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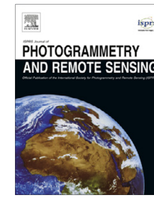

Estimating urban vegetation fraction across 25 cities in pan-Pacific using Landsat time series data

Yuhao Lu *, Nicholas C. Coops, Txomin Hermosilla

Integrated Remote Sensing Studio, Department of Forest Resources Management, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada

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ABSTRACT

Urbanization globally is consistently reshaping the natural landscape to accommodate the growing human population. Urban vegetation plays a key role in moderating environmental impacts caused by urbanization and is critically important for local economic, social and cultural development. The differing patterns of human population growth, varying urban structures and development stages, results in highly varied spatial and temporal vegetation patterns particularly in the pan-Pacific region which has some of the fastest urbanization rates globally. Yet spatially-explicit temporal information on the amount and change of urban vegetation is rarely documented particularly in less developed nations. Remote sensing offers an exceptional data source and a unique perspective to map urban vegetation and change due to its consistency and ubiquitous nature. In this research, we assess the vegetation fractions of 25 cities across 12 pan-Pacific countries using annual gap-free Landsat surface reflectance products acquired from 1984 to 2012, using sub-pixel, spectral unmixing approaches. Vegetation change trends were then analyzed using Mann-Kendall statistics and Theil-Sen slope estimators. Unmixing results successfully mapped urban vegetation for pixels located in urban parks, forested mountainous regions, as well as agricultural land (correlation coefficient ranging from 0.66 to 0.77). The greatest vegetation loss from 1984 to 2012 was found in Shanghai, Tianjin, and Dalian in China. In contrast, cities including Vancouver (Canada) and Seattle (USA) showed stable vegetation trends through time. Using temporal trend analysis, our results suggest that it is possible to reduce noise and outliers caused by phenological changes particularly in cropland using dense new Landsat time series approaches. We conclude that simple yet effective approaches of unmixing Landsat time series data for assessing spatial and temporal changes of urban vegetation at regional scales can provide critical information for urban planners and anthropogenic studies globally.

1. Introduction

Urbanization can be defined as a gradual land cover change in the form of urban sprawl and densification (Sexton et al., 2013). Urban sprawl, or urban expansion is the physical growth of a city, primarily through conversion from non-urban land cover (e.g. vegetation) to the presence of urban land cover (e.g. impervious surfaces). Urban densification most often occurs adjacent to existing urban areas where the natural land cover has already been disturbed to some extent. The interplay between urban sprawl and densification is consistently re-shaping the local geometric and ecological properties of urban environments, increasing the density of anthropogenic infrastructure while replacing local vegetation, interrupting micro climate, habitat loss, energy fluxes, and modifying the water and carbon cycles (Kahn, 2000; Groffman et al., 2014; Ziter, 2015). Previous studies have suggested that urbanization has a direct association with a series of environmental issues, such as urban heat island (UHI, Oke, 1982), habitat loss (McKinney, 2002, 2006), and water shortage (Gober, 2010; Wu and Tan, 2012; Kummu et al., 2010).

An effective way of mitigating the negative impacts brought about by urbanization is through urban vegetation (Jim, 2004; Nowak and Dwyer, 2007; Escobedo et al., 2011). Urban vegetation is a term that collectively describes urban greenspaces, including parks, wetland, grassland, and patches of urban gardens (Ridd, 1995; Kumagai, 2008; Tooke et al., 2009). The presence of urban vegetation is known to be beneficial to modifying the local climate, and thus the social, and physical environments through temperature control (Oke, 1982), air pollution reduction (Nowak et al., 1998), noise and storm water control (e.g. Glass and Singer, 1972; Alberti, 2005), and habitat preservation (e.g. Nowak and

* Corresponding author.
E-mail address: luyuhao@mail.ubc.ca (Y. Lu).

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Dwyer, 2007). Studies have also indicated the significant social (Grahn and Stigsdotter, 2003; Westphal, 2003), economic (Tyrväinen et al., 2005), and aesthetic values (Jim and Chen, 2006; Tyrväinen et al., 2005) associated with urban vegetation. As a result, urban vegetation has been utilized as an effective tool to achieve sustainable and functional urban environments. Efforts towards preserving healthy urban vegetation can therefore be found worldwide, particularly in developed regions, such as in North America and Europe (Nowak et al., 1996).

In less developed areas, despite the benefits and services offered by urban vegetation, economic growth and urbanization often receive higher prioritization than preserving and maintaining urban vegetation (Grimm et al., 2008). Vegetation in these urban environments often grows in more isolated and fragmented patches compared to vegetation grown in more novel and well-managed urban environments, making it more challenging to manage for local urban planners. Another concern associated with poorly managed and fragmented urban vegetation is ecological inequity (Heynen et al., 2006), causing uneven access for local residents to quality urban green space. With the majority of new urban residents located in less developed regions (Grimm et al., 2008), there is a strong need for data and methodological approaches that are capable of quantifying and tracking vegetation changes over space and time (Clancey, 2004).

