variations in the data across all USUs and all land use/land cover types, and thus are important constituents and ecological indicators for understanding and modeling urban environment. Herb richness is more strongly correlated with tree and shrub density than with tree and shrub richness ($r = -0.472$, $p < 0.05$). However, other geographic and socioeconomic factors showed no significant relationships with urban plant diversity or abundance.

1. Introduction

The existence of urban plants and their associated ecological processes play an important role in the structure, function and dynamics in urban ecosystems (Pickett and Cadenasso, 2008). Urban socioeconomic system means a set of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems (Berkes et al., 2003). The urban forest, along with buildings and surfaces, is a principal element of urban structure (Ridd, 1995). Plants contribute to the spatial structure of urban systems not only through their presence in parks and reserves, but also throughout the entire urban mosaic. The urban forest, which includes individual trees along streets and in backyards as well as stands of remnant forest (Nowak et al., 2001), has become one of the most extensively researched topics in urban ecology because of its environmental, social and economic benefits (Peckham et al., 2013). Specifically, environmental benefits include urban heat island effect mitigation

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(Yuan and Bauer, 2007), carbon sequestration (Jo and McPherson, 1995; Nowak and Crane, 2002), air purification (Nowak et al., 2006), habitat provision (Young, 2010), and an increase in local biodiversity (Kong et al., 2010). Social benefits include, for example, esthetic pleasure (Smardon, 1988), improved human health (Maas et al., 2006, 2009; Qureshi and Breuste, 2010), faster recovery from illness through establishment of a tranquil and healthy environment (Kuo and Sullivan, 2001), and reduction of crimes and fear of crime (Troy et al., 2012). In terms of economic benefits, urban forest could help increase real estate values (Anderson and Cordelland, 1988), and also stimulate higher economic activity (e.g., tourism and direct provision of timber) in tree-covered areas (Baines, 2000).

Many researchers have studied urban forest and plant diversity changes as well as the driving forces behind these changes in different cities around the world. However, the driving force has not been found to be the same everywhere. For example, in many U.S. cities, plant diversity and the proportion of vegetation cover is closely related to residents' income (Iverson and Cook, 2000; Martin et al., 2004; Clarke et al., 2013), the proportion of immigrants (Troy et al., 2007; Szantoi et al., 2012), and the geographic slope (Kim and Zhou, 2012). Other studies in different regions of the world suggested that policy or governance-related factors played a leading role. For example, rapid urbanization and greening policies accounted for the process of green space change in Kunming, China in Zhou and Wang (2011). Kendal et al. (2012) found that 'top down' political factors in Ballarat, Australia were more important than individual behaviors in determining tree cover, and physical rather than socioeconomic factors were better predictors of species richness across all land uses. In Bloomington, Indiana, USA, urban land use as governed by municipal zoning policies plays a role in the abundance, distribution, and potential future location of urban trees independent of policies meant specifically to manage canopy (Mincey et al., 2013). Therefore, comparative studies in varying cultural, political and geographic contexts are required to improve our understanding of how socio-economic conditions may drive patterns of urban vegetation.

Beijing, as one of the fastest growing cities in China, harbors 618 plant species belonging to 349 genera, 103 families, and 14 different chorological spectra (Zhao et al., 2010). The area dedicated to public green space reached 15.7 m^2 per capita in 2013 (BD, 2014). Urbanization results in homogenization of the landscape, and is often the main cause for the loss of overall biodiversity and native species in modified landscapes (McDonnell, 2011; Pauleit et al., 2010). For example, 53% of the plant species in Beijing are aliens (Zhao et al., 2010; Wang et al., 2011). Urban structural unit is a good model to explore urban vegetation cover and plant diversity changes in complex urban ecosystem. Urban structural units (USUs) are work (or similar) units in urbanized areas, such as parks, areas of commerce, and areas for transportation (Wang et al., 2013). Wang et al. (2013) examined single linear relationships between forest cover and the construction period/housing price in three USUs (i.e., universities/colleges, parks and residential areas). However, the urban ecosystem is highly heterogeneous, having biotic and abiotic components, and the relationships among these components are not simple linear relationships between pairs (Pickett and Cadenasso, 2008).

Recently, some studies (e.g. Egoh et al., 2008; Naidoo and Ricketts, 2006; Nelson et al., 2009) explore the spatial patterns of provision of multiple services across landscapes, and these studies focused on spatial concordance among services as evidence of win–win opportunities for conservation of multiple ecosystem services and biodiversity. However, it is scarce to explore more types of USUs with PCA and multivariate regression in urban ecosystem, while understanding the driving factors of urban green space and plant diversity in highly heterogeneous landscapes of Beijing is crucial for deciding how to best maintain biodiversity and the provision of ecosystem services.

We focused on three questions in this study. Firstly, how does the urban green space vary by urban structural unit (USU)? Secondly, how do the geographical, social and economic factors interrelate with each and to what extent can they explain the variations of urban green space at the USU level? Thirdly, at the USU level, how do plant species richness and density vary by USUs, and what factors may influence the urban plant communities? We intended to identify key indicators that could predict patterns across all land use cover types. We also explored the driving force(s) behind forest cover and plant diversity in Beijing, which would provide important implications for better incorporating biodiversity and the provision of ecosystem services in future urban planning and design.

2. Method

2.1. Study area

Beijing is located at the northwestern border of the North China Plain. The city has an annual average temperature of 11.7 °C and annual average precipitation of 595 mm, with most of this precipitation occurring in the summer. Beijing has a nearly 3000-year history as China's political and cultural center, 800 of which Beijing has been the capital city in China following the Yuan dynasty (1271–1368, AD). The central urban area is confined within the fifth ring road (Fig. 1) and covers an area of 650 km^2 (BISM, 2005). In 2009, Beijing's population reached 21.14 million, and the permanent resident population density is of 1311 persons/km^2 (GD, 2014). Its urban greening percentage is up to 46.8% (BMBS, 2012). The economy experienced fast growth following the implementation of a market-oriented reform policy in late 1970s. For the past several decades, Beijing has also undergone a rapid urbanization, with urban areas increasing from 64 km^2 in 1978 to 16 thousand km^2 in 2009; the area within the fifth ring road as of 2009 is 650 km^2 in BMBS (2009).

2.2. Sampling design

An even grid based stratified sampling method was developed for this study. First, we obtained two scenes of cloud-free SPOT 5 (Satellite Pour l'Observation de la Terre) images with spatial resolution of 10 m and acquisition dates of 30 August and 25 October 2002, respectively. Both images were geometrically rectified by ground control points from orthorectified images and then mosaiced using ERDAS Imagine™ software. The images within the fifth ring road of Beijing were extracted and tilted into 160 2 km × 2 km grids. Then, one to four USUs within each grid were selected randomly in each grid cell. The boundary of each USU was determined on the printed photo by referring to Google Earth (accessed from June to July in 2010), Beijing City Atlas (BISM, 2005, scale 1:50,000) and in situ surveys (including interviewing local people for a given USU's boundaries). Finally, referring to the SPOT 5 images, the boundaries were drawn by on-screen digitization of the images with ArcGIS 10 (Fig. 1).

In this study, we did not adopt a completely random sampling approach mainly because we did not know a priori where the sampling sites would be. Furthermore, the urban vegetation and socioeconomic data of sampling plots could not be accessed if they fell on water-covered areas (e.g., Kunming Lake of the Summer Palace) or impermeable surfaces (such as Tian'anmen Square). Our sampling method had the likelihood to introduce some sampling bias; therefore, we increased the sampling size (number of samples) for each USU type in order to minimize the bias as much as possible.