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A GIS-based risk rating of forest insect outbreaks using aerial overview surveys and the local Moran's I statistic

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A B S T R A C T

The objective of this study is to provide an approach for assessing the short-term risk of mountain pine beetle *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae) attack over large forested areas based on the spatial-temporal behavior of beetle spread. This is accomplished by integrating GIS, aerial overview surveys, and local indicators of spatial association (LISA) in order to measure the spatial relationships of mountain pine beetle impacts from one year to the next. Specifically, we implement a LISA method called the bivariate local Moran's I_i to estimate the risk of mountain pine beetle attack across the pine distribution of British Columbia, Canada. The bivariate local Moran's I_i provides a means for classifying locations into separate qualitative risk categories that describe insect population dynamics from one year to the next, revealing where mountain pine beetle populations are most likely to increase, stay constant, or decline. The accuracy of the model's prediction of qualitative risk was higher in initial years and lower in later years of the study, ranging from 91% in 2002 to 72% in 2006. The risk rating can be continually updated by utilizing annual overview surveys, thus ensuring that risk prediction remains relatively high in the short-term. Such information can equip forest managers with the ability to allocate mitigation resources for responding to insect epidemics over very large areas.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae) is the most destructive insect pest of pine forests in western North America (Safranyik, 1988). Since 1999, the insect has affected more than 16 million ha of pine forests in western Canada (Westfall & Ebata, 2010). The current epidemic, largely located in British Columbia, has resulted in substantial commercial timber loss (Pederson, 2004), increase risk to fire and habitat loss (Coops, Waring, Wulder, & White, 2009; Jenkins, Herbertson, Page, & Jorgensen, 2008), and alterations to carbon cycling processes (Coops & Wulder, 2010; Kurz et al., 2008; Pfeifer, Hicke, & Meddens, 2011). In addition, there is concern that the beetle will infest further beyond its historical range (Sambaraju et al., 2011) as warmer seasonal temperatures exacerbate the outbreak and permit it to move to higher latitudes and elevations than previously recorded (Logan, Régnière, & Powell, 2003), and across the geoclimate divide as defined by the Rocky Mountain range of North America (Safranyik et al., 2010). Such concerns indicate a need for risk analyses that can inform forest management decision making over vast areas in a timely manner.

In British Columbia, the mountain pine beetle mostly attacks lodgepole pine (*Pinus contorta*) (Flint, McFarlane, & Muller, 2009). The process begins in the summer as beetles emerge from their host and spend time in flight searching for a new tree to attack. Once located, the beetle attempts to bore through the bark and release pheromone chemicals to attract additional beetles to the suitable host (Powell et al., 2000). After boring through the phloem of the tree, beetles copulate and proceed to dig galleries that are used to oviposit (Raffa et al., 2008). As beetles bore through the bark, they inoculate the tree with two types of blue stain fungi that rapidly penetrate living tree cells, thereby impacting the capacity for translocation of moisture and nutrients through the tree, consequentially limiting the ability of the tree ward off attack (Paine, Raffa, & Harrington, 1997; Six & Paine, 1998). The combination of pheromone release and fungi inoculation facilitates a mass attack of beetles on an individual tree that are needed to overcome a tree's defensive mechanisms (Safranyik, 2004).

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Reproduction ensues in the weeks following tree mortality, and young beetles then overwinter under the bark and then emerge in the following summer to repeat the same process.

Individual trees vary in their susceptibility to attack as beetles have preference for trees that provide ample resources for reproduction and growth while also providing minimal resistance to attack (Berryman, 1978). Trees with larger diameters, for example, receive relatively higher densities of attack because the rougher bark associated with larger trees is preferred for initiating galleries (Safranyik, 1971), and the thicker phloem provides protection from predators and extreme temperatures (Reid, 1963), thus increasing the likelihood of progeny survival. Beetles also prefer older trees, generally over 80 years of age, because their vigor diminishes as age increases (Safranyik, 2004). In addition, dense stands of older trees are preferred as increased competition for resources comprise their ability to resist attack (Mitchell, Waring, & Pitman, 1983).

Identifying forest stands at risk to mountain pine beetle attack aids in the mitigation and prevention of outbreaks. The term risk in the bark beetle literature has come to refer to "the short-term expectancy of tree mortality in a stand as a result of mountain pine beetle infestation" (Shore, Safranyik, & Lemieux, 2000, p.44), with risk being a function of both stand susceptibility (i.e., the ability of a stand to support a beetle population) and the magnitude of surrounding mountain pine beetle populations – often referred to as population pressure (Bentz, Amman, & Logan, 1993).

