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Assessing the drivers shaping global patterns of urban vegetation landscape structure

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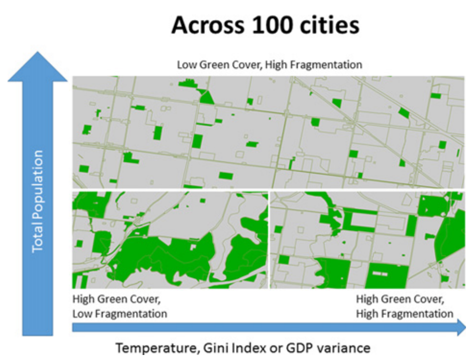
HIGHLIGHTS

- We studied urban vegetation at the landscape scale for one hundred cities and its relation to sociodemographic and climate
- The landscape metrics best describing urban vegetation structure: amount, fragmentation and distribution of green cover
- The climate and socioeconomic context relates to the degree of fragmentation and amount of urban vegetation
- Planning can improve vegetation structure by increasing, connecting and better distributing vegetation in cities

GRAPHICAL ABSTRACT



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ABSTRACT

Vegetation is one of the main resources involve in ecosystem functioning and providing ecosystem services in urban areas. Little is known on the landscape structure patterns of vegetation existing in urban areas at the global scale and the drivers of these patterns. We studied the landscape structure of one hundred cities around the globe, and their relation to demography (population), socioeconomic factors (GDP, Gini Index), climate factors (temperature and rain) and topographic characteristics (altitude, variation in altitude). The data revealed that the best descriptors of landscape structure were amount, fragmentation and spatial distribution of vegetation. Populated cities tend to have less, more fragmented, less connected vegetation with a centre of the city with low vegetation cover. Results also provided insights on the influence of socioeconomics at a global scale, as landscape structure was more fragmented in areas that are economically unequal and coming from emergent economies. This study shows the effects of the social system and climate on urban landscape patterns that gives useful insights for the distribution in the provision of ecosystem services in urban areas and therefore the maintenance of human well-being. This information can support local and global policy and planning which is committing our cities to provide accessible and inclusive green space for all urban inhabitants.

1. Introduction

Urbanization constantly reshapes the structure and extent of cities and towns. The consequences of this process includes the expansion of urban areas, urban population growth, environmental degradation, and exploitation of natural resources which are often detrimental to

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biodiversity and the provisioning of ecosystem services (McDonald, 2008; Secretariat of the Convention on Biological Diversity, 2012). Urban planning and local and international policymaking can minimise or even reverse these impacts by integrating the process of urbanization with urban greening in cities (Grimm et al., 2008a; McDonald, 2008). Implementing these goals relies on the recognition and understanding of the effects of urbanization on biodiversity and ecosystem services.

Vegetation is one of the main providers of ecosystem services in urban environments, sequestering and storing carbon, regulating climate, facilitating soil productivity, providing recreational opportunities; and, regulating flooding (Escobedo and Nowak, 2009; Dobbs et al., 2011; Pataki et al., 2011). Urbanization results in massive changes in vegetation patterns, which typically become reduced, fragmented and dispersed. Understanding existing composition and structural patterns of urban vegetation is necessary to inform planning and aid in achieving sustainable development. The quantification of global urban vegetation patterns is required to provide baseline information for assessing ecosystem services and for determining which local planning instruments are best suited to facilitate the development of sustainable cities (Grimm et al., 2008a).

The structure of vegetation, as an expression of its configuration and connectivity in the landscape, is important for understanding how urbanization is linked to the provision of ecosystem services (Mitchell et al., 2013). Yet previous studies have typically focussed on the quantity of vegetation alone (e.g. tree cover) rather than the structure of the vegetation (e.g. patchiness, connectivity). For example, Kendal et al. (2011) and Aronson et al. (2014) explored the composition of urban vegetation globally but not the spatial context in which those species were embedded. Many global studies of urbanization have explored urban form (Bigsby et al., 2014) and focused on the measurement of impermeable surfaces (Angel et al., 2005; Huang et al., 2007; Schwarz, 2010). Studies focussed on the landscape structure of vegetation are more commonly explored at the city and at the regional scale (Schneider and Woodcock, 2008; Seto and Shepherd, 2009); however, there has been little exploration of urban landscape vegetation patterns in much of the world including Australasia, Latin America or Africa (Luck et al., 2009; Inostroza et al., 2012; Banzhaf et al., 2013).

