IS LODGEPOLE PINE MORTALITY DUE TO MOUNTAIN PINE BEETLE LINKED TO THE NORTH AMERICAN MONSOON?

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Abstract.—Regional precipitation patterns may have influenced the spatial variability of tree mortality during the recent mountain pine beetle (*Dendroctonus ponderosa*) (MPB) outbreak in the western United States. Data from the Forest Inventory and Analysis (FIA) Program show that the outbreak was especially severe in the state of Colorado where over 10 million lodgepole pines (*Pinus contorta* Dougl. Ex Loud.) succumbed to MPB between 2002 and 2009. Aerial detection maps of MPB–related mortality show that the infestation was initially widespread and evenly distributed throughout the range of lodgepole pine in Colorado, but gradually became more severe in the northern portion of the state. Because southern Colorado receives relatively high summer precipitation due to the effects of the North American monsoon (NAM), the spatial pattern of MPB-related mortality suggests that infestation severity was lower in areas with the higher summer precipitation. This study investigated the link between lodgepole pine mortality due to MPB and seasonal precipitation patterns associated with the NAM in Colorado. Data regarding insect-related tree mortality and damage data were summarized from FIA data collected between 2002 and 2009, and gridded precipitation data were acquired from the North American Regional Reanalysis Project. Results indicated that while absolute NAM-related precipitation was not an important predictor of infestation severity, the deviation of a five-year average of summer and fall precipitation relative to climatic means was important.

INTRODUCTION

An outbreak of mountain pine beetle (Dendroctonus ponderosae) (MPB) has killed millions of trees across the western United States and Canada in the past decade. In Colorado alone, over 10 million lodgepole pines (Pinus contorta Dougl. Ex Loud.) died due to MPB infestation between 2002 and 2007 (Thompson 2009). Thompson et al. (2010) noted a spatial pattern in the distribution of insect-related mortality of lodgepole pine in Colorado. The relatively minor infestation severity in the southern part of the state mirrors the distribution of summer precipitation related to the North American monsoon (NAM). During the months of July, August, and September, the NAM alters regional wind patterns and introduces tropical moisture to northwestern Mexico and parts of the southwestern United States, including southern Colorado (Higgins et al. 1997). As a consequence, these areas experience relatively high seasonal precipitation until wind patterns return to a more dry and westerly flow in autumn. Based on this geographical phenomenon, it seems possible that MPB infestation severity is inversely related to seasonal precipitation associated with the NAM.

The purpose of this study was to identify a subset of stand-level and precipitation variables that have the strongest influence on infestation severity. Hicke and Jenkins (2008) identified several tree-level and stand-level variables that affect the susceptibility of lodgepole pine to MPB. However, the influence of

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monsoonal precipitation patterns on the severity of MPB infestations in the southwestern United States has not yet been explored. Based on the apparent geographically inverse linkage between NAM-related precipitation and lodgepole pine mortality due to mountain pine beetle, we expected that cumulative precipitation for the months of July, August, and September would be among the best predictors of infestation severity.

METHODS

Stand-level data were queried from the national Forest Inventory and Analysis (FIA) database. Between 2002 and 2009, a total of 497 FIA plots with at least one tallied lodgepole pine were measured in Colorado. This analysis included 248 Colorado plots that contained a minimum of 20 tallied lodgepole pines that were either live or recent mortality trees at the time of survey; 185 plots included at least one tree with insect-related damage or mortality on the plot. Infestation severity was calculated as the percentage of tallied lodgepole pines that were recorded either as mortality trees with insects listed as the mortality agent, or as live trees with severe insect damage. Infestation severity was negative log-transformed for normality.

Independent variables included both stand-level variables, which were queried from the FIA database, and precipitation data (see Table 1). Because field

Table 1.—Variables considered as potential predictors of insect-caused lodgepole pine damage and mortality. Data sources are the National Forest Inventory database (FIADB) and North American Regional Reanalysis (NARR) Program. Intervals used to calculate 3-year and 5-year means end in the year equal to the median mortality year.

