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Ecological legacies of fire detected using plot-level measurements and LiDAR in an old growth coastal temperate rainforest

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ABSTRACT

Vegetation succession following fire disturbances has long been of interest in ecology, but the evolution of landscape pattern and structure following low-severity ground fires is poorly understood. In coastal temperate rainforest ecosystems historic fire disturbances are not well documented and time since the most recent fire is largely unknown. We sampled 6000 tree cores from 27 forest plots that burned 124 years ago and 11 plots with no recent history of fire (within the last 1000 years) to understand the legacies of fire on forest stand structure in a British Columbia high-latitude coastal temperate rainforest. We assessed the timing and spatial extent of historic fires with a 700 year fire history reconstruction built from fire scars, and applied light detection and ranging (LiDAR) to ground-truth plot-level measurements. We sampled an additional 32 plots with known fire histories to validate the ability of LiDAR to detect and characterize historic fire legacies. In total, we sampled 70 plots for stem density, stand structure, and stand composition. Trees in burned plots were significantly taller, and the mean stem density was less than half that of unburned plots despite 124 years since the most recent fire. LiDAR analyses had similar results and also showed that burned plots had lower canopy cover and greater canopy complexity. Field-based measurements are still required to resolve differences in community structure and composition in our temperate rainforest study area. However, LiDAR may be an important tool to bridge the spatial information offered by plot-level measurements to larger area characterizations in the future. Our comparative analyses provide an improved understanding of fire legacies and temperate rainforest structure, which increases our ability to detect fire disturbances in heterogeneous forests and is important for forest resource management and conservation.

1. Introduction

Ecological memory or the degree to which a landscape is shaped by its past patterns and processes is important to how ecosystems respond to disturbance and can be identified in the physical structure of vegetation, soil substrate, and resource availability (White and Pickett, 1985; Peterson, 2002; Johnstone et al., 2016). Fire can be both a natural and anthropogenic disturbance that is nearly ubiquitous in terrestrial ecosystems (Bowman et al., 2009; Whitlock et al., 2010). Fire affects successional vegetation patterns by opening canopies, consuming horizontal and vertical fuels, preparing seedbeds, and changing soil substrate and water hydrology (McKenzie and Kennedy, 2011; Bolton et al., 2015). Although the feedback between fire and landscape pattern is ecosystem specific (Bowman et al., 2011), recently burned forests often have characteristic patterns of spatial variability that can be detected with remote sensing techniques such as light detection and ranging (LiDAR; McKenzie and Kennedy, 2011). Nevertheless, we have little understanding of how these patterns change over larger spatial and longer temporal scales, specifically when fire disturbances are low-severity and much of the forest structure remains intact as standing live trees (Falkowski et al., 2010; Goetz et al., 2010; Krasnow et al., 2016). The rate of vegetation recovery and legacies of fire disturbance depends on several factors including time elapsed since the most recent fire event (TSF), and the fire frequency, fire severity, fire extent, and fire-sensitivity of vegetation (Foster et al., 1998; Johnstone et al., 2016; Stevens-Rumann and Morgan, 2016). Species life histories and local site factors such as topography also influence vegetation recovery (Foster et al., 1998; Bartels et al., 2016).

Ecologists are often challenged by the scale limitations of field assessments, which constrain their ability to compare plot-level

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measurements to landscape level processes (Swetnam et al., 2015). This is especially true in heterogeneous landscapes characterized by patch dynamics where plot-level measurements provide important inventories of historic disturbances and vegetation succession, but are limited in their spatial application (Foster et al., 1998). Fortunately, the capacity to locate and characterize historic fire disturbances is increasing with the widespread availability of remote sensing techniques such as LiDAR, which provide site-specific measurements and regional characterization of vegetation (Lim et al., 2003; White et al., 2016). LiDAR has the potential to greatly advance the spatial area of vegetation measured following disturbance, particularly canopy height metrics, and associated biomass (Houghton et al., 2009; Goetz et al., 2010; Bolton et al., 2015; Nijland et al., 2015). However, the potential of this technology to reconstruct historic fire disturbances remains largely untested, especially in complex and heterogeneous landscapes where natural variability in forest structure is high (Swetnam et al., 2011). This is especially true of high-latitude coastal temperate rainforests like those in British Columbia, Canada, where historic fire disturbances are not well documented (Daniels and Gray, 2006; Hoffman et al., 2016a, 2016b, 2017).

Analyses that assess a range of spatial scales from small patches to broader, landscape-level legacies are important when studying disturbances such as fire which are controlled by several processes operating at different scales (Falk et al., 2007). Quantifying relationships between fire history and forest structure across large forested areas may provide an improved understanding of both spatial and temporal variability in heterogeneous coastal temperate rainforests, which is important for ongoing forest resource management (Tepley et al., 2013). We use airborne LiDAR and plot-level measurements to assess differences in burned and unburned forests in a high-latitude temperate rainforest on the Central Coast of British Columbia. We ask the following questions: (1) What fire legacies are apparent in forest stand structure and composition after a 124 year post-fire period? (2) How does historic fire activity affect regeneration dynamics through changes to canopy structure and stand density? (3) Can LiDAR detect differences in forest stand structure that are apparent in plot-level measurements? We hypothesize that historically burned forests remain more open, have higher conifer diversity and contain lower-density stands with taller and wider trees.

