Interactions of insects, fire and climate on fuel loads and fire behavior in mixed conifer forest

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Abstract

Mixed-conifer forests in the interior Pacific Northwest are subject to sporadic outbreaks of the western spruce budworm, the most destructive defoliator in western North America. Such outbreaks usually occur synchronously over broad regions and lead to widespread decreases in growth rates and low to moderate levels of mortality. In the last century, changing land use and fire suppression have led to an increase in the amount and density of host tree species, and changed fire regimes. This has altered the severity and frequency of both fire and western spruce budworm. In spite of the ecological and economic significance of these disturbances, their interactions with each other and with climate are not fully understood. We used two approaches to examine these interactions across a range of temporal and spatial scales. First, we used dendrochronological methods to examine the climatic drivers of budworm outbreaks and fires and to assess the association of fire and budworm over three centuries in 13 stands across Oregon, Idaho, and Montana. Second, we used a mechanistic fire behavior model, the Wildland-urban interface Fire Dynamics Simulator (WFDS) to examine the sensitivity of crown fire to multiple aspects of defoliated crown fuels, including changing crown bulk density and branchwood moisture.

The dendrochronological reconstructions revealed repeated western spruce budworm outbreaks and fires over the past several centuries, with different climate events associated with each disturbance. Outbreaks sometimes persisted more than a decade and were often synchronous among sites. An average of 12 outbreaks occurred at each site, each lasting an average of 12 years in length, with an average of 15 years between outbreaks. Outbreak initiation was often regionally synchronous. Synchrony was higher in the second half of the record (since 1900), possibly due to increased abundance and continuity of host trees during the fire suppression era. Outbreak duration and frequency were also somewhat higher after approximately 1890. We found that warm-dry conditions occurred one to three years preceding outbreak initiation, suggesting that drought-stressed trees permit population growth to a level at which predators no longer strongly limit the budworm population. The mean fire return interval in these mixed-conifer stands was 34 years (range: 16 – 53 years). Fires tended to occur during warm-dry years. We found no evidence of a consistent relationship between the timing of fires and western spruce budworm outbreaks. Western spruce budworm is associated with the ends of droughts and fire is simply associated with single drought years.

The simulation study found that defoliation reduces both torching and crowning potential, requiring greater surface fire intensity for crown ignition than undefoliated tree crowns with the same crown base height. Single, highly defoliated trees (80%) experienced little or no torching, and moderately defoliated trees (50%) required about twice the surface fire intensity of undefoliated trees to produce the same heat output. For example, at a surface fire intensity of 700 kW/m^2, 99% of the canopy fuel from the undefoliated tree was consumed, leaving 2 kg of foliage on the tree, compared to 81% consumption of a moderately (50%) defoliated tree, leaving 15 kg of foliage. The effects of defoliation were somewhat mitigated by canopy fuel heterogeneity and potential branchwood drying, but these effects were less pronounced than defolation itself. Our study suggests that areas heavily defoliated by western spruce budworm may inhibit crown fire spread and may thus promote non-lethal surface fires.

Background and purpose

Outbreaks of western spruce budworm (*Choristoneura occidentalis* Freeman) are an important driver of forest dynamics in the mixed conifer forests of the interior Pacific Northwest. By feeding on needles, larvae of this species primarily defoliate Douglas-fir (*Pseudotsuga menziesii*) and several true fir species (*Abies grandis* and *A. concolor*). Larvae emerge from silken tents (hibernacula) in late spring and burrow into the buds of host trees, preferentially feeding on new foliage (Fig. 1). In subsequent years, the tree flushes using stored carbon. New foliage is then available to the larvae, so that during outbreak conditions there is an outer zone of defoliated branches while an inner zone of older foliage remains less consumed. Host trees with large canopies are less defoliated and rarely die from outbreaks whereas host trees with small canopies are more heavily defoliated and often die within a few years (Fig. 1). Western spruce budworm outbreaks may extend over tens to hundreds of kilometers and persist for over a decade.