Variable	Type	Source
-Log(Percent [damage + mortality])	Continuous	FIADB (calculated)
Measurement year	Class	FIADB
Median mortality year	Class	FIADB (calculated)
Elevation	Continuous	FIADB
Stand age	Continuous	FIADB
Live basal area	Continuous	FIADB
Number of all trees	Count	FIADB (calculated)
Number of lodgepole pines	Count	FIADB (calculated)
Mean diameter at breast height (d.b.h.)	Continuous	FIADB (calculated)
Standard deviation of d.b.h.	Continuous	FIADB (calculated)
Mean tree height	Continuous	FIADB (calculated)
Winter (Jan/Feb/Mar) climatic mean, 1981-2010	Continuous	NARR (calculated)
Spring (Apr/May/Jun) climatic mean, 1981-2010	Continuous	NARR (calculated)
Summer (Jul/Aug/Sep) climatic mean, 1981-2010	Continuous	NARR (calculated)
Fall (Oct/Nov/Dec) climatic mean, 1981-2010	Continuous	NARR (calculated)
Winter (Jan/Feb/Mar) 3-yr mean	Continuous	NARR (calculated)
Spring (Apr/May/Jun) 3-yr mean	Continuous	NARR (calculated)
Summer (Jul/Aug/Sep) 3-yr mean	Continuous	NARR (calculated)
Fall (Oct/Nov/Dec) 3-yr mean	Continuous	NARR (calculated)
Winter (Jan/Feb/Mar) 5-yr mean	Continuous	NARR (calculated)
Spring (Apr/May/Jun) 5-yr mean	Continuous	NARR (calculated)
Summer (Jul/Aug/Sep) 5-yr mean	Continuous	NARR (calculated)
Fall (Oct/Nov/Dec) 5-yr mean	Continuous	NARR (calculated)
Winter (Jan/Feb/Mar) 3-yr anomaly	Continuous	NARR (calculated)
Spring (Apr/May/Jun) 3-yr anomaly	Continuous	NARR (calculated)
Summer (Jul/Aug/Sep) 3-yr anomaly	Continuous	NARR (calculated)
Fall (Oct/Nov/Dec) 3-yr anomaly	Continuous	NARR (calculated)
Winter (Jan/Feb/Mar) 5-yr anomaly	Continuous	NARR (calculated)
Spring (Apr/May/Jun) 5-yr anomaly	Continuous	NARR (calculated)
Summer (Jul/Aug/Sep) 5-yr anomaly	Continuous	NARR (calculated)
Fall (Oct/Nov/Dec) 5-yr anomaly	Continuous	NARR (calculated)

crews in the Interior West region of the FIA assign an estimated mortality year to each mortality tree, we used the median mortality year for all mortality trees on the plot, rather than measurement year, as the year of most severe impact. For insect-damaged live trees, which are defined as those already infested and unlikely to survive, the mortality year was estimated as the year following the measurement year and then incorporated into the median mortality year calculation. Median mortality years ranged from 1999 to 2009.

Precipitation data were acquired from the North American Regional Reanalysis (NARR) Project (Mesinger et al. 2006). The initial dataset consisted of gridded monthly precipitation at a resolution of 32 km for the period 1993-2009. Seasonal precipitation for each year was calculated as the sum of precipitation during 3 months, where summer consisted of July, August, and September to coincide with the NAM (see Table 1). Climatic mean precipitation was calculated for each calendar month based on the 30-year period 1981-2010, and these monthly climatic means were summed in 3-month intervals to obtain seasonal climatic means. Seasonal 3-year and 5-year interannual precipitation means were also calculated for each plot, where the average associated with each plot was based on the period ending in the median year of lodgepole pine mortality for that plot. To calculate 3-year and 5-year seasonal precipitation anomalies, which are defined here as the simple difference between short-term precipitation and long-term climatic conditions, the 30-year climatic means were subtracted from the 3-year and 5-year interannual means. Therefore positive anomalies indicate relatively wet periods, while negative values indicate dry periods.

