

Probabilistic Risk Models for Multiple Disturbances: An Example of Forest Insects and Wildfires

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Abstract

Building probabilistic risk models for highly random forest disturbances like wildfire and forest insect outbreaks is a challenging. Modeling the interactions among natural disturbances is even more difficult. In the case of wildfire and forest insects, we looked at the probability of a large fire given an insect outbreak and also the incidence of insect outbreaks following wildfire. We developed and used a probabilistic model framework for estimating (1) the probability that a wildfire, at a given location and time, reaches a given size class under the conditions at the site—including history of insect outbreaks; and (2) the probability of an insect infestation at a given location and year under the conditions at the site—including history of fire occurrence and size. The study used historical data (1980 through 2004) on fire occurrence and forest insect outbreaks collected in Oregon and Washington. Spatial data on insect activity was obtained from aerial sketch maps created by the Forest Service Forest Health Protection program. Federal wildfire data obtained from the Desert Research Institute included information on the date, location, and size of the fire. Average monthly temperature and Palmer Drought Severity Indices were obtained from the National Climatic Data Center's climate division data set Web page. The methods employed provide an objective tool for modeling complex hybrid processes and estimating associated probability maps.

Keywords: Forest threats, multinomial regression, multiple stressors, nonparametric regression, spatial regression, spline functions.

Introduction

Wildfire and insect infestations are two major disturbances of forest lands in the United States. Historically, insect infestations and wildfires have had a dominant influence on successional processes in forests of the Western United States (Agee 2003). Fire suppression over the past 100 years has resulted in larger, more severe wildfires and insect outbreaks (Hessburg and others 1994). In 2005, over 0.14 million hectares (0.34 million ac) of Federal lands in Oregon and Washington were affected by wildfires (<http://www.nifc.gov>) and approximately 0.8 million hectares (2.1 million acres) sustained damage from insects such as bark beetles and defoliators (<http://www.fs.fed.us/r6/nr/fid>). In response to concerns over the size and severity of wildfires and insect outbreaks, Federal land management agencies have adopted forest management strategies that call for restoration activities that include reintroduction of natural and prescribed fire over wide areas of the Western United States. These activities have demonstrated beneficial effects in terms of moderating wildfire, but the potential effects on insect dynamics and insect-caused tree mortality are less clear.

A reciprocal and synergistic association has frequently been described between fire and insects. For example, tree mortality resulting from insect outbreaks has been seen as setting the stage for subsequent wildfires (Geiszler and others 1980, Parker and Stipe 1993). Conversely, wounding and mortality from fire can create focus trees, which act as magnets for bark beetles (McCullough and others 1998). In separate studies, McHugh and others (2003) and Cunningham and others (2005) followed tree mortality and beetle attacks for 3 years after wildfire and found bark beetles more likely to attack trees with fire injury. Similar results were found following prescribed fire (Bradley and Tueller 2001, Wallin and others 2003). However, others have found that beetles did not preferentially attack trees with fire-injured boles, but attack success was higher in injured trees when beetle population levels were low (Elkin and Reid 2004). Additionally, Sanchez-Martinez and Wagner (2002)

found low population levels of bark beetles regardless of stand treatment history, including stand replacement by wildfire. These results confirm that the association between insects and fire is a complex one, particularly when evaluated over time and at a large scale.

Numerous studies have begun to examine functional and numerical interactions between insects and fire at the tree and stand level, but few quantitative studies have been carried out that consider the spatiotemporal dynamics of wildfire and insect outbreaks at the landscape scale (Barclay and others 2005, Bebi and others 2003, Fleming and others 2002, Kulakowski and others 2003, Lynch and Moorcroft 2004, Veblen and others 1991). Existing analytical techniques for spatiotemporal analysis of multiple interacting disturbances are not well developed, and large-scale data sets suitable for studying interactions are few (Lynch and Moorcroft 2004).