In spite of the ecological and economic impact of western spruce budworm, its outbreak patterns, population dynamics, responses to climatic variability, and effects on fire occurrence and behavior are not fully understood. Historical logging and more recent fire suppression may have increased the synchrony -- as well as severity, duration, and/or frequency -- of western spruce budworm outbreaks by increasing the extent, homogeneity, and density of forests while increasing the proportion of host tree species (Youngblood and Wickman 2002). In 1986, at the peak of its last major outbreak, western spruce budworm impacted more than 5.2 million hectares in the United States (Hofacker et al. 1987). The potential synergisms between outbreaks and fire, especially how fire behavior changes during and after outbreaks, is relevant for setting management goals in forests considered at risk for both disturbance types. While some recent large fires have occurred in areas with budworm defoliation and mortality (e.g., the 2003 B&B Fire in Oregon), other studies found a negative relationship between western spruce budworm and fire in space and time without explaining the cause of the dissociation. Media reports and some peer-reviewed journal articles, however, often assume that budworm outbreaks result in increased fire risk.

Our overall objective was to identify the occurrence and strength of interactions between western spruce budworm outbreaks, fire, and climate. To achieve this we used a combination of field measurements of historical disturbances and simulation modeling of the effects of budworm defoliation on subsequent fire behavior, especially crown fire. The field-based portion reconstructed outbreak events from tree-ring records, fire events from fire-scarred ponderosa pines within the same stands, and used existing, independent climate reconstructions to produced multi-century histories of the relative timing of these disturbances with respect to each other and to climate. The simulation modeling portion involved a state-of-the-art fire behavior model to examine the response of changing canopy bulk density to crown fire. Together, the dendroecological reconstruction and the simulation model provide a mechanistic explanation for the historical patterns of budworm outbreaks and fire.

Climatic controls of budworm outbreaks

Two competing hypotheses have been used to explain patterns observed between climate and insect outbreaks: the stress hypothesis and the vigor hypothesis. According to the stress hypothesis, drought or other abiotic stressors can trigger insect outbreaks by increasing the concentration of nitrogen and other chemical compounds that improve the nutritional quality of foliage (Mattson and Haack 1987). Alternatively, the plant vigor hypothesis proposes that high moisture levels benefit herbivorous insects by increasing the quality or quantity of foliage (Price 1991). These contradictory results reflect a broader uncertainty regarding the role of climate in triggering outbreaks of herbivorous insects. While tree-ring reconstructions of western spruce budworm outbreaks have supported the vigor hypothesis (Swetnam and Betancourt 1998), observational studies have supported the stress hypothesis (e.g., Campbell 1993).

Synergism of budworm outbreaks and fire: Historical patterns

Insect outbreaks, including those of western spruce budworm, have been thought to increase potential forest fire severity and probability of occurrence due to increased dead fuel loads (Schowalter 1986; Stocks 1987; McCullough et al. 1998; Hummel and Agee 2003; Ryerson et al. 2003; Pohl et al. 2006; Parker et al. 2006). Previous reconstructions of western spruce budworm outbreaks and fires using dendrochronological methods did not explicitly analyze disturbance interactions, and a casual association between the two disturbances was not apparent in the results (Anderson et al. 1987; Swetnam and Lynch 1993). The only studies to explicitly examine the statistical relationship between fire and western spruce budworm outbreak records reported a negative correlation (Preisler et al. 2005; Lynch and Moorcroft 2008). However, the applicability of these studies is limited because they examined outbreaks solely during the 20th century, during a time of changing climate and fire regimes.