Remote sensing is an exceptional data source to urban planners and researchers (Jensen and Cowen, 1999). Although studies using fine spatial resolution imagery (e.g. Benz et al., 2004), hyperspectral data (e.g. Roberts et al., 1998; Heiden et al., 2007), and aerial photography (e.g. Hodgson et al., 2003) have shown promising results all have limited spatial and temporal coverage limiting their global application. A recent review by Schneider (2012) highlighted the potential value of multi-temporal dense image stacks generated from moderate spatial resolution (e.g. 30 m) remote sensing platforms such as the Landsat series of satellites to urban remote sensing research. Recently, increased accessibility of the Landsat data archives (Woodcock et al., 2008; Wulder and Coops, 2014) with more sophisticated image processing procedures (e.g. Griffiths et al., 2013; White et al., 2014) and compositing techniques (e.g. Hermosilla et al., 2015) have allowed mapping of urban land cover as well as quantitatively describing urban physical features and patterns at regional scales over 30 years.

However, with a 30-m pixel size, spectral information collected by the Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) are more likely to contain a mixture of surface materials (Small, 2001). Spectrally mixed pixels are commonly seen in Landsat images where multiple surface materials jointly occupy one pixel (Keshava and Mustard, 2002). Sub-pixel analysis or spectral unmixing has been developed to determine the areal amount of pure, distinct, surface materials within a single pixel. Spectral unmixing is well established in the remote sensing literature and has applied in a large number of studies across a broad range of spatial resolutions (e.g. Van der Meer and De Jong, 2000; Asner and Heidebrecht, 2002; Vikhamar and Solberg, 2003).

While urban environments are highly heterogeneous, there are some common land cover properties consistent across all cities, such as vegetation, impervious surfaces, and soil (e.g. the V-I-S model of Ridd, 1995) and as a result systematic unmixing models can be generated. Spectral unmixing involves two critical steps, identifying pure surface materials (i.e. endmember) followed by decomposing mixed pixels (Shi and Wang, 2014). Theoretically, the selected endmembers should represent all spectral variations in the image. Based on previous work (e.g. Van der Meer and De Jong, 2000), although endmembers derived directly from the image are relatively less divergent compared to laboratory measured spectra, they have the advantage of sharing a more similar atmospheric conditions which is essential for unmixing Landsat time series.

The majority of previous research has focused on unmixing single images with less research on unmixing multi-temporal time series data. Building upon previous urban spectral unmixing research (Ridd, 1995; Small, 2001; Tooke et al., 2009), this paper aims to further contribute to this field by (i) incorporating pixel-based compositing (PBC) techniques to produce seamless annual image composites, B) examine the capacity of spectral unmixing approaches to be applied to dense annual Landsat composites from 1984 to 2012 to determine vegetation cover of 25 urban environments in the pan-Pacific region; and Bi) generate temporal and spatial information on urban vegetation features based on the distance and orientation from urban centers and boundaries. Such information is valuable for local urban planners as it offers insights into the within-urban spatial and temporal dynamics of urban vegetation change, and importantly, it has potential to assist regional cross-urban study in areas such as the pan-Pacific region, one of the most diverse and fastest growing areas in terms of urbanization (Lo and Marcotullio, 2000).

2. Material and methods

The opening of Landsat achieve has allowed the chronicling of land cover changes over a large spatial area with longer and denser temporal dimensions than previously available. This work focused on 25 urban environments located in the pan-Pacific region (Section 2.1) and utilized images from the entire Landsat archive from 1984 to 2012 to generate annual gap-free image composites for each individual urban environment (Section 2.2). The amount of vegetation in each pixel and year was determined by applying spectral unmixing analysis to each multi-temporal urban image stack (Section 2.3). The temporal trends in urban vegetation were then estimated using the Theil–Sen estimator (Theil, 1950; Sen, 1968) on the estimated vegetation fraction (Section 2.4). Image processing in this paper was done in IDL 8.3, ENVI 5.2, and ArcMap 10.2.2 and statistical analysis in R 3.1.1.

2.1. Study area

For this analysis we selected 25 major urban environments across the pan Pacific region to cover a range of population sizes and economic development status (Table 1, Fig. 1). Nine cities are located in China, and six in Southern Asia and South America, all of which are highly dynamic urban areas. The rest of the cities are located in more developed areas with four in United States, three in Canada, two in Australia, one in Japan, and one in South Korea. Urbanization in the pan-Pacific region overall is diverse and fast. Among the 25 urban environments, 8 are located in mega-city area (population over 10 million), namely, Tokyo, Shanghai, Seoul, Mexico City, Tianjin, Bangkok, Shenzhen, and Harbin.

Small cities, particularly those in developing regions are often less attractive to researchers (Bell and Jayne, 2009). Therefore, our work included cities such as Changsha that are not as economically developed as other selected mega-cities. We also selected urban environments that located across a variety of landscapes from costal mountainous region (e.g. Vancouver, Dalian) to plain and dry inland (e.g. Las Vegas, Denver). The inclusion of cities with various physical and developing status spurred interests in recent urban research community, and in part contributes to the motivation for this work.

To avoid inconsistent use of administrative boundaries and city centers, previous studies (e.g. Woodcock et al., 2008) have used concentric ring buffers (e.g. 40 km diameter) to define urban boundaries for regional urban research. We defined the edge of each city and utilized a 60 km radius to ensure we captured the