The present study describes a framework for estimating probabilities, at a landscape level, of various forest disturbances as a tool for quantifying associations between multiple interacting disturbances. The framework builds on related work by the authors and collaborators on estimating wildfire probabilities in relation to weather and fire danger indices and spatial location (Brillinger and others 2003, Preisler and Westerling 2007, Preisler and others 2004).

Methods

Data

Our study area was Oregon and Washington national forest lands. We obtained historical Federal wildfire occurrence data (1980 through 2004) from Desert Research Institute (DRI), <http://www.dri.edu>. The DRI fire occurrence data are based on the National Interagency Fire Management Integrated Database (NIFMID) at the USDA Forest Service National Information Technology Center in Kansas City, Missouri. The data included information on the date, location, and size of the fire. The DRI version of the data had been subjected to a quality-control procedure in which each fire-occurrence record was flagged as usable or otherwise (Brown and others 2002). Fire locations are the latitude and longitude of the fire when first discovered.

We obtained average monthly temperature and Palmer Drought Severity Indices (PDSI) from U.S. Climate Divisions (NCDC 1994). The values at the climate-division level were projected onto a 1-km² grid to provide a monthly climate record for each grid cell. Variables at the climate division level may not be good estimates for local weather conditions, but they were used here to demonstrate how weather variables can be included in the model.

Spatial data on insect activity was obtained from aerial sketch maps created by the Forest Service Forest Health Protection program (<http://www.fs.fed.us/r6/nr/fid>). In particular, we obtained data on (1) total number of trees (lodgepole pine, *Pinus contorta* (Dougl. ex Loud.), and ponderosa pine, *P. ponderosa* (Dougl. ex Laws.) killed by two bark beetle species (mountain pine beetle, *Dendroctonus ponderosae* Hopkins, and western pine beetle, *D. brevicornis* LeConte) per year (1980 through 2004) in each square milometer grid of Forest Service lands (Region 6); and (2) total area defoliated by western spruce budworm (*Choristoneura occidentalis* Freeman) in each square kilometer of Forest Service land per year.

In this study we did not use information on fire boundary. Consequently, the models described below are used for estimating associations between histories of fire sizes and insect infestations within 1 km of each other. Additional predictors (e.g., distance to nearest infestation or fire) may improve estimation results. In this study, we are mainly concerned with describing the statistical framework given a set of predictors.

Probability Framework

We are interested in obtaining estimates of disturbance probabilities in the presence of multiple stressors. For example, we would like to quantify:

Prob {damage from disturbance 1 given the size of damage from disturbance 2 and values of other predictors}

Two specific disturbances, bark beetle infestation and fire size, were analyzed in the present case study. Fires of all sizes were used in the analysis.

Bark Beetle Infestation—

Let Y be a random variable such that $Y_i = 1$ if an infestation is present in a square kilometer grid at location $(utmxi, utmyi)$ and year yr_i and $Y_i = 0$ otherwise. The random variable Y is assumed to follow a Bernoulli distribution with probability of response

$$\pi_i = \Pr[Y_i = 1 | \mathbf{X}_i] = e^{\theta(\mathbf{X}_i)} / [1 + e^{\theta(\mathbf{X}_i)}] \quad [1]$$

where $\theta(\mathbf{X}_i) = \beta_0 + g(utmxi_i, utmy_i) + \sum g_k(X_{ik})$

and where the matrix $\mathbf{X}$ of predictors includes history of fire and insect infestation in previous years and within 1 km of infestation. The functions $g_k(X_k)$ in equation [1] are transformations of the variable X_k using linear-basis splines (Hastie and others 2001). For the spatial component, $g(utmxi, utmy)$, we utilized the two-dimensional version of the basis function, specifically, the thin plate spline function. All estimations were done within the statistical package R (R Development Core Team 2004). The required modules for fitting thin plate splines within R were downloaded from the Web (Geophysical Statistics Project 2002). By including variables such as location and history of insect infestation in the model, we were able to study the effect of fire (occurrence and size), on the probability of an infestation, in the presence of confounding factors (e.g., presence of infestations in previous years). The spatial component in the model can be viewed as a surrogate for other predictors (e.g., elevation, fuel type, and other variables) that do not change substantially over time and are not part of the model for a variety of reasons (Hobert and others 1997). Because the number of cells with no insect damage was very large (2.4 million), only a random sample of insect-free locations was included in the analysis. The final probabilities were then adjusted accordingly (Maddala 1992, Preisler and others 2004).

