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Mapping dead wood distribution in a temperate hardwood forest using high resolution airborne imagery

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ABSTRACT

Dead wood, in the form of coarse woody debris and standing dead wood, or snags, is an essential structural component of forest ecosystems. It plays a key role in nutrient cycling, ecosystem functions and provision of habitat for a wide variety of species. In order to manage dead wood in a temperate hardwood forest, an understanding of its availability and spatial distribution is important. This research evaluates airborne digital camera remote sensing for mapping temperate forest dead wood across an area within Gatineau Park, Canada. Two approaches were evaluated: (1) direct detection and mapping of canopy dead wood (dead branches and tall snags) through the combination of three techniques in a hybrid classification: ISODATA clustering, object-based classification, and spectral unmixing, and (2) indirect modelling of coarse woody debris and snags using spectral and spatial predictor variables extracted from the imagery. Indirect modelling did not provide useful results while direct detection was successful with field validation showing 94% accuracy for detected canopy level dead wood objects (i.e. 94% of validation sites with canopy dead wood were detected correctly) and 90% accuracy for control sites (i.e. 90% of validation sites with no canopy level dead wood were identified correctly). The procedures presented in this paper are repeatable and could be used to monitor dead wood over time, potentially contributing to applications in forest carbon budget estimation, biodiversity management, and forest inventory.

1. Introduction and background

The importance of dead wood in a forest is well understood as it plays an essential role in the health and functioning of the ecosystem at a variety of scales. Forest dead wood can be in the form of standing dead trees, commonly referred to as snags, as well as fallen material on the forest floor, referred to as woody debris, which is a direct result of dead or dying trees. Researchers and forest managers understand the benefits of dead wood in a forest in terms of its importance for nutrient cycling, long term carbon storage, as well as providing critical habitat for the maintenance of biodiversity (e.g. Stevens, 1997; McComb and Lindenmayer, 1999; Arsenault, 2002; Bull, 2002; Harmon, 2002; Tews et al., 2004; Tobin et al., 2007; Depro et al., 2008). Measures of dead wood are often incorporated in studies and protocols that monitor the health and biodiversity of forests, including national forest inventories (e.g. Canada's National Forest Inventory (CFIC, 2004)). As a result of the importance to forest ecosystems, dead wood has the potential to be used as an indicator of habitat or biodiversity on its own, as well as contributing to more comprehensive measures of overall structural complexity (e.g. McElhinny et al., 2006; Pasher and King, submitted for publication).

Snags can be inventoried through sampling (e.g. Bate et al., 1999; Kenning et al., 2005) and woody debris can be sampled using various methods (e.g. Van Wagner, 1964; Valentine et al., 2001; Stahl et al., 2002; Jordan et al., 2004). The non-uniform distribution of these structures in the forest (Ducey et al., 2002; Kenning et al., 2005) requires complex and intensive sampling strategies to properly survey an entire forest. Field methods are limited to point, line, or plot based sampling and, as a result, cannot provide spatially continuous information. Modern harvesting and forest management regulations often require a certain density or volume of dead wood to remain (following timber removal) in order to provide habitat and support ecosystem sustainability (e.g. Franklin et al., 1997; Holloway et al., 2007). Additionally, forest conservation in areas not managed for timber production is often concerned with identification of areas of high biodiversity potential. A continuous map showing the locations and spatial distribution of dead wood across a forest could support such management and conservation goals as well as be useful in habitat modelling and mapping for individual species.

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1.1. Research objectives

Based on the potential utility of spatially continuous information related to the distribution of dead wood across a forest, the goal of this research was to determine the potential of high resolution multispectral remote sensing for mapping dead wood across a temperate hardwood forest. The specific objectives were to: (1) evaluate *direct* detection using a hybrid classification process incorporating pixel, sub-pixel, and object-based information, (2) map the spatial distribution of dead wood across the forest, and (3) evaluate *indirect* regression-based modelling of downed and standing dead wood using spectral, spatial, and object-based image information.

1.2. Direct detection and mapping of dead wood

The direct detection and mapping of snags has shown potential in coniferous forests, as well as in deciduous forests specifically for the detection of dying oaks caused by sudden oak death. Butler and Schlaepfer, 2004 created snag distribution maps from 1:10 000 color infrared (CIR) air photos for spruce dominated forests within the sub-alpine zone in Switzerland. While the results were excellent, the research was carried out in sparse forests with isolated snags, and more importantly, it relied on manual photo interpretation and digitizing of dead trees, which is extremely time consuming. Others have used automated methods, including Haara and Nevalainen (2002) who developed a method to segment individual trees in 1:5000 CIR air photos of spruce dominated forests in southern Finland. For three forest stands, the average detection accuracy was 67% for dead and dying trees (61–100% needle loss). Leckie et al. (2004) used 60 cm resolution airborne multispectral imagery to detect and assess trees suffering from laminated root rot in Douglas fir forests in coastal British Columbia, Canada. They were able to successfully detect snags with fully intact crowns as well as those with missing branches using classification and automated tree crown delineation methods (Gougeon, 1995).

