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Comparison of airborne laser scanning and digital stereo imagery for characterizing forest canopy gaps in coastal temperate rainforests

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ABSTRACT

Forest canopy gaps play an important role in forest dynamics. Airborne laser scanning (ALS) data provide demonstrated capacity to systematically and accurately detect and map canopy gaps over large forest areas. Digital aerial photogrammetry (DAP) is emerging as an alternative, lower-cost source of three-dimensional information for characterizing forest structure and modelling forest inventory attributes. In this study we compared the relative capacities of ALS and DAP data to map canopy gaps in a complex coastal temperate rainforest on Vancouver Island, British Columbia, Canada. We applied fixed- and variable-height threshold approaches for gap detection using both ALS and DAP data, and validated outcomes using independent data derived via visual image interpretation. Overall accuracies for ALS-derived gaps were 96.50% and 89.50% for the fixed- and variable-height threshold approaches respectively, compared to 59.50% and 50.00% for the DAP-derived gaps, with DAP data having large errors of omission (> 88%). We found that 70% of ALS-derived gaps were identified in old seral stage stands (age > 250 years), while 65% of DAP-derived gaps were located in early seral stage stands (age < 40 years). For the DAP data, gap detection accuracy was 80% in early seral stands, compared to 50% in old seral stands. In contrast, ALS detection accuracy varied by only ~6% between early and old seral stages. We compared detected gaps using a variety of metrics and found significant differences in the number and average size of gaps detected using ALS and DAP data. Using the fixed-height threshold, the ALS data identified 16 times more gaps and 6.5 times more gap area than the DAP data, with a mean ALS-derived gap size that was half that of the DAP data. The average amount of overlap between ALS- and DAP-detected gaps was 13.26% and 42.90% for the variable and fixed thresholds, respectively. We attribute these differences in gap detection to the nature of the DAP data itself, which characterizes primarily the outer canopy envelope, as well as to the confounding effects of canopy complexity and related occlusions and shadows on image matching algorithms. We conclude that DAP data do not provide analogous results to ALS data for canopy gap detection and mapping in coastal temperate rainforests, and that ALS data enable markedly superior accuracy and detailed gap characterizations.

1. Introduction

Natural disturbances play an important role in forest ecosystems. Some disturbances, such as wildfire (e.g. Burton et al., 2008) or insects (e.g. Safranyik et al., 2010), can impact large areas over relatively short time frames. In contrast, the mortality of single trees or small groups of trees create openings or gaps within the continuous forest canopy that are either devoid of trees or contain trees that are markedly smaller than their immediate neighbours (Runkle, 1982). Canopy gaps play an important role in the ecological processes in natural forests and influence forest structure, particularly in mature and old stands (Spies et al., 1988). Gaps influence tree recruitment and regeneration success (Gray and Spies, 1996; Yamamoto, 2000; Muscolo et al., 2014), play a role in the maintenance of biodiversity (Gray et al., 2012), and can provide a matrix of preferred forage species for ungulates (Harestad, 1985; Massé and Côté, 2012; Tahtinen et al., 2014). In unmanaged coastal temperate forests of British Columbia, Canada, canopy gaps are the primary agent influencing forest composition and structure (Lertzman et al., 1996; Daniels and Gray, 2006). In this environment, gaps result in enhanced growth responses (Stan and Daniels, 2010, 2014). Lertzman et al. (1996) distinguished between ephemeral developmental gaps caused by tree mortality and branch fall, and more persistent gaps, which result from edaphic or topographic conditions, such as streams or rock outcroppings. By definition, canopy gaps are considered localized and discrete, and are not part of an "open-ended" system such as a wetland or a large burned area. While edaphic gaps contribute to openness of

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the forest canopy and to landscape forest structure, they are not considered significant contributors to forest dynamics (Lertzman et al., 1996).

In the study of canopy gaps, both the spatial and temporal variation in the formation of canopy gaps is of interest (Lertzman et al., 1996). However, landscape-level spatial assessments of canopy gaps are often constrained by gap detection and mapping methods, which have primarily been ground-based measurements at sample locations (Schliemann and Bockheim, 2011). Given the level of effort and expense required to obtain ground-based measurements, the areas covered by these surveys are often small and not spatially contiguous. An improved understanding of the temporal variation in gap formation processes has also been limited by the lack of time series data to enable such investigations (Lertzman et al., 1996), and by the difficulties associated with repeat measurements. Conventional gap surveys often involve some form of transect sampling, as the accurate delineation of gap perimeters (determined by vertically projecting the outline of peripheral trees) is challenging (St-Onge et al., 2014), and research has demonstrated significant differences in gap size estimates using different field-based measurement methods (de Lima, 2005). Runkle (1992) identified the potential of aerial photography for mapping canopy gaps, and subsequent work by Fox et al. (2000) compared the accuracy of canopy gap maps generated from ground surveys to those generated from manual interpretation of high resolution (1:15,000) air photos. The authors found that maps generated from air photo interpretation were more accurate, with the latter having an omission rate of only 4.7% compared to 25.6% for the ground survey; however, although the air photos enabled a more synoptic detection and mapping of canopy gaps, they could not provide the same detailed information on the characteristics of the vegetation within the gaps, as would be provided by a ground survey (Fox et al., 2000).