It is necessary to understand links between vegetation patterns, social systems and human behaviour (Angelstam et al., 2013); as urban vegetation patterns are the result of both biophysical and socio-cultural factors (Alberti and Marzluff, 2004; Grimm et al., 2008a; Bigsby et al., 2014; Ramage et al., 2013). Most research on the drivers of urban vegetation patterns have been restricted to biophysical factors; however, a few studies have found that income, race and education are important drivers of vegetation diversity (Kinzig et al., 2005; Escobedo et al., 2006; Boone et al., 2009; Cook et al., 2011; Kendal et al., 2012; Bigsby et al., 2014) and structure (Grove et al., 2006; Lin et al., 2017). The relationship between vegetation patterns and socio-economic variables is not unidirectional and depends on the characteristics of both the city and its inhabitants. Analogous results have been found in the urban morphology literature, where patterns of the urban form were related not only to urban economies, topography or hydrology, but also to technological advances and political change (Irwin et al., 2009). Like Irwin et al. (2009), we recognize the existence of underlying processes that drive urban dynamics and that the effects of these are not necessarily equal among cities. There is a need however for increased understanding of how the interaction among bio-socio-political factors and nature creates spatial heterogeneity (Musacchio, 2011) and how to incorporate this information into decision-making.

Here we seek to understand, at a global scale, the combination of economic, social and bioclimatic processes shaping vegetation structure that are forming and transforming cities. We determine their role using a landscape approach, which integrates social and ecological systems (Folke et al., 2005; Axelsson et al., 2011). In order to demonstrate this relationship, a selection of commonly used landscape metrics obtained from remote sensing were used to compare vegetation patterns from 100 cities located on six continents. We hypothesize that observed patterns are not necessarily the same for cities with similar demographics, economies or climate alone, but that the combination of these factors shapes the amount, size and distribution of vegetation. Understanding the range of consequences that urbanization has for vegetation is necessary to better inform urban planning. The information generated by this research will add to the knowledge on the effects of urbanization on vegetation and inform the development of appropriate urban greening targets based on the social and biophysical context of a city.

2. Materials and methods

One hundred cities around the world were selected from a pool of urban areas with >100.000 inhabitants stratified by location i.e. America, Australasia, Europe and Africa. The set of cities include a wide range of climate, economies, demographics, political backgrounds, ages, sizes, and shapes. The list of cities is supplied in Supplementary material (Table A.1). Cities were selected from a global pool where good quality satellite imagery (Landsat 5 TM) was available during the vegetation growing season between years 2006 to 2011. Remote sensing was used to extract urban vegetation; we used Landsat imagery captured within the last 5 years (USGS, http://earthexplorer.usgs.gov/) and from late spring in each hemisphere. A detailed description of the method to extract urban vegetation can be found in Dobbs et al. (2014).

To extract vegetation, the red and infrared bands were used and a combination of the normalized difference vegetation index (NDVI) and normalized built-up index (NDBI) was calculated (Zha et al., 2003). An unsupervised classification was applied to the resulting image following the methods used by Zha et al. (2003), Jensen (2005), Buyantuyev and Wu (2007) and He et al. (2010). We created a map with 3 classes: vegetation, impermeable surface, and water. An accuracy assessment of the classification was done by selecting 160 random points from high resolution imagery (Google Earth) for each city. The land cover accuracy as determined by the Kappa coefficient was 0.8, suggesting that classification is in substantial agreement with observed land cover (Coops et al., 2011). The user's accuracy was 75% and 85% for vegetation and impermeable areas respectively, while the producer's accuracy for vegetation was 80% and for impermeable areas 82%.

2.1. Landscape metrics

To evaluate the spatial patterns of vegetation and corresponding biodiversity and ecosystem services they support, the mean and standard deviation of 13 landscape metrics were calculated from the extracted vegetation land cover map, following Forman (1995), Riitters et al. (1995) and Vogt et al. (2006). The selected metrics included measures of landscape composition, connectivity and configuration (Table 1). Vegetation patch size, core area (i.e. patches big enough to provide one hectare of interior habitat: Vogt et al., 2006; Bierwagen, 2007) and connectivity affect ecosystem services such as carbon sequestration, flood regulation, climate regulation, biodiversity potential (Whitford et al., 2001; Tratalos et al., 2007), the probability of occupancy and persistence for some species (Fahrig, 2003); and, the flows of energy, material and species across the urban landscape (Zipperer et al., 2000). The distribution of urban vegetation can also influence human well-being by spatially aggregating/segregating ecosystem services within an urban landscape (Pedlowski et al., 2002). Segregation of urban vegetation can affect thermal comfort (Jenerette et al., 2016) and access to green spaces and natural areas (Romero et al., 2012).

2.2. Socio-biophysical metrics

We used commonly used socioeconomic, demographic and biophysical variables (Table 2; Kinzig et al., 2005; Escobedo et al., 2006; Seto et al., 2012; Kendal et al., 2012) to assess urban vegetation patterns. Summary statistics are given in Supplementary material (Table A.2).