Results of fitting equation [1] were expressed as maps of estimated probabilities (and estimated standard errors) that are spatially explicit on 1-km² grid cells. The maps may be used to forecast probabilities of occurrence of an insect infestation for a succeeding year, given the history of fire and insect infestation up to that year. Outputs can be appraised directly by comparing observed frequencies of occurrences with predicted probabilities using cross-validation.

Using this model, we were able to quantify the interactions between different disturbances by studying the significance and shape of the relationships between the probability of an infestation and the occurrence and size of fire in previous years. In particular, we produced estimates of the odds of an infestation as a function of fire size relative to the odds when no fire is present. Odds were defined as $\pi/(1 - \pi)$, where π is the probability of a response of interest, in this case, bark beetle attack.

Fire Size

To study the association between insect disturbances and the risk of wildfire becoming large at a given location, we divided fires into three size classes. Consider the ordinal random variable Y where $Y_i = 1$ if a fire at location $(utmxi_i, utmy_i)$ and time t_i burns an area less than or equal to 1 ha; $Y_i = 2$ if area burned is 1100 ha; and $Y_i = 3$ if area burned is greater than 100 ha. Next, assume that the random variable, Y , follows a multinomial distribution with probability of response at level k ($k = 1, 2, 3$), given by $\pi_{ik} = \Pr[Y_i = k | \mathbf{X}]$ and $\pi_{i1} + \pi_{i2} + \pi_{i3} = 1$. The list of predictors, $\mathbf{X}$, included average monthly temperature and PDSI, size of bark beetle infestation (trees killed per square kilometer), and size of spruce budworm infestation (area defoliated per square kilometer) in the previous 6 years. We obtained estimates for π_{ik} by fitting a complementary log-log function to the conditional probabilities of response. Specifically, we used the model

$$p_{ik} = \Pr[Y_i = k | Y_i > k-1, \mathbf{X}_i] = 1 - \exp[-\exp[\beta_0 + g(utmxi_i, utmy_i) + \sum g_j(X_{ij})]] \quad [2]$$

where the functions $g(utmxi_i, utmy_i)$ and $g(X)$ are as defined in (“Bark Beetle Infestation”). We obtained estimates of the multinomial probabilities from the conditional probabilities using the relationships $\pi_{i1} = p_{i1}$; $\pi_{i2} = (1 - p_{i1})p_{i2}$; and $\pi_{i3} = (1 - p_{i1} - p_{i2})$. As in section (“Bark Beetle Infestation”) the model goodness-of-fit was appraised by comparing observed and predicted frequencies of fires in the three different size classes.

We produced maps of estimated probabilities displaying the spatial patterns of fires of different size classes. We also studied association between insect infestations and fire size by producing graphs of estimated odds of a fire of a

