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LANDSCAPE PATTERNS OF BALSAM WOOLLY ADELGID OCCURRENCE & SUBALPINE FIR MORTALITY, OLYMPIC PENINSULA, WA

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INTRODUCTION

Subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) trees are experiencing visible decline on the Olympic Peninsula, WA (USA). Annual aerial detection surveys (ADS) conducted jointly by Washington State Department of Natural Resources (DNR) and the United States Forest Service (USFS) have identified extensive areas of defoliation and mortality in the subalpine fir zone and attribute this decline to infestations of an exotic insect, the balsam woolly adelgid (BWA) (*Adelges piceae* [Ratzeburg]) (Ciesla 2006; USDA 2010). As many as 79-98% of true fir trees (*Abies* spp.) have been killed in some locations of the Appalachian Mountains and Cascade Range since the introduction of BWA to North America from Europe in the early 1900's (Mitchell and Buffam 2001; Witter and Ragenovich 1986). A similar pattern of adelgid-induced decline may be occurring on the Olympic Peninsula since the first documented sighting in 1969.

Tree mortality is complex, and involves multiple predisposing, inciting and contributing factors that interact across scales (Manion 1981; Wu and Loucks 1995). Forests world-wide have been experiencing mortality due to a combination of climate factors, and insect and disease outbreaks (Berg et al. 2006; van Mantgem et al. 2009; Allen et al. 2010). On the landscape level, tree mortality can create spatial heterogeneity, diversity, and natural cycles in forest vegetation and succession that support ecosystem stability; however, a change in one or more biotic or abiotic disturbances that exceeds the historic range of variability can disrupt natural cycles and permanently alter an ecosystem (Holling et al. 2001; Seastedt et al. 2008; Turner 2010).

Climate change and exotic insects are two factors with potential to cause permanent ecosystem change. Insect-induced defoliation stresses host trees, reduces carbohydrate production and tree growth, compromises tree health, kills pre-weakened or otherwise infected trees and makes healthy trees vulnerable to attack by endemic agents (Houston 1992; McDowell et al. 2008). The etiology may not be initially clear due to numerous interacting agents and varied environmental conditions.

The balsam woolly adelgid is now a part of subalpine fir ecosystem dynamics as a slow but consistent defoliator. There are currently no effective methods for controlling BWA on a broad scale (Mitchell and Buffam 2001). Similar to the aphid, the adelgid feeds by inserting sucking mouth parts into phloem cells and injecting hormones that alter cambial cell growth (Doerksen and Mitchell 1965). The flow of water and nutrients to branches is reduced, resulting in defoliation, growth reduction, and dieback. Subalpine fir is susceptible to winter desiccation, early and late frost, abnormal warming events (Manion 1981), windthrow (Alexander et al. 1984), and infestation by bark beetles and wood decay fungi (Franklin and Mitchell 1967; Goheen and Willhite 2006); trees with decreased growth due to defoliation are more susceptible to environmental stressors and pathogens (Houston 1992).

The objectives of our research are to (1) identify environmental conditions and disturbance agents associated with subalpine fir mortality, (2) determine the distribution and role of balsam woolly