Synergism of budworm outbreaks and fire: Mechanistic understandings

Most studies of fire-insect relationships have focused on insects that cause high mortality, such as mountain pine beetle and eastern spruce budworm. In contrast, western spruce budworm causes less tree mortality and there are normally only small amounts of uneaten, dead needles retained in the crown. Thus, the impacts of western spruce budworm on fuel loads and fire behavior are likely different from other defoliators or bark beetles. Defoliation removes foliage from tree crowns, which could reduce potential torching (ignition of the crowns of individual trees) or crowning (spread between tree crowns). Hummel and Agee (2003) employed the most comprehensive stand-level fire model available at the time (FFE-FVS; Reinhardt and Crookston 2003). However, this model is not sensitive to the sub-meter scale at which defoliation removes crown fuel and its underlying fire modeling framework has significant limitations for crown fire (e.g., Cohen et al. 2006; Cruz and Alexander 2010; Jolly et al. 2012). We attempt to improve on this effort by using a new mechanistic model, the Wildland-Urban Interface Fire Dynamic Simulator (WFDS), which allows us to investigate fine scale changes in crown fuel using a physics-based approach.

Figure 1. Left: Topkill of a Douglas-fir tree by western spruce budworm defoliation. Center: Needle consumption Right: Needle consumption with some remnant needles held by budworm silk. Photos by Aquila Flower and Greg Cohn.

Study description and location

Field study

Our thirteen sites are located between central Oregon and western Montana (Fig. 2). These sites are mixed conifer stands dominated by a combination of Douglas-fir, ponderosa pine, and grand fir. We targeted specific sites based on the presence of relatively old Douglas-fir and grand fir ("host") trees, field evidence or archival records of historical western spruce budworm outbreaks, and, where possible, the absence of recent stand-replacing fires, logging or other anthropogenic disturbances.

To identify past outbreaks, we compared ring-width series from host tree species (Douglas-fir and grand/white fir) with ring-width series from a "non-host" tree species (ponderosa pine). At each site, we collected samples from eighteen or more host trees with a diameter of at least 40 cm at breast height (1.4 m) by removing two cores at breast height using an increment borer. Non-host sites were located in nearby stands that had few host trees so as to avoid contamination of their climate signal by growth releases due to reduced competition during defoliation events. At least 10 ponderosa pine trees were sampled at each non-host site to create a chronology that could be used to control for climate. Two cores were taken from each tree.

We prepared core samples according to standard dendrochronological protocol, measured ring widths, and verified the measurements by statistical crossdating. The host and non-host ring-width series were conservatively standardized (detrended) to retain most or all of the variability at the time scales relevant to western spruce budworm outbreaks. We subtracted the mean non-host chronology from each standardized host tree series following existing methods aimed at isolating the budworm defoliation signal. This "corrected index" indicates departures in growth rate from that expected by climate. We developed criteria to optimize outbreak detection by comparing corrected indices with known periods of western spruce budworm outbreaks detected by annual aerial surveys. The optimal criteria to identify budworm infestation on a tree required (1) a period of negative corrected indices with no more than one consecutive year of positive values, (2) negative values persisting for ≥ 4 years, and (3) at least one year with a corrected index <1.28. Stand-wide outbreaks were defined as periods during which at least 40% of the host trees recorded infestation for four or more consecutive years.

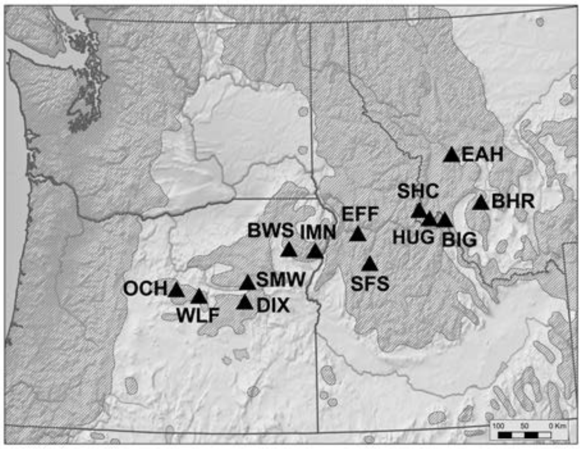

Figure 2. Locations of 13 study sites in mixed conifer forest. Shaded area shows the general distribution of Douglas-fir and grand fir.

