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Spatiotemporal mapping of potential mountain pine beetle emergence – Is a heating cycle a valid surrogate for potential beetle emergence?

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ABSTRACT

The mountain pine beetle emergence is temperature dependent. We hypothesize that heating cycles defined and determined by summer (July and August) daily temperature series represent reliable windows for potential beetle emergence. In this study, we first downscaled two coarse resolution meteorological datasets (the North American Regional Reanalysis data and provincial gridded climate data) using an elevation correction approach. We mapped heating cycles spatially and temporally across the province using the maximum daily temperatures derived from the downscaled meteorological data. The mean absolute errors (MAEs) and mean bias errors (MBEs) in the downscaled maximum daily temperature based on 30 weather stations reveal that the elevation-based downscaling approach is effective and the average errors do not significantly affect the spatial and temporal patterns of heating cycles in terms of the four key variables and frequency distributions of heating cycles. The temporal patterns of heating cycles for most of the monitoring years sufficiently capture the major emergence peaks observed at 16 monitoring sites. Therefore, the hypothesis above is valid and potential beetle emergence can be spatially and temporally mapped using heating cycles at the landscape scale.

1. Introduction

The current outbreak of mountain pine beetle *Dendroctonus ponderosae* Hopkins in British Columbia (BC) is unprecedented in recorded history (Chen, 2014). A warming climate has been a key factor contributing to the outbreak (Carroll et al., 2004). The recent IPCC report (IPCC, 2013) reconfirms that climate warming is unequivocal and will continue beyond the twenty-first century. The continuing warming climate in western North America has been predicted to increase the climate suitability of mountain pine beetle habitat (Bentz et al., 2010; Safranyik et al., 2010), leading to a successful establishment of beetle populations in the boreal forest of northern Alberta with the new host, jack pine (*Pinus banksiana*), a dominant species in the boreal forest of Canada (Cullingham et al., 2011). This imposes an increasing likelihood that mountain pine beetle may eventually expand eastward across the entire boreal forest of Canada (Safranyik et al., 2010; Nealis and Cooke, 2014).

Mountain pine beetle is poikilothermic and its life cycle is under direct control of temperature (Bentz et al., 2010; Régnière and Powell, 2013). Therefore, mountain pine beetle needs to maintain an appropriate emergence time in a year (seasonality) to synchronize key development stages and to avoid lethal temperatures. It also needs to synchronize emergence timing (synchrony) to achieve successful pheromone-mediated mass attacks. Both seasonality and synchrony are closely related to beetle emergence and they are strictly temperature dependent (Logan and Bentz, 1999; Logan and Powell, 2001).

Emergence, the beginning of the 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 (Safranyik and Carroll, 2006). Ambient temperature is most likely a critical determinant to initiate beetle emergence and affect how long emergence could persist. The rate of beetle emergence is closely related to ambient temperatures with a peak emergence occurring around 24 °C within an optimum range of 22–32 °C (Fig. 7 in Safranyik and Carroll, 2006).

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In western North America, the patterns and timing of beetle emergence have been observed through field monitoring studies at the local scale (Reid, 1962; Safranyik and Linton, 1993; Lindgren, 1993; Safranyik et al., 2000; Bentz, 2006). To our knowledge, the spatiotemporal patterns of beetle emergence have rarely been studied at the landscape scale due to the cost of intensive field work. The motivation of this study is twofold. First, this study is a part of mountain pine beetle long-distance dispersal research. Determining the synoptic weather conditions related to the beetle long-distance dispersal at the landscape scale requires a spatiotemporal mapping of beetle emergence across the landscape (Jackson and Murphy, 2004) because emergence varies spatially and temporally (Safranyik and Carroll, 2006). Because of the lack of emergence data, Jackson and Murphy (2004) first proposed the "heating cycle" as a surrogate of emergence. They defined a heating cycle as a potential emergence window where the maximum daily temperature (TMAX) should be over 20 °C but less than 30 °C over at least four consecutive days. The concept of the heating cycle is based on the fact that emergence is temperature dependent (Fig. 7 in Safranyik and Carroll, 2006). It also relies on the field observations that beetles were most likely to emerge after experiencing warm and dry weather (Safranyik and Carroll, 2006) with emergence peaking when the mean daily temperature remained above 20 °C for at least three consecutive days (Safranyik and Linton, 1993). The key hypothesis is that a heating cycle defined by an ambient air temperature time series represents a reliable window for the potential beetle emergence. However, this hypothesis has yet to be verified. Second, in the context of continuous climate warming, the landscape-level spatiotemporal patterns of beetle emergence not only better inform the appropriate timing of mitigation and management strategies (Gaylord et al., 2008) but also facilitate the prediction of beetle outbreak at broader scales.

