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# A spatiotemporal pattern analysis of potential mountain pine beetle emergence in British Columbia, Canada

Huapeng Chen[a,*], Peter L. Jackson[b,1], Peter K. Ott[a], David L. Spittlehouse[a]

[a] British Columbia Ministry of Forests, Lands, Natural Resource Operations, 727 Fisgard Street, Victoria, British Columbia V8W1N1, Canada
[b] Environmental Science and Engineering Programs, Natural Resources and Environmental Studies Institute, University of Northern British Columbia, 3333 University Way, Prince George, British Columbia V2N 4Z9, Canada

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## ABSTRACT

Emergence, the beginning of the mountain pine beetle life cycle and initiation of dispersal leading to colonization of new hosts, is a key beetle population process but it is also probably the least understood. Although from the management perspective information on beetle emergence is crucial in determining an appropriate timing to monitor beetle populations and mitigate outbreaks, especially at the landscape scale in a changing climate, no attempt has yet been made to map the spatiotemporal patterns of beetle emergence across the landscape. In this study, we used a novel heating cycle approach to map potential beetle emergence spatially and temporally. This study reveals that the thermal environment and timing for potential beetle emergence are spatially and temporally synchronous across the landscape. The spatial synchrony in potential beetle emergence occurs at a distance of more than 1500 km across the BC landscape. The spatiotemporal patterns of potential beetle emergence vary with the defined factors (region, period, latitude, elevation, and landform type). At the provincial and regional levels, the thermal environment for potential beetle emergence is surprisingly warmer during 1977–1987 compared to 1999–2010 except for the Southeast region although the provincial climate and weather are generally warmer during 1999–2010 than during 1977–1987, suggesting a small increase in annual temperature may not be enough to significantly improve the thermal environment. A warmer thermal environment with a larger temporal window for potential beetle emergence (i.e., the potential emergence starts earlier and ends later) is associated with the Southeast region, lower latitude and elevation, and landscape topographic features of canyons and valleys. However, although the thermal environment varies with the defined factors, the timing and window of potential beetle peak emergence remain consistent among these defined factors, suggesting that beetles may take different strategies to adapt to temporally synchronized thermal windows in the regions and areas with varied thermal environments. The summarized variables of heating cycles are limited in generally predicting the beetle infestations for a specific period, especially at endemic and incipient levels. However, they may play a greater role in predicting more severely infested areas. The heating cycle approach demonstrated in this study may provide a simple complementary tool to the existing climate suitability models in assessing the impacts of climate change on beetle outbreaks, particularly for those bark beetle species whose physiological responses to temperature have not been fully studied.

## 1. Introduction

Mountain pine beetle *Dendroctonus ponderosae* Hopkins is poikilothermic and temperature is the most important determinant in its life cycle (Safranyik and Carroll, 2006). Therefore, temperature plays a fundamental role in the mountain pine beetle population dynamics (Powell and Bentz, 2009; Régnière and Powell, 2013). Mountain pine beetle is constrained in its distribution by climate rather than its host distribution (Carroll et al., 2004) and a warming climate has been a key driver to extend the current range of mountain pine beetle far more north and east beyond its historic distribution (Carroll et al., 2004; Chen and Walton, 2011; Chen, 2014; Fettig et al., 2013; Nealis and Cooke, 2014).

Mountain pine beetle lacks a physiological mechanism such as diapauses to synchronize its life cycle events and maintaining

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[*] Corresponding author. Tel.: +1 (250) 387 2710.
*E-mail addresses:* huapeng.chen@gov.bc.ca (H. Chen), peter.jackson@unbc.ca (P.L. Jackson).
[1] Tel.: +1 (250) 960 5985.

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temperature-driven adaptive seasonality is an essential ecological requisite to ensure success of its populations, particularly in a changing climate (Bentz et al., 2010; Régnière and Powell, 2013; Creeden et al., 2014). Adaptive seasonality is closely related to a key beetle life history trait, emergence, which is the beginning of the beetle life cycle and a final development expression of successive life cycle stages through egg, larvae, pupae, and adult (Safranyik and Carroll, 2006). Mountain pine beetle achieves an adaptive seasonality in its life cycle by adapting the development of its life cycle stages to local temperature so it can maintain an appropriate emergence time in a year to avoid lethal temperatures and synchronize emergence timing to achieve successful pheromone-mediated mass attacks (Logan and Bentz, 1999; Bentz et al., 2010).

Various mountain pine beetle phenology process models have been developed based on temperature-driven development rate or time functions to predict the median emergence date of eggs laid on a given date with the G-function model (Logan and Powell, 2001; Powell and Logan, 2005), emergence distribution (Gilbert et al., 2004; Yurk, 2009), voltinism (Logan and Bentz, 1999; Logan and Powell, 2001), population growth rate by linking phenology with the R-function model (Powell and Bentz, 2009), and evolution of phenology (Yurk, 2009). These models have also been applied to predict landscape-level adaptive seasonality (Hicke et al., 2006) and assess the impacts of climate and weather on beetle outbreaks (Bentz et al., 2010; Safranyik et al., 2010; Preisler et al., 2012; Creeden et al., 2014; Nealis and Cooke, 2014). Although from the management perspective the information on the emergence of beetles is crucial in determining an appropriate timing to monitor beetle populations and mitigate outbreaks, especially at the landscape scale in a changing climate, no attempt has yet been made to apply the phenology models mentioned above to map the spatiotemporal patterns of the beetle emergence across the landscape.