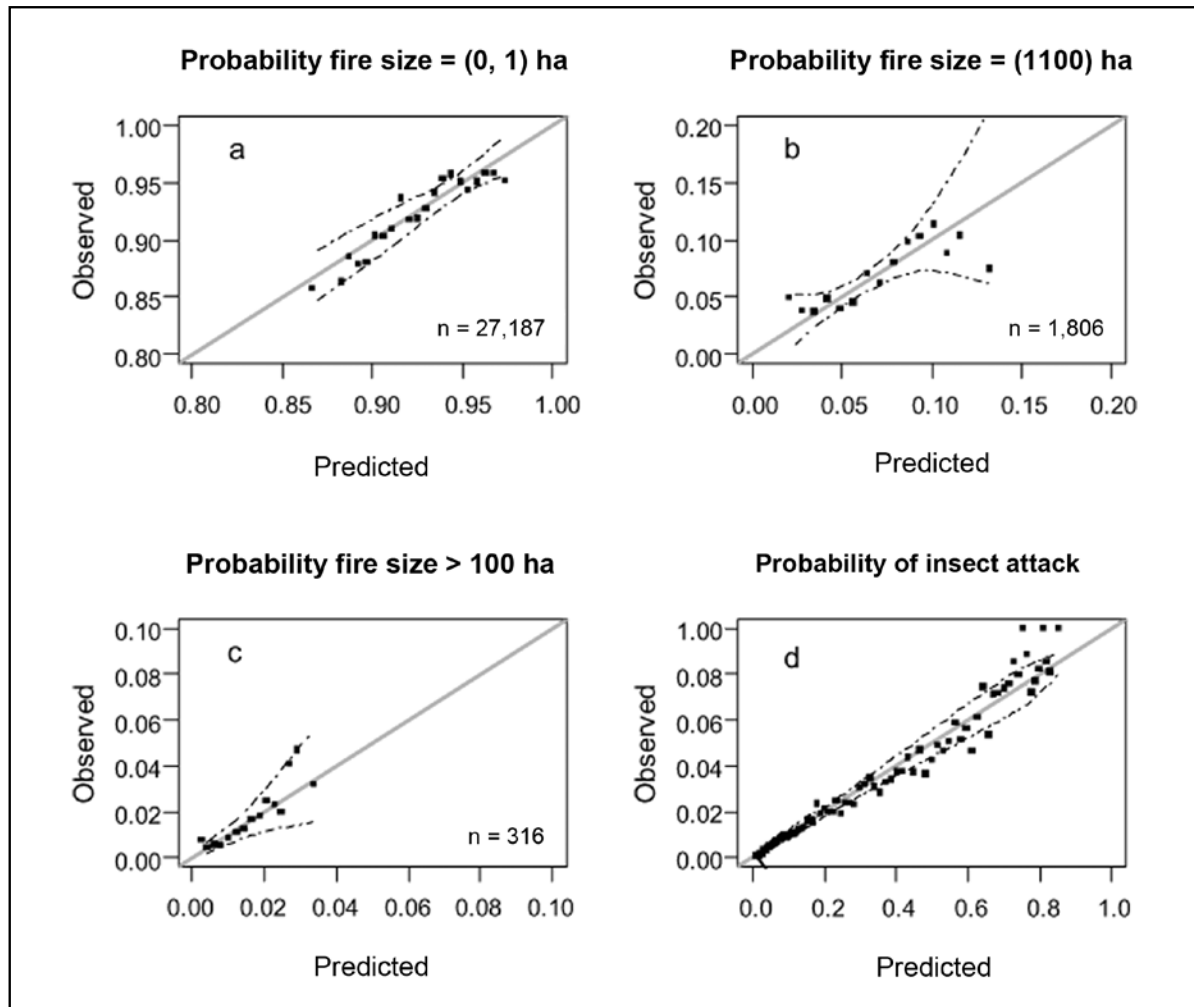


Figure 1—Observed versus predicted multinomial probabilities of a fire reaching size class (a) (0 to 1] ha, (b) (1 to 100] ha, (c) >100 ha. The value n in each panel is the total number of fires in the corresponding size class during the study period. (d) Observed versus predicted probability of a bark beetle occurrence in a given 1-km² grid cell.

given size class—plotted against infestation size—relative to the odds when no infestation is present.

Results and Discussion

The models in equations [1] and [2] appeared to give reasonable fits to 1982 to 2004 data on bark beetle attacks and wildfire sizes on Forest Service lands in Region 6 (Figure 1). For example, consider all cells over the years when the model in equation [1] predicted a 40-percent probability of a beetle attack (bottom right panel, Figure 1), the actual percentage of time an attack was observed was 37 percent, which is well within the 95-percent limits (36 to 40 percent) of the predicted probability.

