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Multi-scale analysis of relationship between imperviousness and urban tree height using airborne remote sensing

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ABSTRACT

The relationship between impervious land cover and tree development is an important component to understanding urban ecological systems. While impervious surfaces are associated with degraded soil conditions, rerouted hydrological networks and urban microclimates, the overall impact of these effects on tree development is highly variable. This study examines this relationship at two spatial scales: within the individual tree's local environment and across the broad-scale urban landscape. Using a fusion of airborne hyperspectral imagery and light detection and ranging (LiDAR) data, a 1.0 m spatial resolution classified land cover map (accuracy of 88.6%) was produced for the city of Surrey, British Columbia, Canada, from which landscape imperviousness was then derived. The stem heights of 1914 trees were estimated from the LiDAR data, to which species-specific height models were fit using planting dates recorded by city authorities. Having accounted for the age of the trees, the residuals from these models (i.e.: the difference between modelled and measured height) were then used as indicators of tree development. When aggregated to 0.5 km^2 spatial units, negative relationships (r^2 between 0.292 and 0.753) were found between height model residuals and the degree of land cover imperviousness. These relationships did not persist when examined at the individual tree level, for which imperviousness was measured within the direct vicinity of each tree using the same imperviousness map. We conclude that, using this approach, imperviousness does not appear to be a significant driver of tree height variation, with broad-scale relationships likely due to correlations with other environmental variables associated with the urban-rural gradient. Despite some limitations, the integration of hyperspectral and LiDAR data proved to be a powerful tool for mapping imperviousness, with LiDAR metrics being particularly important for distinguishing between types of urban land cover.

1. Introduction

1.1. Relationship between tree development and impervious land cover

The urban environment presents a wide range of challenges to the growth of trees. Cities possess distinct microclimates, hydrological systems and soil compositions, as well as higher levels of pollution than exurban areas (Pickett et al. 2011). From a physiographic perspective, urban environments are characterized by extensive impervious surfaces, such as roads, parking lots, rooftops and other artificial structures that prevent water infiltration. The extent of impervious land area is a commonly used indicator of urbanization and has important impacts on urban ecological systems (Arnold Jr. & Gibbons, 1996). The degree of impervious cover correlates with elevated concentrations of heavy metals, high levels of soluble salt and increased acidity in urban soil (Pouyat et al., 1995). Paved surfaces reduce soil aeration and modify the underlying vertical distribution of moisture (Morgenroth and Buchan 2009). By absorbing and transforming solar energy into sensible heat, impervious surfaces also create microclimates which can contribute to the well-documented urban heat island effect (Arnfield 2003).

Previous studies have investigated the effects of these conditions on various indicators of urban tree development. Viswanathan et al. (2011) found that high CO_2 soil levels under paved concrete inhibited root development of American sweetgum (*Liquidambar styraciflua*). Soil compacted during the construction of impervious features can constrain tree growth by preventing water infiltration and reducing the intake of major mineral nutrients (Jim 1993; Kozlowski 1999). Mueller and Day (2005) found that microclimatic differences between paved and unpaved ground cover had season-specific relationships with urban plant growth in terms of relative biomass and leaf area. High levels of upward infrared radiation from pavement can affect tree transpiration, stomatal conductance and leaf temperature (Kjelgren and Montague 1998).

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1.2. Remote sensing for broad-scale urban ecological studies

While links between impervious land cover and tree development have been established, few attempts have been made to examine this relationship at a citywide level. Since obtaining field measurements of trees is both costly and time-consuming, previous studies have focused on relatively small numbers of plots or sample trees (Kjelgren and Montague 1998; Pouyat et al. 1995; Viswanathan et al. 2011). This logistical limitation can be overcome by using remote sensing technologies, which are capable of obtaining comprehensive information on both individual tree metrics and land cover at a wide range of spatial scales. The use of airborne light detection and ranging (LiDAR) systems for estimating individual tree attributes, for instance, has been the focus of extensive research (Hudak et al. 2009). LiDAR systems emit pulses of light which are reflected off the landscape and then recorded by a sensor, providing precise three-dimensional measurements of the terrain and its features (Wehr and Lohr 1999). LiDAR data has been successfully used in forestry applications to measure tree metrics such as a stem height, crown width, diameter at breast height and stem volume (Falkowski et al. 2006; Yu et al. 2011).

Remote sensing is also a tool for mapping impervious surfaces at a range of spatial scales (Weng 2012). These range from sub-pixel analysis for medium- to coarse-scale imagery (Weng et al. 2008) to object-oriented algorithms for high spatial resolution sensors (Hu and Weng 2011; Miller et al., 2009). A common approach for high spatial resolution imagery is image classification, by which pixels are classified into discrete land cover classes from which imperviousness can be assessed (Weng 2012). While land cover classification is most often applied to multispectral imagery, certain classifiers are able to incorporate different data types from multiple sources. For instance, spectral information can be used in conjunction with airborne LiDAR data to produce accurate classifications of urban areas (Huang and Zhu 2013) and map imperviousness in urban land parcels (Hodgson et al., 2003).

