Forest Ecology and Management 399 (2017) 166–178

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Analysis and out-year forecast of beetle, borer, and drought-induced tree mortality in California

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ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 11 May 2017
Accepted 22 May 2017

Keywords:
Bark beetle outbreak
Drought
Fuels reduction
Forest planning
Generalized additive models
Predictive tool

ABSTRACT

The level of tree mortality and drought observed over the past decade in North America has been described as 'unparalleled' in our modern history, in particular in the Sierra Nevada, California. Forest managers could use early warning of where and how much tree mortality to expect in the very near future to plan and prioritize hazard tree removal, pest suppression activities, infer location of funding needs and fuels reduction treatments as well as access for firefighting. To answer these needs, we developed an empirically-based forecast model for expected tree mortality for an upcoming year based on (1) previous years' tree mortality as observed in late summer; (2) previous years' hydrologic year precipitation levels; and (3) site characteristics including amount of available host. Using this approach, initial forecasts for the next growing season can be developed by late fall for the following late summer. We demonstrated the application of this model by developing a forecast for the state of California for 2017. The explanatory variables in the California model accounted for ~43% of the variability in tree mortality. Overall, the model missed forecasting high levels of mortality in approximately 5% of forested or woodland locations for the state of California. Locations with more mortality than expected in 2015 & 2016 were mostly associated with new outbreaks of insects; land use changes, and margins of prescribed- or wildfires not initially attributed. The forecasts may also be useful to natural resource and land managers in locating new outbreaks that may be attributed to novel behavior or exotic insects.

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1. Introduction

Bark beetle and other insect outbreaks have been common, temporally syncopated, and regionally extensive over the last century as recorded by forest entomologists (Grulke et al., 2009). However, larger-than-expected outbreaks with high tree mortality have appeared globally in the late 20th century and into the 21st century (Allen et al., 2010). Extensive tree mortality has been associated with greater wildfire risk (Hicke et al., 2012).

Among bark beetles and wood borers, higher than average winter minimum temperatures, longer summers with higher average temperatures, and drought are correlated with bark beetle outbreaks (Régnière et al., 2012). Higher winter temperatures, and longer growing seasons are expected to become increasingly common into the future (IPCC, 2014): these may act as antecedent drivers and intensifiers of insect population growth in some cases. Drought-induced tree mortality may also intensify, but its location, severity, frequency, and longevity in an upcoming year is more difficult to accurately predict. Multiple-year droughts can significantly increase the level of tree mortality due to accelerated increase in bark beetle populations (Buotte et al., 2016; Preisler et al., 2012; Grulke et al., 2009).

Although empirical data on inciting factors of outbreaks are available for model parameterization (Bentz et al., 2010 and references within), relatively few insect species have been adequately characterized. Empirical relationships between environmental drivers and insect demographics are needed to parameterize dynamic vegetation models, which translate analog changes in environment into changes in vegetation assemblages through the end of the century. Analog vegetation models (in contrast to state-and-transition vegetation models) permit modeling well into the future, and at the landscape level. Others (Young et al., 2017; Seidl et al., 2015) have identified attributes to explain tree mortality at the landscape level, but not to forecast mortality (within- year, and following

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http://dx.doi.org/10.1016/j.foreco.2017.05.039
0378-1127/Published by Elsevier B.V.

year). The most extensive collection of insect responses to the environment and demographic consequences has been developed by entomologists of the USFS Forest Health Protection program (and academics), and assembled by the USFS Forest Health Assessment and Applied Sciences Team (FHAAST, previously known as FHTET; Krist et al., 2010). However, the current level of insect outbreaks and tree mortality observed in British Columbia (Cudmore et al., 2010), in the northern Rocky Mountains (Meddens and Hicke, 2014), and in the Sierra Nevada, CA (Young et al., 2017) are outside the range of values observed at these locations in the recent past. Furthermore, wood or fir borers, often thought to be secondary invaders, can be primary causes of tree mortality (California Forest Pest Council, 2016; flat headed fir borer in Douglas fir, Bill Schaup, pers. comm.; and California flat-headed borer in Jeffrey pine, Nancy Grulke, pers. obs.). There is no, or little, empirical data with which to develop demographic models for the wood borers, as well as other insects with a similar potential in the future. These data take decades to collect. Demographics of yet-to-invade exotic species are particularly difficult to anticipate, yet potential functional types are being identified and anticipated by the Animal and Plant Health Inspection Service (APHIS) and others.