To reconstruct fire dates at each site, we used a chain saw to collect partial cross sections from three to eleven visibly scarred and well-preserved stumps, snags, and living ponderosa pine. We dated fire scars by visual and statistical crossdating of collected cross-sections. We conservatively defined fire years as those in which at least two trees at a site had a fire scar, or in which a single fire scar was corroborated by a previously completed fire reconstruction nearby. At two sites, previously published fire histories were used in lieu of new reconstructions because they were completed at the same location. Dates of outbreak initiation, outbreak cessation, and fire and were compared to each other among sites and to climate data developed from independent sources (Cook et al.).

Simulation study

Western spruce budworm outbreaks might alter fire behavior in several ways. Defoliation removes foliage from tree crowns, which could reduce potential torching (ignition of an individual tree) or crowning (fire spread between trees). Crown fuel that remained, however, could be more flammable if its moisture content was diminished. Fire behavior could change indirectly as well, through changes in the environment such as an increase in wind speeds resulting from reduced canopy drag, increases in surface fuels due to tree mortality, or decreases in surface fuel moisture resulting from decreased shading by defoliated trees. In our approach, we acknowledge that multiple factors affect surface fire intensity and instead focus on simulating crown-fire occurrence given prescribed levels of defoliation and surface fire intensity.

Our objective was to infer the effects of western spruce budworm defoliation on the potential for surface fires to torch (ignite individual trees) and crown (spread between the crowns of multiple trees). First, we used WFDS to simulate the interacting effects of defoliation and surface fire intensity on torching of a single tree and also to examine model sensitivity to the: (1) distribution of defoliation within the canopy, (2) drying of defoliated branches, and (3) spatial resolution of the model. Second, we used WFDS to simulate the interacting effects of defoliation and surface fire intensity on crowning in a row of trees.

We modeled a single mature, co-dominant, Douglas-fir tree that could possibly torch due to low canopy base height (2m), and is a validated species in WFDS. It was 12 m tall and 49 cm in diameter. We defined canopy fuel as two distinct, but spatially overlapping, fuel components: foliage and small diameter branchwood (<5 mm). Undefoliated, our modeled tree had a foliage bulk density of 0.32 kg/m^3 and a branchwood bulk density of 0.2 kg/m^3.

We explored the sensitivity of several aspects of how outbreaks are represented in WFDS. We simulated four levels of defoliation between 0% and 80%, based on observed defoliation (e.g., Alfaro et al. 1982). Defoliation was first simulated as spatially homogeneous and then as an isolated outer shell of the crown. We varied branchwood moisture content from 20% to 100%. Numerical models can be sensitive to the cell size at which calculations are resolved. To ensure our simulations were adequately resolved, we tested three cell resolutions (cubes of 1 m, 0.5 m, and 0.25 m on a side). Fire behavior in a single tree crown (e.g., foliage consumed and radiant heat released) was examined across a range of surface fire intensities.

To model the effect of defoliation on crowning, we created a row of five identical trees by replicating our single simulated Douglas-fir tree separated by 1 m. We simulated a range of surface fire intensities (300 kW/m^2 to 700 kW/m^2), based on the torching behavior we observed in the single-tree simulations. Crowning depends on wind speed and crown spacing (Rothermel 1991). We used a wind speed (6 m/s) that was sufficient to spread fire between tree canopies separated by 1 m.

Key findings

1. Western spruce budworm outbreaks were successfully reconstructed at 13 sites, showing regionally synchronous patterns of outbreaks.

The tree-ring records successfully identified outbreak events that were verified with comparisons to aerial survey records. The reconstructions revealed repeated western spruce budworm outbreaks that sometimes persisted more than one decade and that were synchronous among sites. An average of 12 outbreaks, each lasting an average of 12 years in length, occurred at each site. An average of 15 years elapsed between outbreaks (Fig. 3). Outbreak initiation was regionally synchronous as indicated by several statistical tests. Other analyses (not shown) support earlier work indicating that budworm synchrony is higher in the fire-suppression era, possibly due to increased abundance and continuity of host trees.

