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Assessing urban tree condition using airborne light detection and ranging

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ABSTRACT

With increased interest in urban forests on behalf of city dwellers and urban planners, there is a growing need for comprehensive information on urban tree condition. This study examines the potential of airborne light detection and ranging (LiDAR) for evaluating tree condition in the urban center of Surrey, Canada. An approach to detecting and outlining free-growing trees from LiDAR data augmented by a municipal tree inventory was developed and validated. Once the trees were located, LiDAR was used to estimate two field-measured indicators of tree condition: crown density and tree height. Tree heights estimated by LiDAR were, as expected, well correlated with field measurements (Pearson's $r = 0.927$, $p < 0.001$), indicating accurate height estimates of successfully detected trees. Two LiDAR metrics, the percentage of non-ground LiDAR returns and the coefficient of variation of return height, were examined as predictors of crown density. While the percentage of non-ground returns performed relatively poorly (r^2 between 0.005 and 0.23 across multiple tree height classes), the coefficient of variation of return height was able to predict crown density with an $r^2 = 0.617$ for trees over 8 m. In addition, residuals derived using expected height growth from the known planting date and their LiDAR-derived height was found to be a useful tree condition metric. We conclude that despite the complexity of urban tree condition assessment, airborne LiDAR is a promising tool for detecting trees in an urban environment and measuring indicators of their condition.

1. Introduction

1.1. The need for urban tree condition assessment

Through their numerous aesthetic, environmental and economic benefits, trees are a key component to sustainable urban development. As the scientific foundation of urban forestry matures and the popular demand for green space increases, many city governments have undertaken ambitious projects to expand their tree cover (City of Toronto, 2008; Locke et al., 2010; McPherson et al., 2011). However, trees in urban environments are exposed to a wide variety of stress-inducing agents, such as unsuitable soil conditions, rerouted water flows, mechanical damage, and pollution (Jim, 1993, 1998; Malthus and Younger, 2000). As a result, urban forests are intensively managed, with expenditures towards urban trees per acre in the United States surpassing those in forested lands outside of cities (McPherson, 1993).

With the considerable financial investment represented by urban forests, it is incumbent on city authorities to assess the health and vitality of the trees under their purview. Although hypothetical optimal tree vitality is difficult to define, the effects of environmental stressors are reflected by a range of clearly identifiable biochemical, physiological and structural symptoms (Dobbertin, 2005). The overall condition of a tree can be defined as the culmination of these symptoms (Stone et al., 2000). Citywide data on tree condition can help optimize the allocation of resources and guide effective management prescriptions, such as targeted irrigation, pruning or removal, yet city authorities rarely have access to this type of information. Exhaustive ground surveys are prohibitively expensive, while sampling-based approaches may not be appropriate due to the wide range of tree species, age classes and the spatial heterogeneity of the urban environment (McPherson, 1993).

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1.2. The use of remote sensing for assessing tree condition

By providing efficient and repeatable means of acquiring quantitative and spatially explicit data, remote sensing may have the potential to address the need for comprehensive urban tree condition information. Given their capacity to detect changes in the reflectance of tree foliage, optical remote sensors have received considerable attention for this purpose (Goodwin et al., 2005). Manifestations of tree stress, such as leaf chlorosis or necrosis, affect leaf spectral reflectance. Airborne multispectral imagery has been used to estimate chlorophyll content as an indicator of forest health (Sampson et al., 2003), detect root disease (Reich and Price, 1999), and assess tree condition in urban areas (Malthus and Younger, 2000; Nowak and McBride, 1991). Optical sensors are limited, however, when attempting to characterize a tree's vertical structure.

The dimensions and the vertical architecture of a tree are reflective of its net primary productivity and as such, are key indicators of its overall health and vigor (Schomaker et al., 2007). A large, dense crown is an indicator of optimal tree growth, while sparsely foliated crowns are a sign of deterioration and stress (Zarnoch et al., 2004). Tree height can also be used to assess a tree's condition, as healthy trees grow rapidly while stressed trees experience stunted growth (Dobbertin, 2005). Although some vertical tree metrics can be estimated through indirect relationships with combinations of spectral bands (Cohen et al., 1992), airborne light detection and ranging (LiDAR) may provide the means to measure them directly. A LiDAR instrument emits pulses of light that are reflected off trees, ground surfaces, and other terrestrial features. Of particular note is LiDAR's capacity to penetrate through gaps in the foliage, enabling it to directly measure the vertical aspects of tree crowns and forest canopies (Coops et al., 2007).

