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Digital aerial photogrammetry for assessing cumulative spruce budworm defoliation and enhancing forest inventories at a landscape-level

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ABSTRACT

Spruce budworm (*Choristoneura fumiferana* [Clem.], Lepidoptera: Tortricidae) is a native defoliating insect with an important disturbance role in the eastern boreal forests of North America. With an extensive history of outbreaks and associated impacts on forest structural changes and timber supply, the mapping of spruce budworm defoliation has been of major management importance. In this study we assessed the ability of high spatial resolution digital aerial photogrammetric (DAP) data to predict cumulative defoliation as well as basal area and merchantable volume in spruce budworm host stands in the Gordon Cosens Forest south of Kapuskasing, Ontario, Canada. To do so, DAP derived structural and spectral metrics were incorporated to implement a stratified sampling design to improve the efficiency and cost-effectiveness of field surveying. Standard forest inventory measurements including diameter and height, as well as ocular and branch level defoliation assessments were undertaken on thirty 400 m^2 radius plots. A partial least squares analysis was performed to determine whether structural metrics from a DAP point cloud could be influenced by spruce budworm defoliation, as well as determine the relative effectiveness of spectral (e.g. mean NDVI) vs. structural (e.g. 90th percentile of height) metrics, or their combination, for predicting cumulative defoliation. Results indicated that spectral metrics were the most effective for predicting cumulative defoliation ($R^2 = 0.79$), while structural metrics were the least effective ($R^2 = 0.49$). Metrics characterizing variance of the spectral values were found to be the most important predictors. Structural metrics and linear regression were also used to estimate landscape-level volume and basal area per hectare yielding $R^2 = 0.80$ and $R^2 = 0.90$, respectively. Outcomes of this analysis indicate that DAP-derived spectral metrics were more capable of modeling cumulative defoliation, while structural metrics were effective for landscape-level estimations of standard forest inventory attributes. This analysis indicated that the provision of both spectral and structural metrics from a single aerial imagery survey has potential to enhance defoliation monitoring and forest attribute modeling at a landscape-level.

1. Introduction

Forest health monitoring is integral to evaluating ecosystem biodiversity and the sustainability of forest management practices (Franklin, 1993). Monitoring activities that compile information related to current and future status, changes, and trends associated with forest health are ecologically, economically, and socially important (Noss, 1999; Lausch et al., 2017). From a Canadian boreal forest context, changes in phenology, distribution, and reproduction of forest insects such as eastern spruce budworm (*Choristoneura fumiferana* [Clem.], Lepidoptera: Tortricidae) could have major ecological, economic, and social implications (Candau and Fleming, 2005). Spruce budworm disturbances are estimated to account for 41–53% of Canada's volumetric timber losses resulting from biological disturbances (Sterner and Davidson, 1982; Power, 1991), and an average of 1.8 million hectares of forest in Ontario have been subject to moderate to severe levels of annual defoliation since 1990 (NFD, 2017). While defoliation events are natural in boreal disturbance regimes, improved understanding of their timing and trends, distribution, and severity will help long-term management under increasingly variable ecological and economic pressures.

Historical spruce budworm defoliation events ranging in size, intensity, and duration have occurred roughly every 30–40 years with an approximate 10–15 year duration (Royama, 1984; Régnière and Nealis, 2007). Outbreaks of higher intensities lead to losses in previous year's

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foliage due to rapid consumption of the most recent year's growth. Following defoliation, beginning in late June to early July, a characteristic red colour becomes evident across affected forest stands. This discolouration results from dead, hanging foliage that has been caught in silk trails left behind during budworm movement, as well as from feeding tunnel formations. Factors such as outbreak intensity, temporal sequence, host species distribution (Candau et al., 1998), stand characteristics, as well as climate variables such as temperature and precipitation (Blais, 1961; Hardy, Lafond and Hamel, 1983; Gray, 2008) all have potential to influence defoliation severity (MacLean, 1984). Although singular instances of defoliation do not generally kill individual trees unless severity is extreme, repeated annual defoliation has been found to increase mortality risk due to reductions in photosynthetic capacity (Candau and Fleming, 2005). Stands affected by defoliation present forest management challenges associated with altered disturbance dynamics (James et al., 2017), reductions in stand vigour associated with height and diameter increment reductions (Blais, 1958; Miller, 1977; Baskerville and MacLean, 1979), loss of accrued volume (Power, 1991), as well as forest structural and compositional changes (MacLean et al., 2001). Research into accurate and cost-effective methods for enhancing landscape-level forest inventories would help to improve knowledge on the relationship between spruce budworm defoliation and forest structure at a landscape-level, while facilitating long-term monitoring frameworks.

