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Biophysical metrics for detecting more sustainable urban forms at the global scale

Ferdouz V. Cochran *, Nathaniel A. Brunsell

Department of Geography, University of Kansas, 1475 Jayhawk Blvd, Lawrence, KS 66045-7316, United States

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Abstract

To test metrics for rapid identification and global evaluation of more sustainable urban forms, we examine the configuration of the São Paulo Metropolitan Region (SPMR) in Brazil using satellite remote sensing data and landscape metrics. We adopt principles from landscape ecology and urban planning to evaluate urban heterogeneity and morphology that may constitute more sustainable urban forms, including connectivity, density, geometric complexity (mixed land use), diversity, and greening. Using 2-D wavelet multiresolution analysis and satellite-derived fractional vegetation cover (Fr), the variability of landscape metrics from Landsat (30 m) to MODIS (1 km) scales are investigated. According to our findings, metrics of Patch Density and Landscape Shape Index can be used at the 1-km scale to asses density and geometric complexity of urban form. With the addition of MODIS land surface temperature (LST) data, available at high temporal resolution, a move away from or toward more sustainable urban forms is defined in relation to mitigation of the urban heat island. As the geometric complexity and density of finer-scale urban characteristics are related to climatic impacts at the neighborhood scale, sustainability assessments may be more attainable across urban areas.

Keywords: Sustainable urban form; Fractional vegetation cover; Landscape metrics; 2-D wavelet multiresolution analysis

1. Introduction

An urban classification system at the global scale is needed for input in climate models (Jackson et al., 2010) and for monitoring of environmental sustainability. The ability to rapidly classify urban intensity, density, or morphology on a global scale using satellite remote sensing data has eluded researchers for over a decade, though great strides have been made in classifying individual cities using high resolution imagery (Weng, 2012; Schneider et al., 2010). Methods for classification of impervious surface areas (ISA), for example, include pixel-based, sub-pixel based, object-oriented algorithms and artificial neural networks (Weng, 2012). Most of these methods were developed for a resolution of 10–100 m, and the availability of LiDAR data, in particular, is shifting research toward finer scales. Yet, broad application of high resolution urban classifications remains limited by the availability of data (such as cloud-free Landsat scenes in certain regions), computing power, and cultural or regional biases that skew classifications. While more research may be needed on the spectral, geometric and temporal aspects of urban mapping at finer scales (Weng, 2012), continued exploration of urban forms at the coarser, 1-km scale and how they relate

* Corresponding author.
E-mail address: ferdouz@gmail.com (F.V. Cochran).

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to the finer scales may aid in more generalized studies where temporal resolution is key.

The movement toward more sustainable cities requires both broad temporal and spatial analyses, and Grimmond et al. (2010, pg. 259) identify a high need in climate change assessments "at the scale of cities to ensure that the signal of climate change is distinguished from the noise of natural variability." In the context of global climate change, the idea of "fail-safe" urban forms when it comes to sustainability is antiquated (Ahern, 2011). Mori and Christodoulou (2012) identify the need for a City Sustainability Index (CSI) that considers the triple bottom line for strong sustainability, incorporates leakage effects, and assesses developing to developed cities in an equitable manner. Strong sustainability relies on the continued availability of natural capital, whereas weak sustainability allows human capital to replace natural capital (Dietz and Neumayer, 2007). Within city boundaries, one of the most obvious ways to identify natural capital is through fractional vegetation cover related to green infrastructure which provides access to pervious surface areas (Andersson, 2006; Lehmann et al., 2014) and mitigation of urban heat islands (UHI) through shading and evapotranspiration (Oke, 1988; Smith and Levermore, 2008; Stone and Rodgers, 2001).

