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Forest fragmentation, structure, and age characteristics as a legacy of forest management

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ABSTRACT

The combination of forest inventory and satellite-derived landscape composition and structure provides otherwise unavailable information on regional forest conditions and enables investigation of the cumulative effects of forest management over time. Forest pattern results from a range of both natural and anthropogenic factors. This study characterizes the forest pattern of Vancouver Island, British Columbia (>32,000 km^2) at the watershed scale, using new national datasets of Canadian forest composition and fragmentation, and relating these to forest inventory-derived age structure. Vancouver Island is extensively forested, possessing highly valuable and productive forests, and is managed to meet a range of stakeholder interests. Forest fragmentation metrics were derived from a satellite-derived, 25-m spatial resolution land cover map (i.e., grain) to represent patterns within 1 km analysis units (i.e., extent) for the entire forested area of Canada. We summarized forest fragmentation island-wide and compared trends between forest-dominated (>85% forest) and less-forested (<85% forest) watersheds. We also explored these patterns with partial canonical correspondence analyses to determine the independent and shared relationships of landscape composition, forest fragmentation, and spatial variables with forest age structure.

Less-forested watersheds are more fragmented than forest-dominated watersheds, as indicated by more (5.6 versus 2.7 per km^2) and smaller (36 versus 63 ha) forest patches, and a greater edge density (82 versus 55 m/ha). Of the 1283 watersheds examined, 91% were forest-dominated; island-wide trends are thus similar to those of the forest-dominated watersheds. Forest age is related to landscape composition and forest fragmentation, which collectively explain 27% and 53% of the age structure of all and less-forested watersheds, respectively. In both sets of watersheds, young forest stands (1–120 years) are associated with broadleaf forests, agreeing with successional expectations, and patchy forest distributions. For all watersheds, old growth forest stands (>240 years) are associated with dense coniferous forest, but also with early successional communities, smaller patch sizes, and greater edge densities, indicating fragmentation of these forests and reflecting strategies for managing old growth on the landscape. In contrast, watersheds with an abundance of mature forest (121–240 years) are compositionally similar to watersheds with old growth, but are much less fragmented. Our results indicate that although old growth forest stands on Vancouver Island have been retained, they are not typically found within a continuous forest matrix. Medium spatial resolution Earth observation products are now available for the entire forested area of Canada, providing valuable insight into spatial and temporal forest dynamics (i.e., succession, harvesting).

1. Introduction

A major aspect of forest pattern is fragmentation, which is a function of the amount and configuration of forest within a landscape. Fragmentation of forests may be caused by a variety of factors, including both natural processes, such as fires and insect infestation, and anthropogenic activities, such as logging and road building (Linke et al., 2007). Fragmentation can be considered as broadly (e.g., forest versus non-forest) or as subtly (e.g., between forest classes or ages) as desired; here we focus on gross fragmentation of forests in general by non-forested land covers. A forested landscape is understood to be fragmented when it contains a greater number of forest patches that are smaller and more isolated than those in an undisturbed reference landscape or reference time point. Biota may be less able to disperse to and/or persist in small, isolated patches (following island biogeography; MacArthur and Wilson, 1967). Additionally, fragmentation increases the dominance of edge habitat, which has diverse effects on the physical environment (Saunders et al., 1991) and, thus,

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consequences to the resident biota (e.g., Kupfer and Runkle, 2003) and natural disturbance regimes (Franklin and Formann, 1987).

The effects of harvesting and associated road networks on forest pattern have been well documented, with findings indicating that clear-cutting and road building consistently decrease forest patch size and increase the number of forest patches and the amount of edge (Franklin and Formann, 1987; Ripple et al., 1991; Mladenoff et al., 1993). Forest removal also tends to simplify patch shapes (Mladenoff et al., 1993; Reed et al., 1996; Tinker et al., 1998), although the converse may occur when multiple cut blocks merge to form complexly shaped aggregates (Ripple et al., 1991; McGarigal et al., 2001).

However, forest pattern extends beyond spatial structuring alone. Forest stand age is another crucial dimension of forest pattern. The forest age distribution within a landscape is a record of the local disturbance regime (both natural and anthropogenic) and is a key control on ecosystem function (Casperson and Pacala, 2001). Forest age structure is strongly influenced by extractive use, which results in more uniform age distributions up to the rotation age (i.e., the age at which a stand is considered mature and ready for harvesting), followed by a sharp decline in older age classes (Gustafson and Crow, 1996; Fall et al., 2004). This age distribution contrasts sharply with the negative exponential distribution of stand ages expected under many natural disturbance regimes (Frelich, 2002). Changes to forest age distributions are of concern because biodiversity and carbon cycling are closely linked to forest age: old forests provide critical habitat for threatened and endangered species (Berg et al., 1994) and immense carbon storage capacity (Harmon et al., 1990; Pregitzer and Euskirchen, 2004). There has been considerable interest and research on alternative forest management plans, whereby harvesting mimics natural disturbance and maintains natural age distributions and landscape structures (Franklin and Formann, 1987; Gustafson and Crow, 1996; Fall et al., 2004; Didion et al., 2007).

