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Assessing forest vulnerability and the potential distribution of pine beetles under current and future climate scenarios in the Interior West of the US

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ABSTRACT

The aim of our study was to estimate forest vulnerability and potential distribution of three bark beetles (Curculionidae: Scolytinae) under current and projected climate conditions for 2020 and 2050. Our study focused on the mountain pine beetle (*Dendroctonus ponderosae*), western pine beetle (*Dendroctonus brevicomis*), and pine engraver (*Ips pini*). This study was conducted across eight states in the Interior West of the US covering approximately 2.2 million km^2 and encompassing about 95% of the Rocky Mountains in the contiguous US. Our analyses relied on aerial surveys of bark beetle outbreaks that occurred between 1991 and 2008. Occurrence points for each species were generated within polygons created from the aerial surveys. Current and projected climate scenarios were acquired from the WorldClim database and represented by 19 bioclimatic variables. We used Maxent modeling technique fit with occurrence points and current climate data to model potential beetle distributions and forest vulnerability. Three available climate models, each having two emission scenarios, were modeled independently and results averaged to produce two predictions for 2020 and two predictions for 2050 for each analysis. Environmental parameters defined by current climate models were then used to predict conditions under future climate scenarios, and changes in different species' ranges were calculated. Our results suggested that the potential distribution for bark beetles under current climate conditions is extensive, which coincides with infestation trends observed in the last decade. Our results predicted that suitable habitats for the mountain pine beetle and pine engraver beetle will stabilize or decrease under future climate conditions, while habitat for the western pine beetle will continue to increase over time. The greatest increase in habitat area was for the western pine beetle, where one climate model predicted a 27% increase by 2050. In contrast, the predicted habitat of the mountain pine beetle from another climate model suggested a decrease in habitat areas as great as 46% by 2050. Generally, 2020 and 2050 models that tested the three climate scenarios independently had similar trends, though one climate scenario for the western pine beetle produced contrasting results. Ranges for all three species of bark beetles shifted considerably geographically suggesting that some host species may become more vulnerable to beetle attack in the future, while others may have a reduced risk over time.

1. Introduction

Insect epidemics are sharply increasing in coniferous forests throughout North America causing dramatic impacts to ecosystem processes and disrupting forest-dependent economies. Insects and associated pathogens have resulted in extensive tree mortality that, in turn, has altered forest structure, composition, and function (Raffa et al., 2008). Bark beetles (Curculionidae: Scolytinae) have become especially detrimental to coniferous forests. Although most of North America's bark beetles are native and play an integral role in forest dynamics (Fleming et al., 2002; Sanchez-Martinez and Wagner, 2002), recent outbreaks are increasing in frequency, severity and extent (Westfall, 2006; Kurz et al., 2008; Raffa et al., 2008). Tree mortality from bark beetle infestations increased from 1.6 to 4 million ha in the US between 2002 and 2003, the largest annual increase recorded (WFLC, 2009). The extent of the infestation has remained high through the present, impacting approximately 3.6 million ha in 2008 (USDA, 2009). Increases in mountain pine beetle (*Dendroctonus ponderosae*) infestation have been especially noticeable. Between 1990 and 2001, mountain pine beetles infested less than 400,000 ha in the US; however, the extent of the infestation has steadily increased to more than 2.5 million ha by 2008 (USDA, 2009). Outbreaks of the mountain pine beetle have also been problematic in more northern latitudes and at higher elevations. In British Columbia, Canada, mountain

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pine beetles infested 164,000 ha in 1999; by 2004, the outbreak grew to 7 million ha (Ministry of Forests, 2005) and to 9.2 million ha by 2006 (Westfall, 2007). The northern range of mountain pine beetles has been historically limited by climate, as host species occur well beyond climatic thresholds (Carroll et al., 2004). Climate variability over the last few decades has been implicated as the primary cause of the recent expansion of outbreaks in the US and Canada (Hicke et al., 2006; Thomson, 2009). Similar trends have been observed with other herbivorous forest insects, such as the western pine beetle (*Dendroctonus brevicomis*), pine engravers (*Ips pini*) and spruce beetle (*Dendroctonus rufipennis*; Berg et al., 2006; USDA, 2009).

Bark beetles have evolved with native forest ecosystems and are important agents in maintaining host species composition, distribution patterns and mixed age-classes (Waring and Pitman, 1985; Oliver, 1995; Malmstrom and Raffa, 2000). Infestations have long been associated with forest stands that are stressed or dying and with host trees that have lower vigor and fewer defense mechanisms (Rudinsky, 1962; Anderson and Anderson, 1968; Berryman, 1972; Larsson et al., 1983; Klepzig et al., 1991; Reid and Robb, 1999). Other studies suggest that infestations are a function of more complex abiotic and biotic relationships between bark beetles and their hosts. These include reproductive and dispersal opportunities for bark beetles (Aukema et al., 2005; Roberston et al., 2009), transport and infection by fungi and other pathogens (Adams et al., 2008; Bleiker et al., 2009), predation and competition of bark beetles (Berryman et al., 1987; Schlyter and Anderbrant, 1993), fire (Breece et al., 2008; Fettig et al., 2008), and management practices (Waring and Pitman, 1985; Hayes et al., 2008). Although the results of these studies help us better understand local dynamics between bark beetles and their hosts, they are difficult to apply across large spatial or temporal scales.