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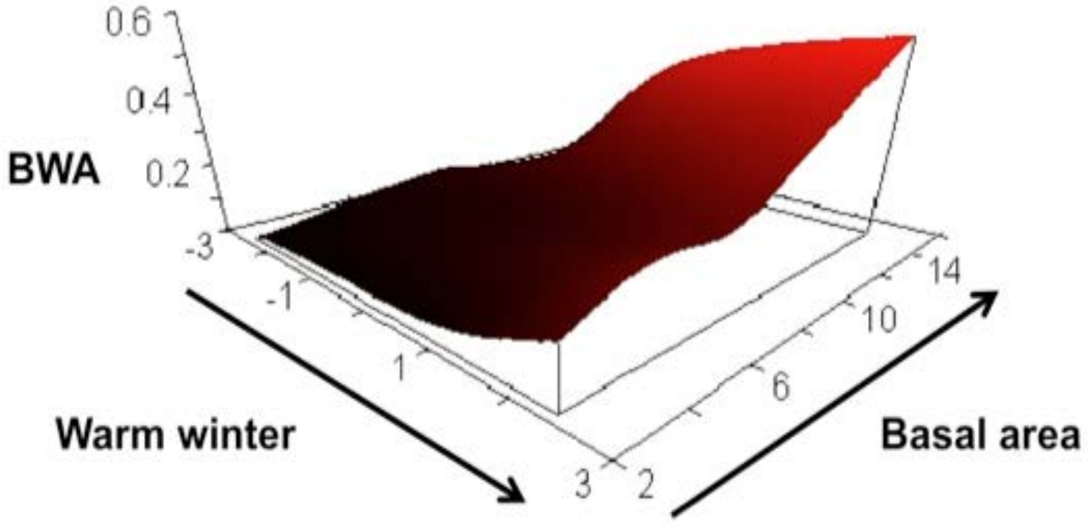
adelgid in subalpine fir decline, and (3) identify susceptible forested areas on the Olympic Peninsula. Preliminary results address objectives two and three. Initial observations and research plans are included to provide an overview of the more comprehensive mortality study currently in progress.

METHODS

This study is being conducted in the subalpine fir zone of the Olympic Peninsula, a mountainous region in northwestern Washington (USA) which is isolated from adjacent mountain ranges. Aerial detection surveys (Ciesla, 2006) and satellite imagery processed by LandTrendr (LT) (Kennedy et al. 2010) were used to identify and differentiate areas of moderate to high tree mortality from areas of no detected mortality.

A total of 105 quick-assessment plots were located within 10 sites, with approximately 12 plots per site. At each site four plots were randomly distributed within each of three polygon types: (1) ADS mortality, (2) LT vegetation decline, and (3) no detected mortality. Overlap occurred between ADS and LT polygons when plots were located in both polygon types.

Only plots with BWA sign or symptoms, and more than two tree-sized ($\geq$ 12.7 cm dbh) subalpine fir were used to assess relationships between BWA severity and stand and environmental variables. It was assumed that BWA absence was a function of dispersal rather than tree resistance, and that plots without BWA had simply not been exposed. Of 105 plots, 54 plots fit our criteria, 41 plots had no subalpine fir, four plots had 1-2 subalpine fir only, and six plots had no BWA signs or symptoms.



Predictor	Tolerance %	Sensitivity
Basal area	14	0.6078
Warm winter	21	0.3379
Warm days	27	0.1736

Figure 1: Factors associated with severity of BWA symptoms as determined by non-parametric multiplicative regression (NPMR).

Stand data collected within the 10-m radius plots included stand age, height, elevation, slope, aspect, average BWA gout-size, seedling and sapling tally by species, and cone-bearing counts for subalpine fir. Tree-level data included tree species, status, diameter (dbh), crown class, health or decay class, presence of BWA insects, gouting and crown collapse, and other damage agents. Boles were assessed visually on the lower 2 m of the stem. USFS Forest Inventory and Analysis (FIA) protocol were followed for data collection, but not for plot design (USDA 2007).

Climate variables were downloaded from PRISM and included 30-year monthly and annual averages of minimum temperature (TMIN), maximum temperature (TMAX), and precipitation (PPT) from 1971 to 2000 (PRISM Climate Group 2004). To reduce the 39 climate variables into fewer composite variables representing dominant plot data axes, principal components analysis (PCA) was conducted using PCORD (McCune and Mefford 2011). Two composite variables were used as explanatory variables in regression analysis.

Non-parametric multiplicative regression (NPMR) (McCune and Mefford 2009) was used to determine associations between the response variable, BWA severity, and explanatory variables, which included landscape- and stand-level climate and environmental conditions. Balsam woolly adelgid severity was calculated by taking the proportion of subalpine fir trees, seedlings, and saplings with signs or symptoms of BWA and multiplying by a factor of gout-size-class 1-3 (i.e., the increase in millimeters of branch radius), after dividing by 3 to standardize the severity index to one. This measure of BWA severity allowed for a quick assessment at each plot, and was an effective representation for areas that had sparse stem infestation, variable symptom occurrence on both overstory and understory subalpine fir, and consistent plot gout size.