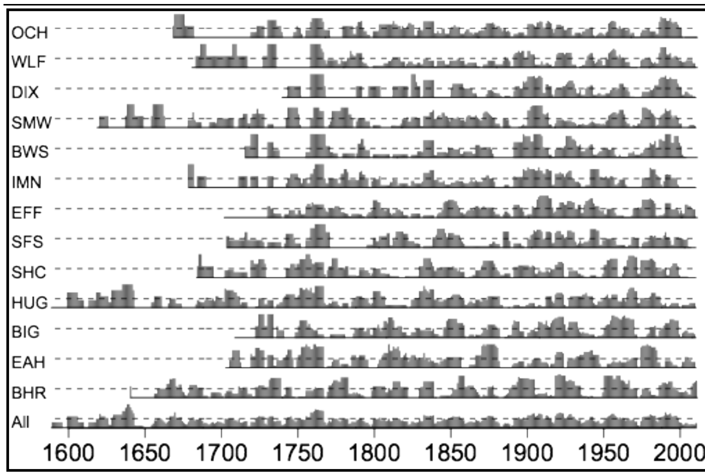

Figure 3: Outbreak records as percent of trees recording an infestation at each site. Bottom plot is the percent of all trees at all sites recording an infestation. Solid line at base of each site's record indicates the total record length, defined as the period in which data were available from at least two trees. Dashed line indicates the 40% threshold used to identify outbreak periods.

2. Western spruce budworm outbreaks were initiated by periods of below average moisture availability.

We found a strong, consistent association where warm-dry conditions occurred in the three years preceding outbreak initiation. A pattern of warm-dry conditions one to three years preceding outbreak initiation has not been reported in previous tree-ring studies, but our results are corroborated by observational records of outbreaks and agree with research addressing larval survival rates. Forests consistently maintain small populations of western spruce budworm, but predation keeps them below outbreak levels. Climate may be a particularly important factor during the earliest stages of an outbreak, before populations have surpassed predation pressures.

3. Forest fires were not associated with western spruce budworm outbreaks.

Within-stand tree-ring reconstructions of fire and outbreaks revealed no consistent relationship between the timing of these disturbances. Although both disturbances were associated with reduced moisture availability, they occurred randomly in time relative to each other. This lack of association may be explained by two factors. First, each disturbance type is associated with slightly different climatic events, with western spruce budworm associated with the ends of droughts and fire simply associated with single drought years. Second, our analysis of the association between climate and fire occurrence indicates that fire is not strongly fuel limited. Rather, fuel moisture and ignition appear to be the dominant limiting factors on fire in these forests. There is a well-established positive association between relatively warm, dry years and the probability of large fire occurrence in the interior Pacific Northwest. We propose that any change to fire risk due to defoliation (for example, due to coarse wood accumulation, increased wind speeds, or decreased canopy fuel) is therefore likely masked by the overriding influence of climatic variability.

4. Simulation results suggest that defoliation reduces both torching and crowning potential.

In our simulations we found that defoliation consistently reduced both the vertical and horizontal spread of crown fire, across a range of surface fire intensities. More defoliation resulted in less canopy consumption by fire and less heat release, regardless of surface fire intensity. Defoliation also increased the minimum surface fire that would torch a tree. Single, highly defoliated trees experienced little or no torching, and moderately defoliated trees (50%) required about twice the surface fire intensity of undefoliated trees to produce the same heat output (>3000 kW). Similarly, a row of defoliated trees released substantially less heat than a row of undefoliated trees. Branchwood drying and heterogeneous fuel arrangement mitigate the effects of defoliation, but these effects, as well as cell size, were less pronounced than the effect of defoliation itself. This dampening effect on torching is likely to affect crown fire spread at the stand scale.

Contrary to other insect disturbances, defoliation has a dampening effect on crown fire behavior because of the unique way that defoliation impacts fuels. Bark beetles such as the mountain pine beetle kill most host trees, leaving dry, dead needles on trees for 2-3 years. In contrast, the western spruce budworm removes needles from trees as it feeds, leaving healthy needles behind and killing few trees. The removal of fuel and low mortality make this a unique insect disturbance.