Alternatively, life cycles of bark beetles are known to be regulated by climate, which can be useful for predicting population dynamics and potential risk across large landscapes and time spans. Climate, particularly seasonal temperatures, may affect bark beetles during multiple stages of their life cycles. For example, several studies on Ips engravers (*Ips* spp.) have demonstrated that colder temperatures disrupt egg development (Jonsson et al., 2009) and synchronized flight activities (Aukema et al., 2005), while extended winters reduce the number of successful broods in a given year (Anderbrant, 1989). Similar studies on mountain pine beetles have found that cold temperatures cause significant mortality for emerging adults in the spring (Amman, 1973) and late larval stages in early fall and late winter (Carrol and Safranyik, 2004). Climate also affects host susceptibility by reducing tree vigor and defense mechanisms creating a more favorable environment for beetle development (Mattson and Haack, 1987; Negron et al., 2009). Healthy trees can often repel bark beetle attacks by producing a protective resin; however, under drought conditions, trees may not be capable of producing enough resin to resist attacks (Smith, 1963; Raffa and Berryman, 1987). Host trees can also be weakened by other disturbances that are correlated with climate, such as fire (McHugh et al., 2003), excessive moisture (Kalkstein, 1976), lightning (Anderson and Anderson, 1968), ice (Smith, 2000) and other pathogens (Klepzig et al., 2001).

Given the projected short- and long-term changes of global climate, the range of bark beetles and the severity of outbreaks will continue to be modified. The ability to predict spatial and temporal shifts of potential bark beetle habitats, and the mechanisms that drive outbreaks, is critical for assessing risk and developing adaptive management strategies that reduce negative impacts. As previously described, local dynamics between bark beetles and their hosts can be extremely variable; and they tend to be poor predictors across large spatial or temporal scales. Climate is being increasingly used with ecological niche models to spatially define a species' range or potential distribution. These methods have been successfully applied to wildlife (Evangelista et al., 2008; Boubli and de Lima, 2009), plants (Pearson et al., 2004; Hijmans and Graham, 2006; Kumar and Stohlgren, 2009), invasive species (Jarnevich and Stohlgren, 2009; Kumar et al., 2009), pathogens (Holt et al., 2009), and insects (Peterson and Nakazawa, 2007). With the availability of future climate scenarios, similar methods can be used to predict a species' range over time (Pearson et al., 2004; Holt et al., 2009; Jarnevich and Stohlgren, 2009). Our objective was to test 19 bioclimatic variables with Maxent modeling methods to predict the potential distribution of the mountain pine beetle, western pine beetle and pine engraver beetles under current climate conditions. Results from each analysis defined the current climate parameters for each species, and they provided a preliminary estimate of potential insect distributions under future climate scenarios.

2. Methods

2.1. Study area

Our study area encompassed the Interior West of the US which is commonly defined by eight states: New Mexico, Arizona, Colorado, Utah, Nevada, Idaho, Wyoming and Montana. These states include approximately 95% of the Rocky Mountains in the contiguous US. The study area covers approximately 2.2 million km^2 with elevations ranging from 25 to 4,280 m a.s.l. The majority of the montane and subalpine forests are dominated by coniferous species, composed largely of ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), whitebark pine (*Pinus albicaulis*), subalpine fir (*Abies lasiocarpa*), and Englemann spruce (*Picea engelmannii*). Eastern margins of the study area are predominantly grasslands of the Great Plains, while the Southwest is generally dominated by semi-arid shrubs, pinyon pine (*Pinus edulis*), and juniper (*Juniperus* spp.) woodlands. Climate throughout the Interior West varies regionally. Generally, southern latitudes are warmer and drier, while northern latitudes are cooler and wetter.

The US Forest Service manages a significant proportion of the forests of the Interior West. Within our study area, the agency conducts operations under four regional administrative units. The Northern Region (Region 1) includes Montana and northern Idaho. The Rocky Mountain Region (Region 2) includes Colorado and most of Wyoming. The Southwestern Region (Region 3) encompasses New Mexico and Arizona. Finally, the Intermountain West (Region 4) covers Utah, Nevada, southern Idaho and the western margins of Wyoming (see http://www.fs.fed.us/contactus/regions.shtml).

2.2. Bark beetle occurrence data

Our analyses relied on aerial surveys conducted by the US Forest Service's Forest Health Protection Aviation Program. Polygons of infested areas were acquired between 2000 and 2008 for Region 1 (www.fs.fed.us/r1-r4/spf/fhp/aerial/gisdata.html); between 1994 and 2007 for Region 2 (www.fs.fed.us/r2/resources/fhm/aerialsurvey/); between 1998 and 2008 for Region 3 (www.fs.fed.us/r3/gis/nm_data.shtml); and between 1991 and 2007 for Region 4 (www.fs.fed.us/r1-r4/spf/fhp/aerial/gisdata.html). Data were not available for Arizona at the time of this study. Polygon data representing infestations were converted to 1 km^2 grids using ArcGIS (version 9.2; ESRI, Redlands, CA, USA). Occurrence points for infestations of each bark beetle were derived by calculating the centroid of each 1 km^2 cell. To reduce spatial autocorrelation effects (Veloz, 2009), we buffered occurrence points by three cells (3×3 km^2), removing adjacent occurrence points. We generated minimum