Non-parametric multiplicative regression was also used to investigate the relationship between proportions of subalpine fir in a plot within different decay classes, live tree health classes, and explanatory variables, which included environmental variables and mortality agents.

PRELIMINARY RESULTS

Preliminary analyses indicated that BWA was distributed throughout the subalpine fir zone on the Olympic Peninsula, with 10% of subalpine fir plots lacking symptoms or sign. Dense stem infestations of BWA were rare (*n=5*) in our study area, and trees with small gouts were generally not defoliated. BWA gout severity increased with temperature and total stand basal area (Figure 1). The preliminary results did not demonstrate a direct and significant statistical relationship between BWA and subalpine-fir deaths (plot-level data), nor did other agents prove to be significant predictors of mortality with the current data collection and analysis methods.

Disturbance agents commonly found in study plots, in addition to BWA, included mechanical damage from snow, wind and falling trees, endemic bark beetles (fir root beetle *Pseudohylesinus granulatus* [LeConte], silver fir beetle *Pseudohylesinus sericeus* [Mannerheim], western balsam bark beetle *Dryocoetes confusus* [Swaine], and fir engraver *Scolytus ventralis* [LeConte]), fungal pathogens (*Armillaria* spp. and *Heterobasidion occidentale* sp. nov.), burl-formation, and bear damage. Some mortality agents common in the Cascade Range were nonexistent or rare in subalpine fir on the Olympic Peninsula, e.g. western spruce budworm (*Choristoneura occidentalis* [Freeman]), mistletoe (*Archeuthobium abietinum* [Englman] Hawksworth & Wiens), and virulent *Armillaria* spp.

DISCUSSION

Understanding mortality dynamics requires an interdisciplinary approach for evaluating interactions among hosts, multiple disturbance agents, and climate. Multiple factors must be acknowledged and teased apart to determine their contribution to specific mortality patterns. Environmental and stand characteristics associated with BWA symptom severity provided preliminary indications of where BWA may play the largest role in tree mortality. Severity was high where warm winter temperatures may be causing earlier snowmelt and consequently greater tree volume growth. This is consistent with observations that BWA has a greater impact in productive stands, during warm years, and where trees have experienced growth release (Johnson et al. 1963; Mitchell and Buffam 2001). Subalpine fir trees in these susceptible locations may be at risk of extirpation (Franklin and Mitchell 1967). Severely affected stands may provide opportunities for experimental management activities or aid the search for BWA-resistant trees. Our research will continue to fine-tune specific temperature and tree growth dynamics related to spatial distribution of BWA severity. Two additional explanatory variables (moisture deficit and predominant wind patterns) will be evaluated in subsequent analyses.

Additional analyses are needed to address tree mortality and potential predictors. Forested areas with subalpine fir (64 plots) appeared to have higher mortality than areas without subalpine fir (41 plots), indicating that subalpine fir is the target host for one or more damage agents. Although stand-level analyses failed to elucidate significant associations, we hypothesize tree-level analysis will help identify relationships between tree health/mortality and associated insects and disease that were not detected in stand averages. Dendrochronology and satellite imagery will also be used to investigate temporal patterns of mortality and decline along a highly visible mountain ridge in the northern part of the Olympic Peninsula. Growth rate reductions and mortality not explained by known climate and growth relationships (Peterson et al. 2002; Ettl and Peterson 1995) may be the result of increased insect or disease activity (Lemieux and Filion 2004). TimeSync (Cohen 2010), a Landsat-image-processing technique, will allow us to observe vegetation decline and recovery trends detected by Landtrendr algorithms (Kennedy et al. 2010) for 90 m^2 grid cells around our study plots. Identification of spatial and temporal trends may further help to identify mechanisms associated with forest decline (Meigs et al. 2011).

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