Several researchers have had success in mapping dead trees caused by sudden oak death in Californian hardwood forests. Kelly et al. (2004) evaluated three classification methods (unsupervised, supervised, and hybrid) applied to 1 m airborne multispectral imagery and achieved a best average accuracy of 96.3% using the hybrid classifier. Guo et al. (2007) developed a hybrid classification method combining object-based and knowledge-based classifications. It first segmented 1 m multispectral imagery into homogeneous objects and then used a set of rules to decide if each object was a dead crown (e.g. maximum size associated with known maximum crown size, compact shape, and adjacency to vegetation). Their results showed an accuracy of 96.1%, compared to supervised classification with an accuracy of 86.8%. Finally, Meentemeyer et al. (2008) were able to detect dead oak trees in 76% of sample field plots in the Big Sur ecoregion using an object-based classification and airborne color 33 cm pixel imagery.

1.3. Indirect modelling of dead wood

A variety of individual forest structural attributes such as stem density, diameter at breast height (DBH), basal area, crown diameter, canopy closure, leaf area index (LAI), etc. have been modelled using high resolution optical remote sensing spectral and spatial information (e.g. Wulder et al., 1998; Lévesque and King, 2003; Seed and King, 2003; Cosmopoulos and King, 2004), as well as other sensors, including airborne synthetic aperture radar (SAR) (Nelson et al., 2007) and laser/lidar data (Bater et al., 2007; Pesonen et al., 2008).

Remote sensing can potentially offer cost effective, rapid, and repeatable methods for inventorying dead wood across a forest. While woody debris for the most part would not be directly visible by airborne or satellite sensors, indirect modelling of coarse woody debris (CWD) can be conducted using image variables related to different aspects of forest structure that are manifested as image brightness variations. This is possible as a result of relationships that exist between dead wood and the surrounding forest structure, in particular the association of dead and dying trees with canopy gaps (Bursing, 2005; Kneeshaw and Prevost, 2007) or the presence of sparse tree crowns, which are visible in high resolution imagery.

In research carried out in Gatineau Park, Québec, Canada (the forest of this study) following a major ice storm in 1998, King et al. (2005) developed a model indirectly predicting the number of downed branches in fifteen field plots using spectral and spatial variables extracted from 25 cm resolution color infrared (CIR) photography (adjusted R^2 = 0.71, $p < 0.001$, standard error = 28.4% of observed mean (29.5 branches) in 20 m × 20 m plots. In a mixed boreal forest in Northern Ontario, Canada, Olthof and King (2000) developed a forest structure index (FSI) using canonical correlation analysis of linear relations between multiple image parameters and field-measured forest structural parameters. The index, which incorporated spectral, textural, and radiometric fraction image information extracted from 50 cm multispectral imagery, was used to explain the variance in a set of field variables that included measurements of fallen dead wood. Cosmopoulos and King (2004) refined the index methodology and applied it in temporal analysis of forest structural change. Working in old growth coniferous forests in Clayoquot Sound, British Columbia, Canada, more recently, Pesonen et al. (2008) used an airborne laser scanner (ALS) to model woody debris volume in thirty-three field plots in Finland (adjusted R^2 = 0.61, $p < 0.001$) based on two predictor variables representing the intensity of the last laser pulse and height variation extracted from the first pulse (i.e. top of canopy). While the model showed a strong R^2, it had an RMSE of 51.6% (14.09 m^3/ha).

Similarly, little research exists using remote sensing to indirectly model snags in the forest. Standing dead wood was also included as a structural variable in the forest structure index research of Olthof and King (2000) as described above. Bater et al. (2007) used a set of lidar variables in order to predict the percentage of dead trees within field plots. In order to overcome extremely skewed distributions, caused by the plots containing mostly live trees, they fit lognormal probability density functions to the frequency distributions of all the trees in the plots (including living and dead trees nine decay classes), and found the mean of the resultant distribution to be highly correlated with the percentage of dead trees (r = 0.88, $p < 0.001$). Their results showed good predictability of this parameter using different lidar variables, with R^2 ranging from 0.42 to 0.75. Pesonen et al. (2008) also modelled standing dead wood (snag) volume (adjusted R^2 = 0.48; RMSE = 78.8% (14.74 m^3/ha)) using the same ALS data mentioned above, leading to the conclusion that air photos were probably more suitable than laser scanning for indirect detection of standing dead trees.

2. Methods

2.1. Study area

This research was carried out in Gatineau Park, which extends from about 20 to 50 km Northwest of the city of Ottawa, Canada. More than 80% of the park's approximately 36 000 ha is forested, with approximately 55% dominated by hardwoods. The forest is dominated by sugar maple (*Acer saccharum* Marsh.), with small patches dominated by American beech (*Fagus grandifolia* Ehrh.), trembling aspen (*Populus tremuloides* Michx.), and red oak (*Quercus rubra* L.). Small numbers of red maple (*Acer rubrum* L.), American