Two phenological process models have been developed to predict the adaptive seasonality (Logan and Bentz, 1999; Logan and Powell, 2001; Powell and Logan, 2005) and cold tolerance (Régnière and Bentz, 2007) of mountain pine beetle. The adaptive seasonality model has been applied to 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 the adaptive seasonality model predicts the median emergence date of eggs laid on a given date with a G-function based on temperature-driven development rate functions throughout the various stages of the beetle life cycle, it does not attempt to map the spatiotemporal patterns of beetle emergence across the landscape except for landscape-level adaptive seasonality in the western United States (Hicke et al., 2006). The adaptive seasonality model is based on the fixed thermal response functions of mountain pine beetle throughout its life cycle (Logan and Powell, 2001), which are originally derived from studies conducted in the United States (Bentz et al., 1991; Régnière et al., 2012) and are not easily available for other bark beetle species (Fuentealba et al., 2013). Some studies (Bentz et al., 2001, 2011, 2014) have suggested that there are variations in the development time of mountain pine beetle across the phenotypes. Although these variations in the development time have been incorporated into a phenotype-dependent advection model (Yurk and Powell, 2010) or could be handled with either individual-based or cohort-based phenology models (Régnière and Powell, 2013), these refined modeling approaches have yet been applied in mapping the landscape-level emergence patterns of mountain pine beetle and in evaluating the impacts of climate change on beetle infestations.

The objectives of this study are: (1) to evaluate the two downscaled meteorological datasets (North American Regional Reanalysis, NARR and BC Variable Infiltration Capacity Gridded Meteorological Data, VIC) for mapping heating cycles at the landscape scale using the Canada Reference Climate Stations (RCS) and Adjusted Historical Canadian Climate Database Stations (AHCCD) data, and (2) to assess the fundamental hypothesis behind the heating cycle using field emergence data. The goal of this study is to establish a solid basis to efficiently and effectively map the spatiotemporal patterns of potential beetle emergence at the landscape scale using heating cycles.

2. Materials and methods

2.1. Study area and data

Most beetles emerge in July and August (Safranyik and Carroll, 2006). Therefore, we mapped the spatiotemporal patterns of heating cycles using the daily TMAXs extracted and downscaled from two meteorological datasets, NARR and VIC (discussed in the next section), over the entire province of BC during these two summer months for two periods (1977–1987 and 1999–2010) covering the outbreaks in the 1980s and recently (Chen, 2014). A grid of 658,399 cells with a spacing of 1200 m (144 ha per cell) was used for mapping the heating cycles across the province (Fig. 1). We defined two types of heating cycle based on the frequency distribution of emergence in relation to temperature (Fig. 7 in Safranyik and Carroll, 2006), fair heating cycle (FHC) and optimum heating cycle (OHC). The FHC is a heating cycle of at least three consecutive days with the TMAX between 20 °C and 32 °C, while the OHC is a heating cycle of at least three consecutive days with the TMAX between 24 °C and 30 °C.

For NARR, the 2 m surface temperature at the Universal Coordinated Time (UTC) 00 (5 pm local Pacific Daylight Time, PDT) was used as the daily TMAX since it is at or close to the time of day when the TMAX normally occurs and is a standard meteorological reporting time that is available in the NARR dataset. The 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. It is produced by the US National Centers for Environmental Prediction (NCEP) and covers the period from 1979 to present. Using an atmospheric model, it assimilates high-quality and detailed meteorological observations into the atmospheric analysis (Mesinger et al., 2006). The VIC is a gridded meteorological dataset for BC. It is produced by the Pacific Climate Impacts Consortium (PCIC) (www.pacificclimate.org) for the BC Variable Infiltration Capacity (VIC) hydrological modeling project. The VIC covers the period of 1950–2006 at a spatial resolution of 0.0625 degree or approximately 28–32 km (dependent on latitude). It provides four daily climate variables near the surface: maximum and minimum temperatures, precipitation, and wind speed. The temperatures of VIC were interpolated from weather station data using the Symap algorithm (Shepard, 1984) and corrected for temporal biases caused by inhomogeneities in the station assemblages (Bennett et al., 2012). In this study, VIC covers the periods of 1977–1987 and 1999–2006 excluding 2004 due to poor data coverage while NARR covers the period of 1999–2010.

We used 29 RCS and one AHCCD weather station data to verify or compare the TMAXs and to assess the heating cycles (FHC and OHC) derived from the downscaled NARR and VIC data. The VIC is produced by interpolating weather station data and the stations used to create the VIC dataset are likely to include the ones that we use to evaluate the VIC dataset in this study. Therefore, the comparisons of TMAX between the VIC and weather station data are only to evaluate the errors resulting from the interpolation algorithms used for VIC and the downscaling method used in this study rather than to verify VIC, which would require an independent dataset. The verification stations were evenly chosen across the province (Fig. 2).

The BC Terrain Resource Information Management (TRIM) DEM with a resolution of 25 m was used in the downscaling of both