Bark Beetle Infestation

The probability of beetle infestation was significantly influenced by spatial location, size of infestation in previous year, and size of 1-year-old fire within 1 km (P -value < 0.05). The estimated probabilities of bark beetle outbreaks, evaluated after controlling for all other significant predictors, demonstrated a spatial pattern with increasing probabilities of outbreak as one moves away from the coastal areas and into the eastern regions of Washington and Oregon (Figure 2). This pattern of declining forest health in the dry coniferous forests of eastern Oregon and Washington has been noted by others in recent assessments

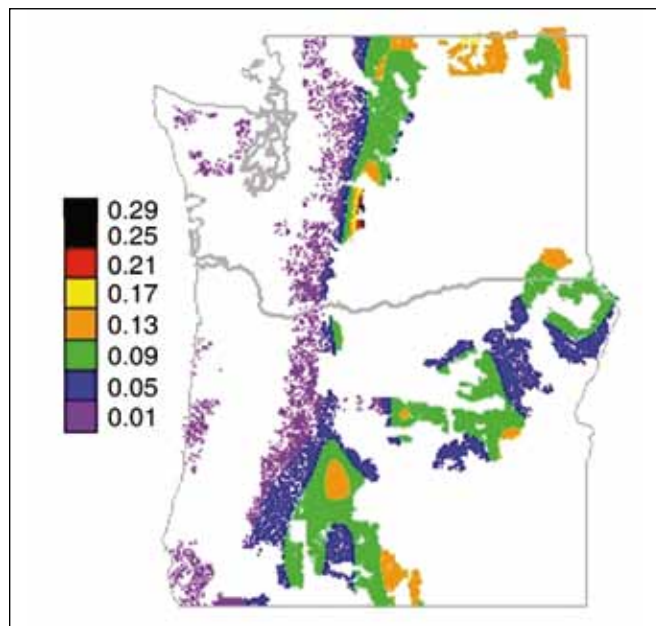


Figure 2—Estimated spatial pattern of beetle attacks on national forests in Washington and Oregon.

and syntheses (Gast and others 1991, Hayes and others 2001, Hessburg and others 1994, Jaindl and Quigley 1996).

One of the most important predictors when evaluating a bark beetle outbreak appears to be size of the beetle infestation in the previous year. The odds of a beetle outbreak seem to increase as the number of trees killed per square kilometer by bark beetles in the previous year increases (Figure 3). Although this outcome is probably expected, given the outbreak dynamics of insect populations in general (e.g., Barbosa and Schultz 1987), it is important to know that it was included in the model and, consequently, is accounted for in a reasonable fashion. The other significant predictor was the size of fire in the previous year. The odds of an insect outbreak appeared to increase as the size of a fire increases from 0 (no fire) to ~750 ha, after which the odds appear to decrease. The standard errors are large, especially for large fire sizes. This result is consistent with the expectation that as fire increases in size, the number of trees with significant crown damage and bole or root scorch increases, and, therefore, susceptibility to bark beetle attack may increase. However, very large fires may completely eliminate susceptible hosts in the area, resulting in less observable beetle damage when large fires are nearby.