When beetle infestations expand over large areas as has occurred with the current outbreak, estimating risk becomes a complicated task because of the data required for calculating susceptibility. Risk models with a susceptibility component (Amman, McGregor, Cahill, & Klein, 1978; Berryman, 1978; Mahoney, 1978; Schenk, Mahoney, Moore, & Adams, 1980; Shore & Safranyik, 1992) rely upon data that provide details concerning, for example, average tree age, tree diameter, phloem thickness, basal area, crown competition and stand growth. Such data can be collected and analyzed in a timely manner when infestations remain relatively small. However, large outbreaks require that risk models be applied over large areas, which means that models must then rely upon regional inventory records to provide the necessary data (Robertson, Wulder, Nelson, & White, 2008). For example, the British Columbia Ministry of Forests, Lands and Natural Resource Operations provides the Vegetation Resources Inventory (VRI), which is a two-phased vegetation inventory with attributes estimates through a combination of aerial photo interpretation and ground sampling (BCMSRM, 2002). The utility of such inventories becomes increasingly limited when bark beetle outbreaks cause changes to forest composition (via beetle-induced tree mortality or harvesting-based mitigation efforts) occur far more swiftly than inventory updates. This is especially true in British Columbia where the current mountain pine beetle outbreak has grown swiftly since 2000 (see Fig. 1).

In contrast to the data needs associated with estimating susceptibility under large-area mountain pine beetle outbreak scenarios, estimating population pressure under similar scenarios can be accomplished through the use of a single dataset: forest health aerial overview survey (AOS) data. In British Columbia, AOS are annual, systematic surveys of a broad range of forest health issues. Designed to cover the largest possible area, the AOS are conducted by trained practitioners in fixed-wing aircraft, who provide estimates of beetle-induced tree mortality and other forest health information (Wulder, White, Bentz, & Ebata, 2006). The AOS is a strategic-level data source that is rapidly disseminated to the public (i.e., within 3 months of survey completion) (Wulder et al., 2009), and that can serve as a surrogate for beetle population pressure. Furthermore, because the AOS are conducted annually, changes in population pressure can be estimated across a region, which is

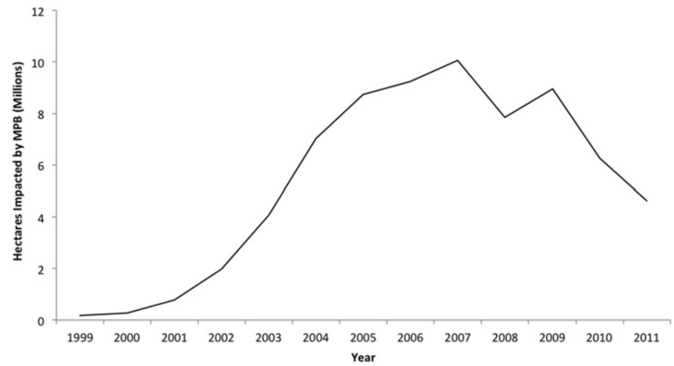

Fig. 1. Number of hectares impacted by mountain pine beetle from 1999 to 2011.

important for determining if populations are increasing or decreasing in specific areas in order to prioritize mitigation efforts.

While focusing risk estimates solely on population pressure is only part of the risk equation, we posit that data on regional population dynamics collected from AOS can aid in identifying and prioritizing areas of imminent risk to mountain pine beetle infestations over large areas. As such, this study proposes a GIS-based risk rating system of mountain pine beetle infestations by integrating multi-year AOS data and local indicators of spatial association (LISA) (Anselin, 1995) for estimating infestation risk at a regional scale. We extend previous applications of LISA for estimating mountain pine beetle infestations (Nelson & Boots, 2008) by applying the bivariate local Moran's I_i to determine local spatial relationships in beetle infestations in subsequent years. The objective of developing a regional risk rating system based on surrogate measures of population pressure across multiple years is to inform management of where lies increasing, constant or declining risk. As mountain pine beetle population dynamics are controlled by numerous local and regional processes that interact with each other over time, it is difficult to project where populations will arrive, increase or diminish from one year to the next over a region without examining the spatial and temporal distributions of populations. We anticipate that this regional risk rating system will be able to be used in unison with more localized data on susceptibility characteristics in order to provide a more effective means of mitigating outbreaks.

Methods

Study site and data

The study site (see Fig. 2) is defined by the distribution of lodgepole pine in British Columbia, which is an area covering approximately 30 million hectares of the provinces' 95 million hectare land mass (BC Ministry of Forests, 2004). The pine distribution data exists as a 1 km resolution raster grid in which each cell is represented by the estimated percentage of pine at that location. The dataset was developed by Robertson et al. (2009) to support estimates of the compositional change of pine forests in British Columbia due to mountain beetle attack.

The severity of mountain pine beetle attack, which refers to the percentage of trees successfully attacked within a given area (Wulder et al., 2006), was used as a proxy for beetle population levels. Severity information was acquired from annual forest health aerial overview surveys (AOSs) (http://www.for.gov.bc.ca/hfp/health/overview/overview.htm), which are conducted province-wide by trained observers in fixed-wing aircraft. These AOS are completed quickly and efficiently, making them ideally suited for