In a review of contemporary literature for actual and potential methods for detecting canopy gaps, Runkle (1992) was prescient in identifying the capacity of future technologies (Runkle, 1992, p. 5):

> "Measurement of actual canopy heights on a regular grid system throughout a stand is another technique for gap surveys. Such a mapped grid provides a more accurate view of variation in canopy structure than a simple gap–non-gap dichotomy. It also clearly locates large gaps and gives a reasonable estimate of the fraction of land area in gaps as the proportion of grid points in gaps."

The capability to which Runkle (1992) was referring is now afforded by airborne laser scanning data (ALS; also referred to as airborne LiDAR), an active remote sensing technology that measures the 3-dimensional distribution of vegetation within forest canopies (Lefsky et al., 1999). ALS data also enable the detailed characterization of terrain under forest canopy with sub-metre accuracy (Reutebuch et al., 2003; Næsset, 2015) and likewise the accurate estimation of plot and stand canopy heights over large areas (Andersen et al., 2006). Indeed, ALS measures of canopy height are becoming the benchmark against which other measures are evaluated (White et al., 2016).

More recently, the capacity to derive detailed canopy surface characterization through an image matching photogrammetric workflow has emerged as a less costly alternative to ALS data (Baltsavias, 1999; Leberl et al., 2010). Commonly referred to as digital aerial photogrammetry or DAP, image-based point clouds are generated using image-matching algorithms that operate in stereo or multi-image matching modes, depending on the image acquisition parameters and degree of image overlap. The emergence of image-based point clouds have been enabled by advances in digital camera systems (increased overlap and improved radiometry) and computational power (Leberl et al., 2010) and numerous image matching approaches and algorithms have been developed (Gruen, 2012, Remondino et al., 2014). However, to date there has been limited benchmarking of acquisition parameters (Bohlin et al., 2012; Nurminen et al., 2013; Puliti et al., 2016) and image matching algorithms (Kukkonen et al., 2017; Granholm et al., 2017; Ullah et al., 2017) in forest environments. Moreover, very few image matching algorithms are designed specifically to operate on forest canopies (Baltsavias et al., 2008), which are particularly challenging targets for image matching algorithms because of shadows (Baltsavias, 1999), which increase with decreasing solar elevations (Honkavaara et al., 2012).

An accurate canopy height model (CHM) can be generated from an image-based point cloud when used in concert with a detailed ALS-derived digital terrain model (DTM) (St-Onge et al., 2008; Bohlin et al., 2012). In a review of the utility of image-based point clouds for forest inventory applications in 2013, White et al. (2013) noted that at the time of their review, there were very few studies that compared the performance of DAP and ALS data (i.e. Bohlin et al., 2012; Järnstedt et al., 2012). Subsequently, several studies have been published that have directly compared the performance of ALS and DAP for the estimation of a basic suite of forest inventory attributes such as height, basal area, and volume across a range of forest environments (e.g. Vastaranta et al., 2013; Pitt et al., 2014; Gobakken et al., 2014; White et al., 2015; Puliti et al., 2016; Bohlin et al., 2017; Rahlf et al., 2017; Hawryło et al., 2017). Using an area-based approach (Næsset, 2002), these studies have demonstrated that ALS and DAP provide comparable outcomes for inventory attributes across a range of forest environments—primarily because both technologies are capable of accurately characterizing canopy heights, which strongly influence the subsequent estimation of attributes such as volume (St-Onge et al., 2008).

The potential utility of airborne laser scanning data for detecting canopy gaps was first identified using airborne laser profiling systems in the mid-1980s (Nelson et al., 1984; Aldred and Bonner, 1985). Since that time, research across a range of boreal, temperate, and tropical forest environments has demonstrated the capabilities of ALS data for detecting and mapping canopy gaps (Table 1). These studies have used ALS data to characterize canopy gaps over very large areas (> 100,000 ha), enabling insights into landscape-level variations in gap size and frequency (Asner et al., 2013), a key information need identified in the ecological literature (e.g., Lertzman et al., 1996). Moreover, time series of ALS data have been used to quantify changes in the size and shape of canopy gaps over time (Vepakomma et al., 2008, 2011, 2012). The majority of studies have used the ALS-derived canopy height model (CHM) with a fixed-height threshold for gap detection. Most studies have not reported gap detection accuracy (Table 1); however, those that have evaluated the accuracy of gap detection report overall accuracies ranging from 82% to 97%. Gaulton and Malthus (2010) compared the use of a relative height threshold on both an ALS-derived CHM and point cloud, finding that gap detection using the point cloud directly provided a slight increase in gap detection accuracy of 3.7%; however, the authors also identified that the use of the point cloud was "considerably more computationally demanding" and given the relatively modest gain in detection accuracy, may not be justified over large areas. We are aware of only one study that has examined the use of DAP data for mapping canopy gaps (Zielewska-Büettner et al., 2016, 2017). In this study, the authors used stereoscopic aerial imagery from 2009 and 2012, and evaluated gap detection results using independent, visual interpretation of the imagery; however, the authors did not directly compare the gaps detected with the DAP data to those detected with the ALS data.

Recent research in less complex forest environments has indicated that DAP may be less effective than ALS data for mapping small canopy openings (Vastaranta et al., 2013); however, the capacity of DAP for this purpose has yet to be fully studied and quantified, and a detailed comparison of the gaps generated from ALS and DAP has yet to be undertaken. There are fundamental differences in the way these two data sources characterize the canopy, with ALS pulses penetrating small openings in the canopy, and thereby capturing the vertical distribution of vegetation, whereas DAP data primarily characterizes only the outer canopy envelope, with image matching algorithms interpolating across