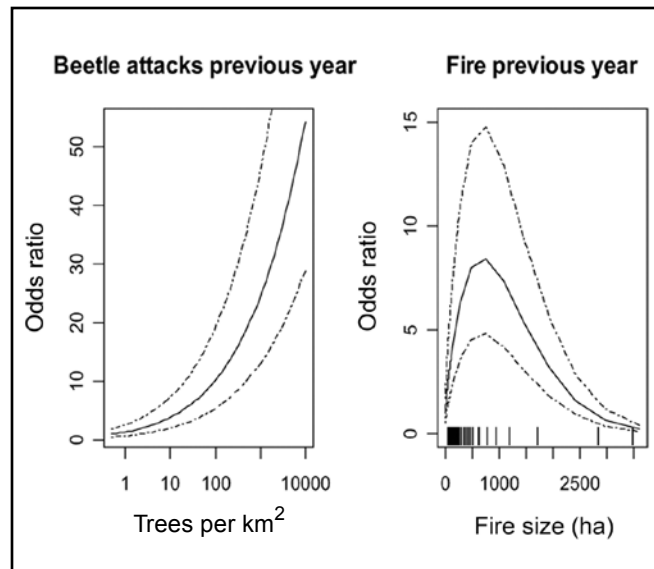


Figure 3—Estimated odds ratio (solid curves) and 95-percent confidence bounds (dashed curves) describing the increase in odds of a beetle attack (a) as the number of trees killed by beetles in the previous year increases from 0 to 10,000 trees/km² (left panel) and (b) as the size of a fire in the previous year, and within 1 km of the infestation, increases from 0 to > 2500 ha (right panel). The hatched marks in the bottom of the right panel indicate distribution of observed fire sizes. Note that only four fires of size > 1000 ha were observed in the sampled data.

Fire Size

The following predictors were found to have significant effects (P -value $\ll 0.05$) on the multinomial probabilities of a fire reaching one of three size classes: spatial location; size of beetle infestations in previous 3 years; size of spruce budworm infestations 4 to 6 year ago; average monthly temperature; and average monthly PDSI.

The estimated spatial pattern of fire sizes (Figure 4) seems to indicate northern Washington and eastern Oregon as some of the regions with the highest probabilities of a fire getting large after controlling for all other predictors in the model. Again, these results appear to be consistent with observed changes over the last 60 to 100 years in fire frequency and size in interior forests of the Pacific Northwest (Hessburg and Agee 2003).

According to the present data, beetle infestations that are 3 to 6 years old do not seem to be significantly associated with fire size; however, the odds of a fire getting large seem to increase significantly when the total size of beetle infestation in the last 3 years is greater than 5,000 trees