While remote sensing provides the benefit of acquiring large quantities of data over wide areas, it also facilitates the analysis of patterns and processes at multiple scales. Scale is a fundamental issue in the study of a wide range of disciplines, including urban ecology, where processes may occur at multiple levels of organizational complexity (Niemelä 1999). For instance, tree health and development indicators can be considered at scales ranging from the microscopic (i.e.: mycorrhizal fungi formation, chlorophyll concentrations, etc.), to the ecosystem level (i.e.: species diversity, forest productivity, resilience to pests, etc.) (Kurth et al. 2015; Rapport et al. 1998). The selection of a single level of analysis is often arbitrary, and can create mismatching results between studies (Wiens 1989). While examining phenomena at broad scales often requires details to be simplified or aggregated, doing so without consideration for linkages between scales can lead to the loss of essential information (Levin 1992). To avoid introducing bias based on an arbitrary scale of analysis, Fotheringham (1989) and Jelinski and Wu (1996) recommended the consideration of spatial units of varying sizes. This approach enables the assessment of the sensitivity of observed statistical relationships to changes in scale and provides a basis for exploring the scale on which a given process occurs. This in turn can help identify other variables of interest and understand the functional relationships between different levels of organization. Though this multi-scale approach is often considered impractical and resource-intensive (Dark and Bram 2007), the use of high-resolution and broad-scale remotely sensed datasets can facilitate this type of analysis.

1.3. Research objectives

This study uses airborne remote sensing technologies to analyze the relationship between tree height and imperviousness in the city of Surrey, British Columbia, Canada. A tree's height at a given age, when compared to a reference of growth for that tree's species, is an indicator of the tree's vitality and can be used to evaluate the tree's reaction to various environmental conditions (Dobbertin 2005). Height estimates for 1914 city trees are derived from LiDAR measurements, while a fusion of LiDAR data and hyperspectral imagery is used to assess citywide levels of impervious land cover. By using municipal tree planting records to control for age and species, the variation in tree height explained by impervious land cover is investigated.

While previous research has revealed localized relationships between impervious surfaces and tree development, this study examines this phenomenon at multiple scales: local effects are considered at an individual tree level, while broad-scale effects are tested by aggregating individual trees to spatial units of varying sizes. The results of this study have implications on the understanding of urban environmental impacts on trees and can help city authorities integrate knowledge of landscape imperviousness into the management of their urban tree stock. The potential and limitations of using airborne LiDAR data and hyperspectral imagery to estimate landscape imperviousness are discussed, which can inform future broad-scale or multiscale urban ecology studies.

2. Data & study site

2.1. Study site

The city of Surrey is located in the Metro Vancouver regional district, in the Canadian province of British Columbia. The area's climate is typical of the Northwestern coast of North America: cool, rainy winters and mild, sunny summers with average daily temperatures ranging between 3.4 °C in December to 18.2 °C in August. The landscape is characterized by gently rolling hills attaining a maximum elevation of 134 m, dissected by wide, flat-bottomed deltaic valleys. The area's uplands are comprised of glacial deposits while its valleys consist of fluvial sediments and peat (Clague et al. 1983). Most of the lowlands within city boundaries are protected under British Columbia's Agricultural Land Reserve, which restricts most urban development to the city's less fertile hills and plateaus.

2.2. Geographical information system (GIS) database

The city of Surrey manages over 100,000 trees across its 316.4 km^2 area, with 3500 to 5000 additional trees being planted every year. All trees directly managed by the city are planted on city property. Each tree's species, subspecies, planting date and approximate geographic coordinates are recorded within a comprehensive GIS database. Tree coordinates are either registered by field crews using mobile GPS receivers, or located using orthographic photos.

2.3. Trees of interest

The five most commonly planted coniferous species in Surrey were selected (Table 1). The goal of this study was to examine the impact of imperviousness on urban tree development, as opposed to the well-documented effects of competition from neighboring trees. Therefore, only unclustered, free-growing trees were considered. Table 1 shows the number of trees per species that were retained for analysis, all of which have corresponding entries in the city's GIS database.

Table 1
Number of trees of interest per species retained for analysis.

Species name (latin)	Species name (common)	Number of free-growing trees
Thuja plicata	Western redcedar	1017
Pseudotsuga menziesii	Douglas fir	583
Sequoiadendron giganteum	Giant sequoia	161
Cupressus nootkatensis	Yellow cedar	78
Picea abies	Norway Spruce	75