5. High intensity, stand replacing fires are unlikely to start in, or spread through defoliated stands

One potential implication of our work is that areas significantly defoliated by western spruce budworm could act as a deterrent to crown fire spread. Infested stands may inhibit crown fire initiation or spread for years after an outbreak, until foliage is fully recovered. Relatively low mortality of large trees from western spruce budworm in conjunction with long outbreak durations create persistent stands of defoliated overstory trees. Combined with high mortality of intermediate and sapling host trees and reduced cone production (Bulaon and Sturdevant 2006), closed stands may be maintained with little regeneration even several years after outbreaks have ended. This may create stands with few ladder fuels, further reducing a stand's susceptibility to stand replacing fires. The reduced torching found in our simulations suggest that western spruce budworm may create a stand structure more conducive to non-lethal surface fire instead of stand replacing fire (Fig. 4).

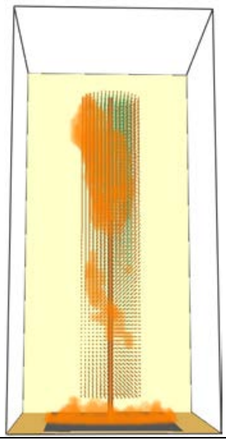

Figure 4. A graphic of a WFDS simulation of torching a single tree. Systematic variation of the level of defoliation and surface fire intensity allowed us to address the partial effects of defoliation on torching of individual trees.

6. **Operational fire models in the US may not capture the effects of insects like western spruce budworm**

Our study found a reduction in crown fire that could not have been identified using operational fire models in the US. We found that the critical surface fire intensity needed for torching changes with canopy bulk density when foliar moisture and canopy base height are held constant. Operational fire behavior models in the US identify transitions from surface to crown fire using only canopy base height and canopy fuel moisture (Finney 1998; Scott and Reinhardt 2001). This study indicates that bulk density also plays an important role.

Conversely, small branchwood, even at low moisture contents, did not have a large effect on crowning in our simulations. Small branchwood is included by many fuel calculation models (e.g., Keane et al. 2006) because it is thought that it is available to the flaming front of an advancing crown fire (e.g., Brown and Reinhardt 1991). In our simulations small branchwood ignites at higher surface fire intensities than foliage, even when concurrent foliage is burning. This would indicate that the branchwood may be consumed during smoldering combustion after the flaming front has passed, and may not contribute to the flaming front of a crown fire. This could be a result of our parameterization of small branchwood in WFDS, which was assigned a lower ratio of surface area to volume than foliage. The effect of branchwood fuel load in operational crown fire models is complex, and based on our simulations, we suggest that further research is warranted.

Relationship to other recent findings and ongoing work

1. We are close to completion of the analysis for a second modeling paper "Canopy structure and defoliation effects on vertical wind profile at a forest edge." We are using WFDS to study how the loss of canopy bulk density due to defoliation affects the wind field within tree crowns. As wind is a key driver of fire spread, the ability to characterize the wind profile associations with crown structure would be very useful for fire behavior modeling. There remains a potential feedback, unstudied in the defoliation simulations to date, in that defoliation results in less wind reduction, which could translate to increased surface fire spread rate. The simulations are using four stands, based on actual tree sizes and density measured in the field-based portion of the study. Simulations over a 1-km domain

will contrast undefoliated and 50% defoliated trees. The simulations for this study are still underway, regrettably, due to issues with computer resources.

2. Future work will address the question of which processes control tree establishment in budworm-affected stands. Past studies indicate tree establishment is controlled largely by climate and fire. The marginal effect of budworm defoliation on tree establishment has not been studied, but several potential mechanisms exist such as decreased seed production or changing understory conditions during an outbreak. Field-work at each of the 13 sites included aging more than 20 trees across a range of size classes to determine the stand-age distribution and therefore infer the establishment history for the past century or more. We will compare stand-establishment histories with disturbance histories and with climate.