2. Methods

2.1. Study area

The study area encompasses a 20 km^2 area located on Hecate and Calvert Islands (North 51° 39 Latitude, West 128° 04 Longitude) within the Hakai Lúxvbálís Conservancy on the Central Coast of British Columbia, Canada (Fig. 1). The coastal margin of British Columbia has many small islands characterized by exposed and rocky homogenous quartz diorite and granodiorite bedrock, subdued terrain, and elevations ranging from sea level to approximately 1000 m (Roddick, 1996). Cool temperatures (average annual ~ 7 °C, average summer ~ 12 °C) coupled with locally abundant (~4000 mm) and year-round rainfall distinguish this temperate climate region (Banner et al., 1993, 2005). The study area is located within the very wet hypermaritime subzone (CHWvh2) of the Coastal Western Hemlock biogeoclimatic classification (Meidinger and Pojar, 1991).

Excess soil water regulates this environment and subtle variations in slope or drainage result in significant differences in forest productivity (Banner et al., 2005). Although several vegetation types have been categorized in the study area (Thompson et al., 2016), four types dominate along a gradient of productivity and are defined by species and closely associated landforms (Banner et al., 1993, 2005). Productive (zonal) forests are found in nearshore and riparian areas with large-diameter western redcedar (*Thuja plicata* Donn ex D. Don.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and lesser amounts of yellow-cedar (*Cupressus nootkatensis* [D.Don] Farjon and Harder), and Sitka spruce (*Picea sitchensis* [Bong.] Carr.) (Meidinger and Pojar, 1991). Bog forests exhibit stunted growth forms and are located on hill slopes dominated by western redcedar, yellow-cedar, western hemlock, and shore pine (*Pinus contorta* var. *contorta* Douglas ex Louden) (Klinka et al., 1996). Bog woodlands are the most common vegetation type in the study area and are comprised of patchy mosaics of forested and unforested sites in subdued or rolling terrain (Thompson et al., 2016). These forests contain roughly equal densities of western redcedar, yellow-cedar, and shore pine with lesser amounts of mountain hemlock (*Tsuga mertensiana* [Bong.]) (Klinka et al., 1996). Blanket bogs are nutrient-poor, sparsely forested wetland areas that contain small amounts of shore pine and yellow-cedar (Banner et al., 1993).

Compared to most of British Columbia, the Central Coast has experienced very small fluctuations in sea levels (± 2 m) during the Holocene (Shugar et al., 2014). This allowed First Nations to continuously inhabit the region for > 13,000 years until European contact in the late 18th and 19th centuries, which decreased First Nations activities in their traditional territories (McLaren et al., 2014, 2015). Lightning-ignited fires are rare and First Nations likely played an important role in igniting fires and controlling the spatial and temporal aspects of fire activity (Hoffman et al., 2016a, 2016b). Ongoing research suggests that fire in the study area may have been intentionally used as a tool for resource management (Trant et al., 2016; Hoffman et al., 2017), but little specific ethnographic information is available regarding how First Nations used fire to control vegetation succession (Turner, 1999, 2014). Historic fire events were composed of low- and mixed-severity ground fires that did not result in significant stand mortality (Hoffman et al., 2017). Although more than a century has passed since the most recent fire event, the ecological legacies of historic fire activity, such as fire-scarred trees and even-aged cohorts remain visible in the study area today. Colonists never settled the region and there is no history of industrial logging or mining (McLaren et al., 2015).

2.2. Ecological field sampling

Terrestrial ecosystem maps and satellite imagery taken in 2012 were used to select the locations of 70 plots (11.28 m radius [0.04-ha]) with a stratified random sampling design representing the range of elevations, aspects, slopes, and four dominant vegetation types on Hecate and Calvert Islands (Fig. 1). Twenty-seven plots were sampled within a low- and mixed-severity 287-ha fire on Hecate Island that most recently burned in 1893 (Fig. 1, hereafter ‘burned’ plots). Forest structure in burned plots was previously reconstructed with a network of 45 living fire-scarred trees (containing 99 fire scars) and 4000 tree cores (Hoffman et al., 2016b, 2017). Burned plots experienced repeated low- and mixed-severity fires of varying sizes (0.01–287-ha) from the first detected fire in 1376 until the last detected fire in 1893 (Hoffman et al., 2016b). The 1893 fire affected all 27 burned plots and these plots experienced an average of five fire events between 1376 and 1893 (Appendix A: Table 1). The 27 burned plots were compared to 11 plots that were selected and sampled with the same methods, but contained no fire scars and had no aboveground evidence of fire activity (hereafter ‘unburned’ plots) on Hecate and Calvert Islands (Fig. 1). Field surveys and the collection and crossdating of an additional 2000 tree cores from the unburned plots confirmed the absence of fire scars and post-fire cohorts. This information together with previous radiocarbon dating of charcoal from historic fires deposited in soils confirmed that the 11 unburned plots had not experienced fire activity for at least 1000 years (Hoffman et al., 2016a). This design allowed for comparison of plots with similar forest stand structure, vegetation, and topographical position but with differing fire histories. Time and financial constraints limited the ability to perform a balanced sampling design.

In all plots, two 5 mm increment cores were sampled from the bases (~15 cm height) of all trees > 7.5 cm diameter at breast height (dbh).