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Risk rating for mountain pine beetle infestation of lodgepole pine forests over large areas with ordinal regression modelling

C. Robertson [a,*], M.A. Wulder [b], T.A. Nelson [a], J.C. White [b]

[a] Spatial Pattern Analysis & Research (SPAR) Laboratory, Department of Geography, University of Victoria, PO Box 3050, Victoria, BC V8W 3P5, Canada
[b] Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside, Victoria, BC V8Z 1M5, Canada

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ABSTRACT

The mountain pine beetle *Dendroctonus ponderosae* Hopkins is endemic to lodgepole pine, *Pinus contorta* var. *latifolia* Engelmann, forests in western Canada. However, the current beetle epidemic in this area highlights the challenges faced by forest managers tasked with prioritizing stands for mitigation activities such as salvage harvesting and direct control methods. In western Canada, the operational risk rating system for mountain pine beetle is based on biological knowledge gained from a rich legacy of stand-scale field studies. Due to the large spatial (millions of hectares affected) and temporal (over 10 years) extents of the current epidemic, new research into large-area mountain pine beetle processes has revealed further insights into the landscape-scale characteristics of beetle infested forests. In this paper, we evaluated the potential for this new knowledge to augment an established system for rating the short-term risk of tree mortality in a stand due to mountain pine beetle. New variables explored for utility in risk rating include direct shortwave radiation, site index, diameter at breast height, the temporal trends in local beetle populations, Biogeoclimatic Ecosystem Classification and beetle–host interaction variables. Proportional odds ordinal regression was used to develop a model for the Vanderhoof Forest District in west-central British Columbia. Prediction on independent data was assessed with the area under the receiver operator curve (AUC), indicating good discriminatory power (AUC = 0.84) for predicting levels of mountain pine beetle-caused pine mortality.

1. Introduction

In recent years, the management of lodgepole pine, *Pinus contorta* var. *latifolia* Engelmann, forests in western Canada has been complicated by an extensive mountain pine beetle, *Dendroctonus ponderosae* Hopkins, outbreak that has caused tree mortality over an estimated 9 million ha of British Columbia (Westfall, 2007). Management of forest resources require decision support tools that enable managers to predict future forest scenarios, set priorities, and evaluate management strategies. In the context of mountain pine beetle decision support, forest managers must know the ability of a forest stand to support an epidemic mountain pine beetle population (i.e., susceptibility), as well as the potential for host tree mortality as a result of an existing beetle infestation (i.e., risk). The distinction between risk and susceptibility or hazard is an important one. Following Fettig et al. (2007), we define susceptibility (hazard) as a function of stand and tree conditions, and risk as a combined function of susceptibility and mountain pine beetle population levels. Susceptibility is determined using stand and site characteristics, independent of surrounding beetle population levels. Conversely, risk is determined by considering the susceptibility of the stand in the context of the local beetle population within the stand and in the vicinity of the stand (Bentz et al., 1993). A risk rating system is a specific decision support tool that is used to identify those forest stands on the landscape that are at greatest risk of timber losses as a result of a mountain pine beetle infestation (Shore et al., 2006).

1.1. Mountain pine beetle risk rating

Many risk rating systems for mountain pine beetle have been developed over the past three decades (see Fettig et al., 2007 for a review of bark beetle risk ratings systems). Safranyik et al. (1975) initially used weather station data to model and map the potential for outbreak populations of mountain pine beetle in western Canada. Amman et al. (1977) used stand characteristics such as elevation, age, and diameter at breast height (dbh) to develop a three-class risk classification system (i.e., low, moderate, high).

* Corresponding author. Tel.: +1 250 885 8065.
E-mail address: colinr23@gmail.com (C. Robertson).

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Other risk rating systems were developed that also relied on stand characteristics and adopted similar approaches to rating stand risk as a categorical variable (e.g., Mahoney, 1978; Berryman, 1978a; Stuart, 1984; Anhold and Jenkins, 1987). Bentz et al. (1993) evaluated the accuracy of three categorical risk rating systems (i.e., those of Amman et al., 1977; Mahoney, 1978; Berryman, 1978a) and one continuous variable risk rating system (Schenk et al., 1980). All of the systems evaluated by Bentz et al. (1993) were found to provide poor estimates of pine mortality, primarily because they failed to consider spatial relationships between host stands and beetle populations. Furthermore, Bentz et al. (1993) concluded that the empirical development of these risk rating systems limits their portability to other geographic areas.