3. Other related work, peripheral to the funded project, addressed whether prior defoliation by western spruce budworm affected subsequent fire severity. A Masters student, Ian David Crickmore, in Gavin's lab at the University of Oregon examined the partial effect of budworm defoliation on fire severity in the 2003 B&B Complex Fire in the Oregon Cascades (Crickmore 2011). Crickmore (2011) developed spatial data layers for burn severity (measured by the Monitoring Trends in Burn Severity project), vegetation type, elevation, daily fire weather, fuel loads from vegetation plots, and a defoliation index of the western spruce budworm. He found that burn severity was best explained by elevation, forest type, and fire weather, but was unrelated to prior defoliation severity.

4. We add to the growing body of work using Computational Fluid Dynamic (CFD) fire models to support ecological findings of insect-fire interactions. Although the tree-ring studies found no relationship between fire and western spruce budworm outbreaks, there is growing evidence that western spruce budworm defoliation may actually decrease subsequent fire risk (Lynch and Moorcroft 2008) or size (Preisler et al. 2010), which we were able to corroborate using a CFD model (WFDS). Recent work has highlighted the inability of US operational models to model heterogeneous insect interactions with fire (Jolly et al. 2012; Moran and Cochrane 2012) and concurrent work has demonstrated the effectiveness of new CFD fire models in exploring insect-fire interactions (Hoffman et al. 2012; Linn et al. 2013). Using WFDS, we demonstrated a reduction in torching and crowning that previous work (Hummel and Agee 2003) with stand-scale models (FFE-FVS; Reinhardt and Crookston 2003) could not identify.

5. Aquila Flower, the PhD student who conducted the field-based portion of the project, is beginning a side project that stemmed from this project. With a National Science Foundation Doctoral Dissertation Research Improvement Grant ("Interactions Among Forest Defoliator Outbreaks, Wildfires, Climatic Variability, and Nitrogen Availability in the Interior Pacific Northwest"), and a grant from the Mazamas, she is investigating the implications of outbreak events on the nitrogen cycle. At two sites in Idaho, she collected new increment cores for measurement of stable isotopes of nitrogen, which should be sensitive to changing nutrient cycling regimes due to fire and drought.

Future work needed

Does defoliation reduce fire-caused mortality of host trees?

Our findings indicate that budworm outbreaks and fire contributed to episodic but not synergistic impacts on the short-needled (Douglas-fir and true fir) component of mixed conifer forests. Despite the disassociation of outbreaks and fire, both disturbances elevate mortality and simulation modeling did reveal that defoliation could notably reduce crown fire behavior under a range of surface fire and branchwood moisture conditions. This pattern brings up the intriguing notion that budworm outbreaks may reduce the probability of mortality from fire. Thus, from the perspective of population dynamics of host tree species, the combined influence of budworm and fire may result in less overall mortality than from fire alone.

To illustrate this idea, we used WFDS output of percent canopy consumption at a range of defoliation levels as input to a tree mortality equation. This equation provided an estimate of mortality for a given defoliation level and surface fire intensity (Ryan and Amman 1994). The results show that for a range of moderate surface fire intensities, total canopy loss and mortality due to defoliation and fire is less than that due to fire alone (Fig. 5). The results suggest that defoliation results in a trade-off between increased risk of mortality due to defoliation and reduced risk of mortality due to fire.