Given the prevalence of spruce budworm induced defoliation and its associated influence on forest health issues, initiatives such as sketch mapping of red stage (current) defoliation have been conducted by a combination of the Canadian Forest Service (CFS) and provincial governments bodies such as the Ontario MNRF Northeast Biodiversity and Monitoring Section since 1941 as a simple, fast, and inexpensive method for helping to inform protection programs and delineate potential harvesting strategies (Leckie and Ostaff, 1988; Candau and Fleming, 2005). These surveys consist of the manual delineation and differentiation of current defoliation into three classes (light (0–25%), moderate (26–75%), and severe (76–100%)), providing data that detail spatial extent and estimated hazard level. While these surveys provide useful approximations of the distribution and size of budworm populations related to current defoliation mapping (MacLean and MacKinnon, 1996), records of light defoliation are often ignored due to unreliability (Sippell, 1983), and surveys are unable to provide insight into the level of cumulative defoliation present within stands. The assessment of cumulative defoliation through time is important for improving knowledge of spruce budworm induced mortality risk as it details foliage losses in multiple age classes rather than just current defoliation manifested by the red stage (Leckie and Ostaff, 1988). Methods aimed at improving available cumulative defoliation data products at a landscape-level would therefore help in guiding operational management and stewardship strategies and provide evidence for formulating effective forest health related policy.

While dendroecology and long-term ecological monitoring into the physiological and biological patterns of spruce budworm outbreaks has been extensively researched for over 60 years (MacLean et al. 2001), there is still a need for spatially explicit information on patterns and interactions at the landscape-level (Senf et al., 2017). As a result, forest managers require accurate, spatially explicit, and detailed information on the extent and severity of disturbances to inform options for operational management. Remote sensing technologies have been used to facilitate fine spatial, spectral, and temporal scale analyses into forest insect disturbances (Trumbore et al., 2015; Senf, Seidl and Hostert, 2017). Numerous studies investigating the assessment of current spruce budworm defoliation have been conducted using aerial photography (Murtha, 1973; Ashley et al., 1976; Leckie and Ostaff, 1988), and Landsat multispectral scanner data (Harris et al., 1978; Madding and Hogan, 1978). Results from these studies found that timing of acquisition, spectral resolution, and imagery scale were important factors for accurately mapping current defoliation with aerial imagery. More recent studies utilizing Landsat TM (Luther et al., 1997) and SPOT derived spectral indices (Franklin et al., 2008) found significant relationships for detecting spruce budworm defoliation. Multiple studies using satellite and aerial imagery with a focus on defoliation caused by western spruce budworm (*Choristoneura occidentalis*, Freeman) have successfully demonstrated the ability to detect defoliation (Franklin et al., 1995; Vogelmannet al., 2009). A growing body of literature focused on the detection of insect induced defoliation from varying optical remote sensing sources and at varying spatial, spectral, and temporal resolutions is promising for incorporation into operational management (Senf et al., 2017).

Potential tools that offer finer scale information beyond conventional aerial and satellite imagery to improve knowledge of cumulative defoliation are three dimensional remote sensing technologies such as digital aerial photogrammetry (DAP) and airborne laser scanning (ALS). These technologies have been proven to provide accurate estimates of forest inventory data such as timber volume and basal area at individual tree and area-based levels (White et al., 2013a,b; Gobakken et al., 2015; Tompalski et al., 2018). While analyses using DAP for forest health purposes have been limited to the detection of individual trees for subsequent classification during bark beetle outbreaks (Näsi et al., 2015), ALS has shown potential for the accurate estimation and mapping of pine defoliation in Scandinavian boreal forest environments (Vastaranta et al., 2013). Findings from their research indicated that plot-level defoliation sampling facilitated integration into operational level forest management and planning and offer additional value to ALS acquisitions. Given the similarities between ALS and DAP derived datasets, the successes of ALS for improving structural knowledge of defoliation, and recent advancements in photogrammetric processing streams, opportunities now exist to examine the utility of DAP for quantifying cumulative defoliation in a spruce budworm context. The application of DAP techniques to aerial imagery acquisitions could provide both spectral and structural metrics that, when combined or used independently, may improve knowledge of the spatial distribution and severity of cumulative defoliation. The provision of these metrics may also serve to improve upon landscape-level estimates of standard forest inventory attributes such as basal area and volume (White et al., 2015), which have been used for the delineation of spruce budworm host species distribution (Wolter et al., 2008). Enhanced inventory products such as wall-to-wall DAP derived attributes also have potential to provide managers with accurate, up-to-date, and multi-use data that facilitate informed forest management decision making (Goodbody et al., 2017a,b). The acquisition of aerial imagery for the purposes of DAP generation therefore present an opportunity to improve upon landscape-level cumulative defoliation, susceptibility, impact damage, as well as forest attribute estimates through time from a single multi-use data set.

In this analysis, aerial imagery acquired over the Gordon Cosens Forest south of Kapuskasing Ontario, Canada, were used to produce DAP point clouds and multi-band visible and near infrared vegetation metrics for the purposes of improving spatial, spectral, and structural knowledge of spruce budworm cumulative defoliation. The main objective was to determine whether spruce budworm defoliation was detectable using DAP point clouds, and in doing so, assess the relative predictive power of structural vs. spectral metrics to model cumulative defoliation at a landscape-level. Additionally we assessed the effectiveness of DAP structural metrics for modelling field measured merchantable timber volume and basal area using the area-based-approach (ABA). The accurate estimation of these inventory attributes could be useful for assessing potential economic impacts of defoliation through time, as well as monitoring changes and trends in forest structure and health (Lausch et al., 2017). Results from this study could help to examine patterns in prevalent ecosystem processes, improve understanding of predominant disturbance regimes, provide a means of evaluating the sustainability of targeted forest ecosystems, and consequently, evaluate the socio-political and economic implications of forest health related changes (Dale et al., 2001).