There are thus intuitive effects of forest management on both age structure and landscape structure, suggesting that there may also be a strong relationship between forest age and spatial pattern. Yet these factors have rarely been studied together and the spatial effects of forest harvesting on specific forest age classes are relatively unknown (but see McGarigal et al., 2001; Etter et al., 2005; Helmer et al., 2008). The overall goal of this communication is to characterize the forest patterns of watersheds on Vancouver Island, British Columbia and determine their interrelationships. To achieve this, we synthesize data from forest inventory and remotely sensed land cover datasets to relate forest age structure to landscape composition, forest fragmentation, and spatial variables (i.e., watershed location and size). Our first objective is to summarize forest fragmentation for all watersheds considered in our analysis, and then compare the forest fragmentation of watersheds that have different levels of forest abundance. Our second objective is to determine the independent and shared relationships of landscape composition, forest fragmentation, and spatial variables with forest age structure. This research provides a valuable assessment of the current baseline conditions and correlations of forest age and landscape structure on Vancouver Island, contributing to our understanding of anthropogenic impacts to these landscapes. It also highlights the capabilities of several newly available, national, remotely sensed datasets and analysis tools that are novel to and merit wider application in landscape scale studies.

2. Materials and methods

2.1. Study area

Vancouver Island is found at the southwestern corner of the province of British Columbia, Canada. It is approximately 460 km long and 80 km wide, with an area of 32,134 km^2. The island is characterized by a maritime climate with mild, wet winters, when temperatures rarely fall below 0 °C, and cool, dry summers (Coops et al., 2007). A mild climate, high amounts of precipitation, and suitable soils promote forest growth over much of Vancouver Island. With the exception of alpine areas, much of the island is occupied by forests dominated by Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), yellow cedar (*Chamaecyparis nootkatensis*), and Sitka spruce (*Picea sitchensis*) (Burns and Honkala, 1990), and has been for more than 12,000 years (British Columbia Ministry of Environment, Lands and Parks, 1999).

Vancouver Island is part of Canada's Pacific Maritime ecozone. The Pacific Maritime ecozone occupies 3% of Canada's area of forest, but accounts for 12% of Canada's wood volume (Power and Gillis, 2006). Since 1848, forest harvesting has been an important economic activity on Vancouver Island (British Columbia Ministry of Environment, Lands and Parks, 1999). Wildfires are well suppressed; harvesting, agriculture, and urban expansion are the primary agents of forest change and, in the latter case, land use conversion (Pew and Larsen, 2001). While 12.9% of Vancouver Island is occupied by protected areas, much of the island is managed in support of forest harvesting activities.

2.2. Data and input variables

2.2.1. Watersheds

British Columbia vector-based third order and higher watershed boundaries at a scale of 1:50,000 were obtained from the Government of British Columbia (Ministry of Sustainable Resource Management, 2004). These data represent 2093 watersheds on Vancouver Island. Watersheds larger than 50 ha were selected for analysis to ensure sufficient within-watershed land cover information ($N = 1429$). Of these, 146 watersheds were excluded from analysis because the land cover classification in these watersheds was incomplete as a result of substantial cloud contamination in the original satellite imagery, or because there were insufficient forest inventory data available in these areas, primarily in the private railroad concession in southeastern Vancouver Island. This omission perhaps improves our analyses and the consistency of the identified patterns as this area is more developed, drier, and thus less representative, in terms of disturbance regimes, landscape structure, and forest age distributions, of the island as a whole. In total, 1283 watersheds were retained to analyze forest patterns. Watersheds were divided into three sets: (1) a full set of all 1283 watersheds; (2) a subset of forest-dominated watersheds (where forests cover $\geq$85% of the watershed area, $N = 1166$); and (3) a subset of less-forested watersheds (where forests occur in <85% of the watershed area, $N = 117$). The 85% forest threshold corresponds to the island-wide mean forest cover.

Spatial variables were derived from the watershed boundaries. Space was represented by a third order polynomial of the geographic coordinates (UTM northing and easting) of the centroid of each watershed (sensu Borcard et al., 1992; Table 1) and by the watershed area.

2.2.2. Land cover classification

Existing land cover data derived from Landsat-7 Enhanced Thematic Mapper Plus (ETM+) were used to represent landscape composition on Vancouver Island (http://www4.saforah.org/eosdlcp/nts_prov.html). Produced by the Canadian Forest Service, with support from the Canadian Space Agency and partnerships with all provinces and territories, the Earth Observation for Sustainable Development of Forests (EOSD) land cover dataset represents circa year 2000 (EOSD LC 2000) conditions and depicts