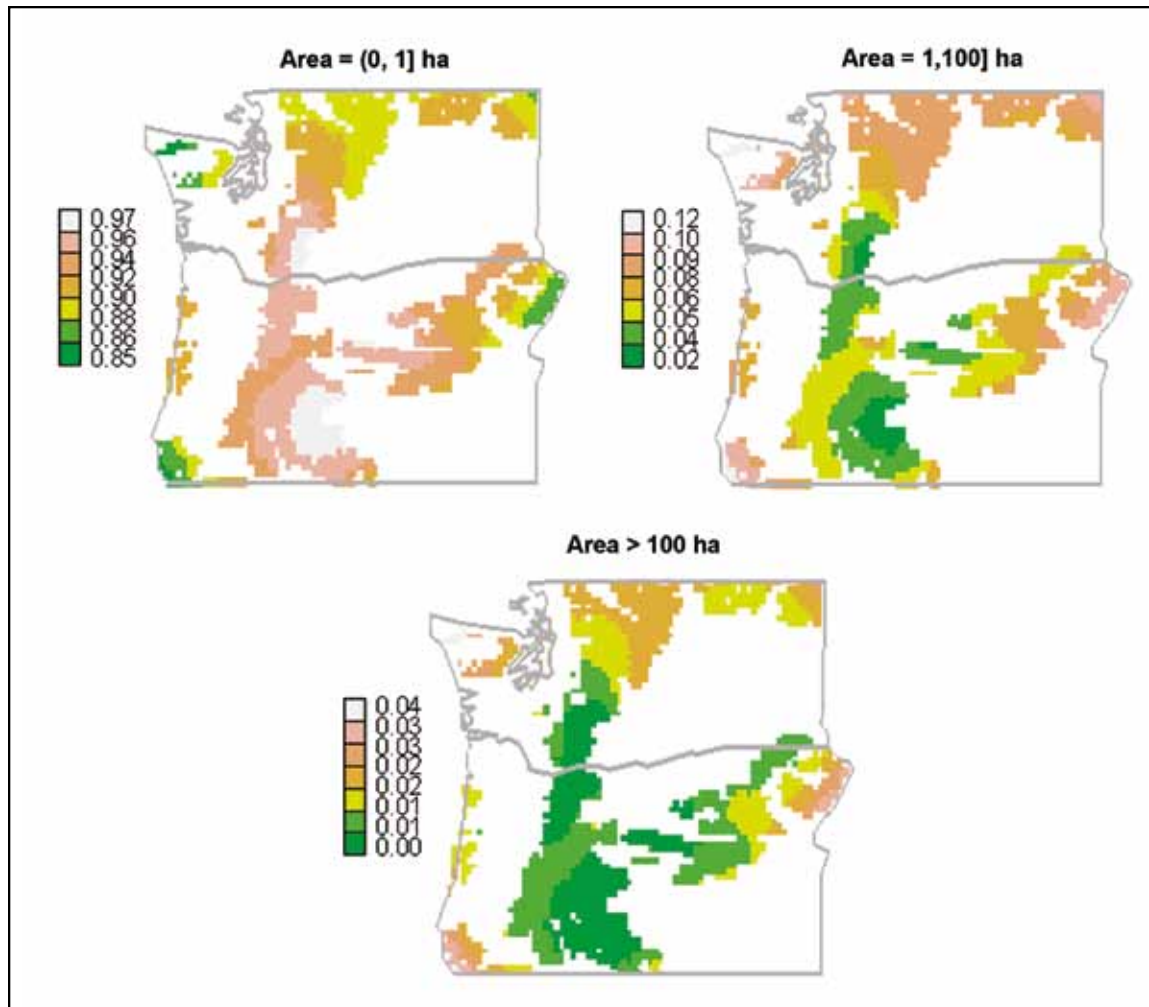


Figure 4—Probability of fire in one of three size classes on national forests in Washington and Oregon, 1970-2004.

killed per square kilometer (Figure 5, top panels). Canopies with residual dead needles and limbs in recently killed trees may contribute to crown conditions that significantly influence fire behavior. Following a simulated outbreak, Ager and others (in press) found that beetle-caused tree mortality increased surface fuel loadings and the potential for stands to sustain crown fire in the simulation. A different association was seen between fire size and size of spruce budworm infestation. No significant association was apparent between recent defoliations (area defoliated in previous 3 years) and sizes of fires nearby. However, a significant decrease was seen in the odds of a fire getting large as the size of older defoliations (total area defoliated 3 to 6 years ago) increased from a total of 100 to 300 ha (Figure

5, bottom panels). Lack of foliage following defoliation 4 to 6 years prior may actually reduce the risk of crown fire. Although the decrease in odds appears to continue as the size of defoliated area increases past 300 ha, the standard error for this range of defoliation is too large to warrant a precise conclusion.

Conclusions

Multiple disturbances, such as wildfire-insect outbreak interactions, are not well understood at provincial scales. Lack of large-scale data sets and easily available analytical techniques to address multiple disturbances have contributed to a limited number of quantitative studies. These studies have had confounding results. Here, we have