While extensive research has demonstrated the utility of LiDAR in natural resource disciplines such as forestry, ecology, wildlife management and hydrology, its uses in urban forestry remain nascent. Zhang et al. (2015) developed an automated algorithm for detecting, outlining and mensurating urban trees directly from a LiDAR point cloud. Several studies have focused on integrating LiDAR with spectral imagery to map urban tree canopy cover (MacFaden et al., 2012; O'Neil-Dunne et al., 2013). LiDAR data can be particularly useful in dense urban areas where the shadowing effect of buildings make the use of spectral imagery problematic (MacFaden et al., 2012). Other applications of LiDAR and high resolution imagery include mapping urban tree species (Zhang and Qiu, 2012), modeling solar radiation effects (Tooke et al., 2009), estimating citywide carbon storage (Schreyer et al., 2014) and detecting invasive plant species (Singh et al., 2015).

1.3. Research objectives

This paper explores the potential of airborne LiDAR as a tool for assessing urban tree condition within the city of Surrey, Canada. The objectives of this study are to:

1. Develop and evaluate an automated method for locating and outlining urban trees that is supported by ancillary GIS data collected by the city.
2. Examine LiDAR's capacity to estimate two dendrological metrics: tree height and crown density. Methods for using these metrics as indicators of urban tree condition are presented and discussed.

Our analysis focuses on free-growing western redcedar trees (*Thuja plicata*) located on city property. Western redcedar is the official tree of the Canadian province of British Columbia, and possesses unique cultural significance in the region. Furthermore, the species is of particular concern to city managers due to its preference for moist soils, and consequently its susceptibility to poor watering conditions (Stewart, 1984).

2. Data & study site

2.1. Study site

The city of Surrey is located in the Greater Vancouver regional district, in the province of British Columbia, Canada. It is one of the fastest growing cities in Canada, with an 18.6% increase in population between 2006 and 2011 (Statistics Canada, 2011). Over 90,000 trees are actively managed on city property, with 3500–5000 additional trees being planted every year. As part of its annual tree maintenance budget, the city spends roughly 600,000 USD on watering alone. The current methods employed for monitoring Surrey's trees are mainly field-based, such as performing soil moisture spot checks in the summer drought months.

2.2. GIS database

The city of Surrey maintains a comprehensive GIS database of all the trees that it plants and manages. Each entry includes a tree's species, subspecies, planting date and approximate geographic coordinates. Tree coordinates are either recorded by field crews using GPS receivers, or, for trees predating the database's creation, located through aerial photo interpretation. Due to inaccuracies inherent to mobile GPS units and the variable methods used for recording coordinates, certain entries contain positional errors, while others may be out-of-date or supply locations for trees that have been removed.

2.3. LiDAR data and derived products

Airborne LiDAR data was acquired over Surrey by Airborne Imaging (Calgary, Alberta), under contract with the city in April 2013. Trees were under leaf-off conditions. A Leica ALS70-HP discrete return LiDAR system, with up to four discrete returns per pulse, was flown at 1000 m above ground level with 688 m swaths with 50% overlap. The pulse rate was 500 KHz, which resulted in an average first-return density of 25 points per square meter.

Before being delivered by the contractor, the raw LiDAR point cloud was classified into land class covers, such as ground, building or vegetation, using TerraScan software (TerraSolid Ltd., Helsinki). A 1 m^2 rasterized digital elevation model (DEM) interpolated from classified ground points using a triangular irregular network (TIN) was also supplied.

3. Methods

3.1. Field data

A ground survey was undertaken of 169 western redcedar trees, all of which had corresponding entries in the city's database. The focus of this study was on detecting trees whose growth is affected by environmental stressors as opposed to competition with neighboring trees, and so the sample was restricted to free-growing trees. The criteria for defining a free-growing tree was that its crown not be in contact with the crown of any trees in its surroundings. Trees planted in parks, parking lots and along roadsides were included.

In March 2015, an initial four sampling sites were visited. For logistical reasons, only sites with high numbers of western redcedar were considered. Accompanying a surge in urban development, a substantial portion of the city's western redcedar were planted in the late 1990s and early 2000s, and consequently, the four initial sites contained mostly trees planted within this period. To ensure