High levels of tree mortality may increase the probability for severe wildfires depending on when fire initiation occurs, relative to dead needle and fine branch retention (Hicke et al., 2012). Forest managers could use forecasts of tree mortality for the following year (current year +1) to anticipate and prioritize hazard tree removal, pest suppression activities, infer location of funding needs and fuels reduction activities and firefighter access to high risk locations.

The concern of the present study is to develop statistical forecasts of combined bark beetle, wood borer, or drought attributed tree mortality (hence forth referred to as BB-WB-D mortality) using prior years observations of the levels and locations of mortalities, availability of host, and environmental conditions known to be inciting factors for that insect guild. The intent of the present work was not to find the best drivers of successful insect attacks, but simply to best forecast the following year location and expected magnitude and range of tree mortality. Only variables that were and are available at least one year ahead of the forecast were used in the forecast models. Given the extreme skewness of the distribution of the variable of concern (number of trees killed per pixel), the level of uncertainty in our forecasts were based on empirical distributions of the data and, consequently, avoid the need for making parametric distributional assumptions.

2. Methods

2.1. Data

Aerial Detection Survey data (ADS) in USDA Forest Service Region 5 (California) and adjacent areas of Region 4 (western Nevada) from the 1993 to 2016 surveys were aggregated to 2.5 min cells (cells roughly four km in width or 1800 hectares in area). ADS collects data on tree mortality using aircraft flying approximately 150–450 m in altitude (Young et al., 2017). Information collected annually includes location, number of affected trees or number of trees per hectare (from 2004 to 2016 only), the likely damage agent, and host tree species. This data was collected on paper maps prior to 2001, and on a georeferenced moving map display on a tablet computer starting in 2001. For this analysis, total hectares with BB-WB-D mortality (regardless of intensity of mortality), were calculated from 1993 to 2016 for each cell, and the total number of trees killed by BB-WB-D, were calculated from 2004 to 2016 for each cell. Cells that were not flown in a given year were assigned a missing value for that year.

Variables pertaining to site characteristics, in addition to those pertaining to weather and 'beetle pressure' are listed in Table 1. Because beetle pressure was not observed directly, we used number of trees killed, or alternatively, area affected with mortality, as a surrogate for beetle pressure. The number of hectares with tree hosts were derived from tree species distribution layers developed by FHAAST (Krist et al., 2010). The datasets were modeled from ground plot data measured by Forest Inventory and Analysis (FIA, Gillespie, 1999) and from predictor datasets consisting of climate, terrain, soils, and satellite imagery (Ellenwood et al., 2015). Area containing host (pooled, regardless of tree species, stand density or basal area) that were affected by BB-WB-D were calculated for each cell. Host tree distributions included ponderosa, Jeffrey, Coulter, Bishop, Monterey, knobcone, sugar, lodgepole, western white, whitebark, limber and pinyon pines; white, grand, red and subalpine fir; and Douglas-fir and big cone Douglas-fir. Area affected by fire in each cell was obtained from CalFire (Table 1). As an estimate of amount of host remaining we used the variable, number of hectares with host minus number of hectares with mortality previous year.

Table 1
List of variables used in predictive models. All variables are at the 2.5′ (1800 ha) grid level.

Variable related to	Units	Source	Description
Site characteristics			
Host	ha	USFS FHTET	Total area with any amount of host (pine, fir, Douglas-fir) present, per cell. Based from data collected 2002–2009
36 year average precipitation	mm	PRISM	Average annual precipitation over years 1981–2016
Cell location	Degrees	ArcMap	Latitude, Longitude
Fire history	ha	CalFire	Area burned each year per cell, 1993–2015
Bark Beetle Attack History			
Area with mortality within cell	ha	USFS FHP	Area with any amount of BB-WB-D mortality within each cell per year, from aerial surveys 1993–2016
Maximum area affected in adjacent cells	ha	USFS FHP	Area with BB-WB-D mortality from one of the eight neighboring cells that has the highest value in that category
Number of trees killed	Number	USFS FHP	Total number of newly killed trees mapped each year from 2004 – 2016 from aerial surveys per cell
Weather History			
Precipitation previous year	mm	PRISM	Total precipitation per year, between Oct 1 of previous year to Sept 31 of current year
Precipitation 2–4 years ago	mm	PRISM	Total precipitation per year, between Oct 1 to Sept 31for previous 2–4 years
Minimum winter temperature	C	PRISM	Lowest daily minimum temperature occurring from December through February of the following year

USFS FHTET – US Forest Service Forest Health Technology Enterprise Team.
USFS FHP – US Forest Service Forest Health Protection.
CalFire – http://www.fire.ca.gov/.
PRISM – PRISM Climate Group, Oregon State University.