Analysis was done using two iterations of PROC GLMSELECT (SAS Institute Inc. 2009). The first iteration did not include any interaction terms, while the second included interactions between stand-level and precipitation variables as well as among precipitation variables. Selection of variables was stepwise, with significance levels of 0.15 for both entering and staying in the model. Final model selection was based on minimization of the Akaike information criterion (AIC). Based on our expectation that seasonal precipitation related to the NAM has an inverse relationship with infestation severity, we expected that climatic mean summer precipitation would be a component of the final model. Because stepwise variable selection methods may overestimate the importance of independent variables (Harrell 2001), correlations were assessed between infestation severity and each of the five variables identified from the stepwise regression to reinforce the interpretation of each variable's importance.

RESULTS

The model with the minimum AIC value included the following variables, in order of entry into the model: 5-year fall precipitation anomaly, mean diameter at breast height (d.b.h.), live basal area, 5-year summer precipitation anomaly, and stand age (Table 2). During the second run of the GLMSELECT procedure, some

Table 2.—Variables included in the model with the minimum Akaike information criterion (AIC), where minimum significance level for entering and staying in the model was 0.15. R values are Pearson correlation coefficients of each variable against the log-transformed response.

Step	Variable	AIC	ΔAIC	F Value	Pr > F	r
0	Intercept only	285.0214	48.34	0.00	1.0000	N/A
1	Fall (Oct/Nov/Dec) 5-yr anomaly	254.3260	17.64	35.38	<0.0001	0.4025
2	Mean diameter at breast height (d.b.h.)	245.2348	8.55	11.25	0.0010	0.2274
3	Live basal area	239.2317	2.55	8.00	0.0052	-0.2298
4	Summer (Jul/Aug/Sep) 5-yr anomaly	237.6833	1.00	3.49	0.0635	0.3705
5	Stand age	236.6843	0.00	2.93	0.0889	-0.0655

interaction terms were selected as important variables in the final model. These included interactions between mean d.b.h. and both summer and fall 5-year precipitation anomalies. However, because this model's AIC value was comparable to that of the initial model, and the selected interaction terms included a nearly identical subset of climatic and stand-level predictor variables as the initial model, results are presented only for the first and simpler model.

Based on values for Pearson's correlation coefficient (Table 2), infestation severity was more strongly correlated with the precipitation variables in the final model than with the any of the stand-level attributes. The 5-year summer and fall precipitation anomalies were negatively correlated with infestation severity. These negative correlations signify that 5-year periods of relative drought during summer and fall are most strongly associated with high infestation severity. Although stand age emerged as an important predictor variable in the AIC-based variable selection, its low correlation with infestation severity suggests it is not important.

DISCUSSION

Of the five predictor variables in the final model, two represented seasonal precipitation anomalies and three were based on stand attributes. The three stand-level attributes (mean d.b.h., basal area, and stand age) are known to affect infestation severity of lodgepole pine by mountain pine beetle (Hicke and Jenkins 2008, Raffa et al. 2008). Several aspects of the two precipitation variables are notable. First, both variables represent anomalies from long-term climatic conditions, indicating that anomalies are more important than absolute precipitation metrics as predictors of infestation severity. Because absolute summer precipitation did not meet the criteria for inclusion in the final model, there is no evidence that the absolute quantity of precipitation associated with the NAM has an impact on infestation severity. However, interannual variability in seasonal precipitation, including precipitation associated with the complex meteorological dynamics of the NAM, may impact infestation severity. Second, the two precipitation variables included in the final model indicate that seasonal anomalies during summer and fall are more important than those during winter and spring. Finally, while the 5-year summer and fall anomalies were important, no 3-year anomalies appeared in the model. Assuming that the inverse relationship between seasonal precipitation anomalies and infestation severity is caused by increased stress during long-term drought, the temporal realm of influence of precipitation anomalies on infestation severity appears to last longer than 3 years.

Other analyses of weather and climate data may yield further insights about the factors affecting infestation severity. Future research should investigate whether the relationship between infestation severity and seasonal precipitation anomalies holds elsewhere, and if so, whether the 5-year timescale is similarly important. While precipitation is thought to affect the susceptibility of trees to insect attacks, temperature data may also be useful for modeling insect populations and infestation severity. Analyses of temperature data, such as monthly and daily maxima, minima, and anomalies, may further illuminate the complex relationships among climate, weather, MPB population dynamics, and lodgepole pine stands.

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