Mountain pine beetle emergence is largely temperature dependent (Safranyik and Carroll, 2006) and temperature variation could provide a template to determine the timing of beetle emergence. Chen and Jackson (2014) have demonstrated that a heating cycle, defined and determined by an ambient temperature time series, is a reliable window for potential beetle emergence. The spatiotemporal patterns of potential beetle emergence can thus be mapped at the landscape scale based on landscape-level patterns of heating cycles. In the present paper, we use the heating cycle approach to map potential beetle emergence spatially and temporally across the British Columbia (BC) landscape, addressing four research questions: (1) Is the potential emergence of mountain pine beetle temporarily and spatially synchronous across the landscape? (2) What are the spatiotemporal patterns of potential mountain pine beetle emergence at the provincial and regional levels during two periods 1977–1987 and 1999–2010? (3) Do the spatiotemporal patterns of potential mountain pine beetle emergence vary with latitude and topography? (4) How much could key heating cycle variables alone explain the severity of infestations at the provincial and regional levels?

## 2. Materials and methods

### 2.1. Study area and data

We defined three regions (Fig. 1) for the spatiotemporal pattern analysis of potential beetle emergence based on provincial ecoregions (Demarchi, 2011) and the spatiotemporal patterns of historical and current outbreaks. The Chilcotin region (CH) is where the current outbreak began and has been severely affected by mountain pine beetles (Aukema et al., 2006; Chen, 2014). The Northeast region (NE) represents an area where the current outbreak has spread from CH including the previously climatically unsuitable habitats in the Peace River Basin due to long-distance dispersal across the northern Rocky Mountains (Chen and Walton, 2011; de la Giroday et al., 2012). The Southeast region is within the BC southern interior mountains and remains at a relatively lower infestation level during the current outbreak (Chen, 2014).

We downscaled the maximum daily temperature (Tmax) of two meteorological datasets (North American Regional Reanalysis, NARR, and BC Variable Infiltration Capacity Gridded Meteorological Data, VIC) into a grid of 658,399 cells (1200 × 1200 m) that cover the province of BC (Fig. 1) using an elevation correction approach described in detail by Chen and Jackson (2014). We defined an optimum heating cycle (OHC) as a temporal window of at least three consecutive days with the Tmax between 24 °C and 30 °C, which has been demonstrated as a valid surrogate for defining a window of potential mountain pine beetle emergence (Chen and Jackson, 2014). The OHCs were mapped spatially and temporally across the province only for two summer months (July and August), which is the major mountain pine beetle emergence period in a year (Safranyik and Carroll, 2006), and over two periods (1977–1987 and 1999–2010), which covers the outbreaks in the 1980s and recently (Chen, 2014). NARR is a long-term, consistent, high resolution (32 km horizontal) and frequency (8 times daily data) 3-dimensional meteorological dataset for the North American domain, covering the period from 1979 to present (Mesinger et al., 2006). VIC is a gridded meteorological dataset for BC, which was interpolated from weather station data and covers the period 1950–2006 at a spatial resolution of 0.0625° or approximately 28–32 km (dependent on latitude). In this study, VIC covers the periods 1977–1987 and 1999–2006 excluding 2004 due to poor data coverage while NARR covers the period 1999–2010.

We used the BC annual aerial overview survey data from 1960 to 2010 to estimate pine mortality caused by mountain pine beetle. The survey data were integrated into the grid using an area-weighted average approach (Chen and Walton, 2011). We used the BC Terrain Resource Information Management (TRIM) Digital Elevation Model (DEM) with a resolution of 25 m to downscale NARR and VIC and to derive landform types using the Topographic Position Index (TPI) (Jenness, 2006) (see Supplementary Material A). We used the ClimateWNA data (http://climatewna.com) (Wang et al., 2012) to derive the mean daily average temperature (Tave) and mean daily maximum temperature (Tmax) in July and August for a comparison between 1977–1987 and 1999–2010 (Fig. G.1). We used the provincial inventory data compiled from the BC land resource data warehouse (http://archive.ilmb.gov.bc.ca/lrdw) to define mature pine stands (i.e., cells with pines older than 60 years).

### 2.2. Spatiotemporal pattern analysis of OHCs and statistical analysis

For the spatiotemporal pattern analysis of OHCs, we derived four key OHC variables at each cell of the grid and the frequency distribution of OHCs across multiple cells of the grid over two summer months of a specific year (Fig. 1). The four key OHC variables include (1) the cumulative days of OHCs (CUD), (2) the number of OHCs (NHC), (3) the start date, i.e., the earliest date that OHCs start (HSD), and (4) the end date, i.e., the latest date that OHCs end (HED). The frequency distribution of OHCs represents the total number of the OHC cells over a specific area across each single day of two summer months for a specific year. In the analysis, we combined the key variables and frequency distributions of OHCs derived from both NARR and VIC for the overlapping years between NARR and VIC (1999–2006, excluding 2004).

The patterns of the two key OHC variables, HSD and HED, will reflect the temporal synchrony of potential beetle emergence (i.e.,