Shore and Safranyik (1992) introduced a continuous variable risk rating system which incorporated those elements of previous systems that had a strong theoretical basis for characterizing susceptibility and risk. Shore and Safranyik (1992) define risk as the short-term expectation of volume loss due to mountain pine beetle attack. There are two components to the Shore and Safranyik risk rating system: stand susceptibility, defined as the inherent characteristics of a stand of trees that affect its likelihood of attack by mountain pine beetle; and, beetle pressure, which is a measure of the size and proximity of the mountain pine beetle population to the stand. Susceptibility in Shore and Safranyik (1992) is determined using stand density, age, composition, and geographic location. Each of these variables has a direct link to biological processes associated with mountain pine beetle. Stand density affects tree competition for light and nutrients, so less dense stands tend to have larger, more vigorous trees; however, low density stands have a negative impact on the microclimate that is required to facilitate pheromone mediated attacks, landing, and emergence rates (Bartos and Amman, 1989). Intermediate stand densities of 750–1500 stems/ha are thought to be more conducive to beetle-induced tree mortality (Anhold and Jenkins, 1987), giving rise to a nonlinear relationship between risk and stand density. Stand age relates to the beetle's preference for large-diameter trees (Safranyik et al., 1974), and stand age has an inverse relationship with tree vigor after maturity, which determines a tree's ability to resist infection by beetle-introduced fungi (Shrimpton, 1973). Once physiological maturity has been reached, trees often become more susceptible to attack, although the rate and likelihood of attack is impacted by other variables such as climate (Shrimpton and Thomson, 1983). Stand composition is included in the Shore and Safranyik model because stand risk relates to the amount of near term volume loss, so greater amounts of the preferred host (i.e., lodgepole pine) contribute to higher risk ratings. The composition variable is measured as the percentage of a stand's basal area that is composed of large-diameter lodgepole pine. The location factor incorporates the impact of geographic location on beetle survival. At higher elevations and northern latitudes, beetles are exposed to colder temperatures, thereby increasing overwintering mortality and disrupting the beetle's development cycle (Amman, 1973).

The first dispersing beetles are usually females and are thought to select their host based on a combination of random landing and visual orientation followed by inspection (Safranyik and Carroll, 2006), however tree stress (Gara et al., 1984) and host kairomones (Moeck and Simmons, 1991) may also influence this process. Upon acceptance of a host, gallery construction is initiated. Lodgepole pine, as with other conifers, defend against attacking beetles by excreting resin, which can interrupt gallery construction, destroy eggs, and flush beetles out of the tree (pitch out). These defenses can be overcome by mountain pine beetle mass attacks, whereby additional beetles are attracted to the tree under attack, coordinated by a complex process involving beetle pheromones and host kairomones (Borden, 1989). Tree defensive capacity is dependent on resin production, primarily determined by vigour, while beetle attack success is dependent on the density of attacking beetles. Representing both host tree vigour and the local beetle population is critical for determining future infestation patterns.

Beetle pressure in Shore and Safranyik (1992) is based on the number of beetles within and proximal to the stand. Beetle population is estimated by the number of infested trees and the likelihood of attack is incorporated by the distance between the stand being rated and the infestation. The maximum distance at which beetles from surrounding areas can enter the stand being assessed is assumed to be 3 km. Susceptibility variables and beetle pressure are combined multiplicatively to determine the overall risk rating for a stand of trees. Recent model refinements have replaced discrete look-up tables with continuous equations for each of the susceptibility variables, the beetle population variable, and for the risk calculation in an effort to reduce the impact of class boundaries on final risk assessments (Shore et al., 2006). However, the fundamental elements of the Shore and Safranyik model remain unchanged: four equally weighted susceptibility variables combined with a spatial measure of the beetle population to determine a relative ranking of stand risk.

With the explosive growth of mountain pine beetle populations in western Canada, the risk rating system has become a recommended forest planning tool (British Columbia Ministry of Forests, 1995). However, there are considerable limitations to implementing the Shore and Safranyik system over large areas. Firstly, the relationships in the model are derived from field research over relatively small (i.e., $<$5 ha) geographic areas (Shore and Safranyik, 1992; Shore et al., 2000). Extrapolating these relationships to new geographic regions may neglect regional variations in mountain pine beetle processes such as emergence rates, dispersal, and lifecycle. Secondly, the data inputs required for operational modelling across large areas often do not exist and substitute variables available in forest inventory data are generally poor replacements (Nelson et al., 2006). Hence, a decision support tool capable of assessing risk over large areas is needed.

1.2. Recent research

Research conducted over the last decade may be able to provide enhancements to existing mountain pine beetle risk rating systems. The growth of geographic information systems (GIS) as a tool for managing complex spatial and attribute information combined with increasing efficiencies in automated and semi-automated data collection technologies has enabled forest managers and researchers to link theoretical and empirical knowledge of ecological processes (e.g., Blackburn and Milton, 1996). Additionally, more advanced analytical methods for spatial data are being developed that facilitate spatially explicit analysis of forest disturbances across large spatial and temporal scales (e.g., Nelson and Boots, 2005).

1.2.1. Landscape-scale red attack modelling

A number of studies have investigated the potential for locating and estimating the severity of mountain pine beetle red attack damage of forested landscapes (red attack is a term used to describe the characteristic fading of an attacked tree's foliage, which typically occurs within 6–8 months following successful attack). Variables useful for predicting red attack over large areas may also be helpful for predicting areas at risk of mass attack. While remotely sensed data have been used in many studies for detecting and mapping red attack damage at a range of spatial scales (Sirois and Ahern, 1989; Franklin et al., 2003; Skakun et al.,