How vegetation relates to land surface temperatures (LST) continues to be investigated in remote sensing studies (Carlson and Arthur, 2000; Gillies et al., 1997; Li et al., 2011; Weng et al., 2004; Yuan and Bauer, 2007). A triangle-shaped scattergram typically results from plotting LST versus normalized difference vegetation index (NDVI) or fractional vegetation cover (Fr), and cold and warm edges of the triangle correspond to the wettest and driest pixels, respectively. What has been termed the "triangle method" has been used for estimating soil surface wetness and evapotranspiration from satellite imagery, and Carlson and Arthur (2000) and Carlson (2007) have shown how the temporal trajectory of pixels within the triangle can be associated with land use changes and urbanization. In addition, Gallo et al. (1993) used NDVI to evaluate urban and rural differences in minimum temperatures and found that NDVI approximated temperature variances more accurately than data on urban populations in the US. They suggested the approach as a method for consistent global evaluation of the surface urban heat island. Our study combines the knowledge of the triangle method, the relationship between LST and NDVI or Fr, with landscape metrics to evaluate the temporal trajectory of urban form.

Urban form can be defined as structural elements that make up a city, including natural features and open space, and the general pattern of building intensity and height (Lynch, 1982). Characteristics of urban form and how they relate to sustainability have been debated and quantified for some time (Burton et al., 2013; Jabareen, 2006; Shirowzhan and Lim, 2013; Stefanov and Netzband, 2005; Williams et al., 2000; Zhang and Guindon, 2006). Satellite imagery is an obvious tool for assessing urban sustainability around the world (Netzband et al., 2007), and one of the first formal indices created on a global scale was the Eco-Value Night Light Environmental Sustainability Index (Sutton, 2003). In addition, the role of landscape ecology in urban planning and the use of landscape metrics for evaluating more sustainable urban forms has been explored for over a decade (Huang et al., 2007; Leitao and Ahern, 2002; Renetzeder et al., 2010; Wu, 2008, 2009; Yang et al., 2014).

Urban forms that may be considered more sustainable are characterized by "urban pattern that is compact, pedestrian oriented, less autodependent, and not disaggregated into single, functional-use zones" (Duany and Talen, 2007). Duany and Talen (2007) proposed a transect approach for urban planning based on ecological theory, where a geographic cross-section of a city might reveal a continuum of human habitats with diminishing intensities from urban to rural that can satisfy all human needs. In transect planning, the attempt to eliminate sprawl discourages "urbanizing of the rural" or "ruralizing of the urban." Transect zones are influenced by principles of traditional neighborhood development (TND) where a sustainable neighborhood pattern is one that fulfills human needs for connectivity and diversity. A sustainable neighborhood is designed for humans, not automobiles.

In biophilic urbanism, a city's inhabitants' physical and mental health, work productivity, and social capital are improved by putting "nature first in its design, planning, and management" (Beatley and Newman, 2013; Beatley, 2009). Biophilic cities can contribute to urban sustainability on many levels, and green infrastructure associated with rivers, floodplains, wetlands and forests usually increase adaptive capacity when it comes to climatic impacts. As urban planners become more aware of the importance of urban ecosystem services, ways of quantifying these services by defining urban vegetation structure types and their associated micro-climatic effects are being investigated (Lehmann et al., 2014). Urban forms that exhibit connectivity and landscape heterogeneity are said to be essential for the provision of ecosystem services and long-term sustainability (Andersson, 2006).

Various definitions of sustainable urban form exist (Burton et al., 2013), and terms of compactness, complexity, connectivity, density, diversity, and greening have been repeatedly considered (Burton et al., 2013; Duany and Talen, 2007; Jabareen, 2006; Shirowzhan and Lim, 2013; Williams et al., 2000). If we combine concepts from Duany and Talen (2007), Beatley and Newman (2013) and Jabareen (2006), over time there should be an increase in connectivity, diversity, and greening for improved urban sustainability. However, when it comes to density and compactness, Burton et al. (2013) conclude that we should look instead for various urban forms that are appropriate depending on scale and location. This recommendation is supported by the concern that policies calling for increased urban density for mitigation of greenhouse gases from vehicle miles traveled may be in conflict with other climate