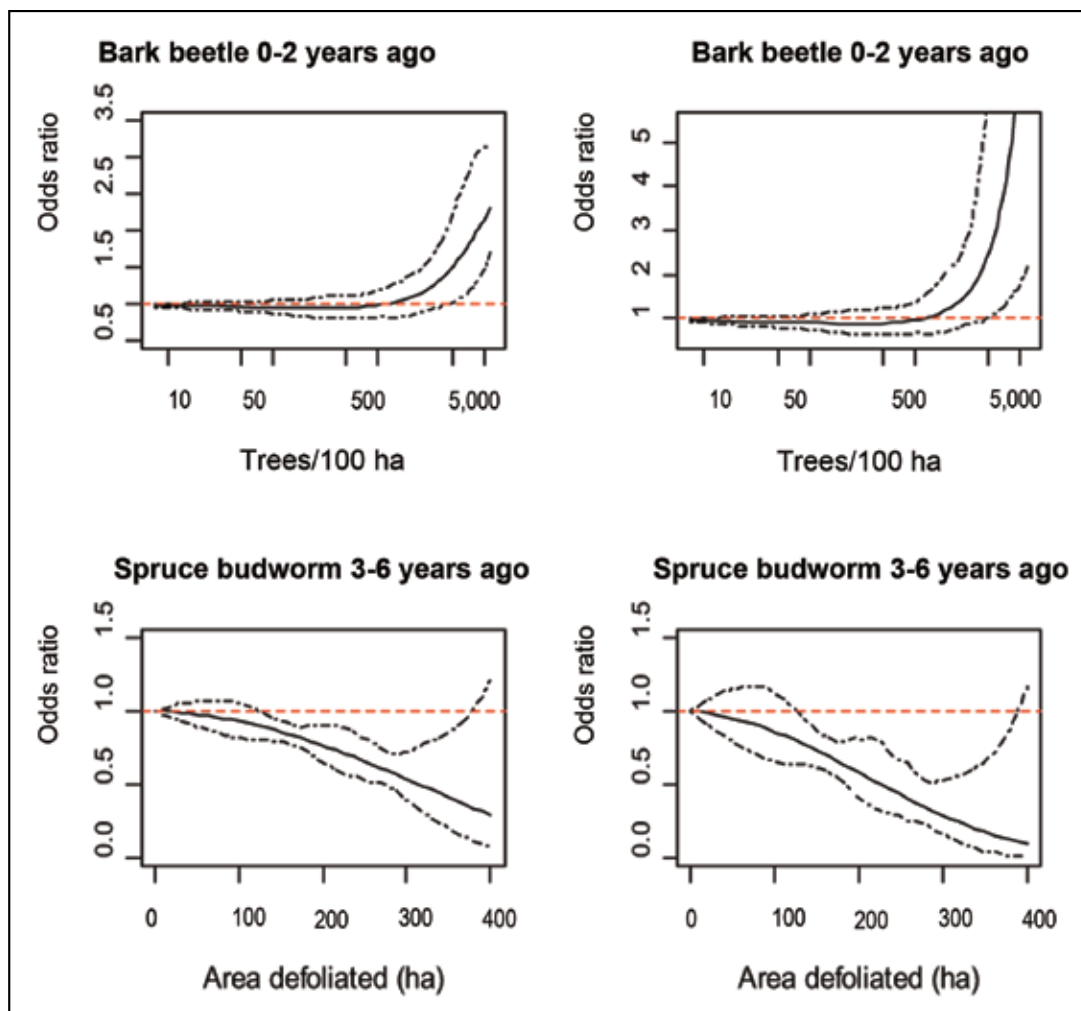


Figure 5—Estimated odds ratio (solid lines) and 95-percent confidence bounds (dashed lines) of fire reaching size class 2 or 3 plotted against values of two predictors (bark beetle and spruce budworm). The odds ratio is relative to when there is no insect infestation. The red dashed line indicates an odds ratio of one. When the red line is within the 95-percent bounds, the odds are not significantly different from the odds when no insect infestation is present.

described a probabilistic model framework that was used in a case study of spatiotemporal interactions between wildfire and insect outbreaks in the Pacific Northwest. To create the model, we used historical spatial data (1980 to 2004) on fire occurrence and insect outbreaks on forested lands of Oregon and Washington along with average monthly temperature and PDSI.

Results of our analyses seem to imply an increasing risk of new bark beetle infestations with increasing size of nearby fires (within 1 km) up to fires of ~750 ha. The latter was indicated by the estimated odds relative to locations with no fire damage. Also, there appears to be a decrease in

risk of a fire getting large at locations with 3- to 6-year-old spruce budworm damage of size greater than 100 ha.

The methods we employed provide an objective tool for modeling complex processes with time lags in the predictors and estimating associated probability maps for competing risks (multiple disturbances). The framework is especially amenable to quantifying uncertainties from multiple sources (stochastic disturbance, sampling and measurement errors, approximate models, and missing predictor variables), which are essential for model appraisal purposes. The analyses can be expanded to other areas using the rich, spatially explicit, historical data set available for wildfire

occurrence across all of the United States (NIFMID). It also has application for forest insects and diseases through Forest Health Protection annual aerial survey data. Although we only examined three insect species (mountain pine beetle, western pine beetle, and western spruce budworm), other stressors could be considered, including nonnative invasive species and stress level owing to pollution. Risk assessment maps can be produced by multiplying the estimated probabilities by a loss function.

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