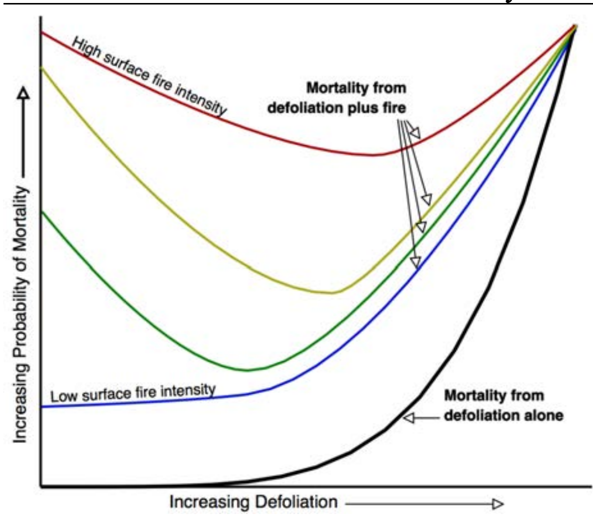

Figure 5. Hypothesized relationship between surface fire intensity, budworm defoliation, and host tree mortality. Mortality increases with both increasing fire intensity and defoliation, but increased defoliation reduces fire-caused mortality over a range of moderate surface-fire intensities. This relationship emerged from simulation modeling of crown consumption by the WFDS model.

The potential reduction in mortality due to defoliation, which emerges from our simulation study, requires more investigation. The simulation study focused on the marginal effect of the reduction in canopy bulk density, but also included effects of reduced branchwood moisture. Notably, the study did not address the effect of defoliation on surface fire intensity (which is being pursued in ongoing work on modeling the wind field in defoliated stands). Field studies may potentially address the marginal effect of defoliation for fires that occurred in stands where fuel conditions are mapped. Such a study by Crickmore (2011), described above, could be repeated under better-controlled conditions, such as prescribed burns. In addition, individual trees could be ignited in controlled conditions to test the predictions from the WFDS model.

Deliverable Cross-Walk Table

Proposed	Delivered	Status
Website	geography.uoregon.edu/envchange/pbl/ and firelab.org/research-projects/fire-ecology/150-interactive-fb	Updated as needed
6 presentations (3 regional or national and 3 at local land offices)	Flower, A., 2013. Interactions between western spruce budworm outbreaks and wildfires in the interior Pacific Northwest: a multi-century dendrochronological record. Oregon Academy of Science. Salem, OR. Cohn, G. 2012: Western spruce budworm defoliation induced canopy fuel reductions increase thresholds for torching and crowning. Fifth International Fire Ecology and Management Congress. Portland, OR. Flower, A., 2012. Interactions between western spruce budworm outbreaks and wildfires in the interior Pacific Northwest: a multi-century dendrochronological record. Fifth International Fire Ecology and Management Congress. Portland, OR. Flower, A., 2012. Interactions between western spruce budworm outbreaks and wildfires in the interior Pacific Northwest: a multi-century dendrochronological record. Association of Pacific Coast Geographers. Olympia, WA. **Christopherson Geosystems Award for Best Applied Geography/Earth Systems Graduate Student Paper*. Flower, A., 2012. Interactions of insects, fire and climate on fuel loads and fire behavior in mixed conifer forests. Central Oregon Fire Science Symposium. Bend, OR. Flower, A., 2011. A multi-century dendrochronological history of western spruce budworm outbreaks in the interior Pacific Northwest. Association of Pacific Coast Geographers. San Francisco, CA. **Tom McKnight and Joan Clemens Award for an Outstanding Student Paper.* Flower, A., 2011. A multi-century history of western spruce budworm outbreaks in the Douglas-fir forests of northeastern Oregon, central Idaho, and western Montana. Association of American Geographers. Seattle, WA. Flower, A., and Gavin, D.G., 2011. Using Tree	Completed.

	Rings to Reconstruct Western Spruce Budworm Outbreak Histories in the Interior Pacific Northwest. Oregon Academy of Sciences. Portland, OR. Flower, A., 2010. Western Spruce Budworm Outbreak, Climate, and Wildfire Interactions in the Interior Pacific Northwest. Association of Pacific Coast Geographers. Coeur d'Alene, ID. *Best Poster Award.* Flower, A., Gavin, D.G., Heyerdahl, E.K., and Parsons, R.A., 2010. Western Spruce Budworm Outbreak, Climate, and Fire Interactions in the Mixed Conifer Forests of the Interior Pacific Northwest. MtnClim. Blue River, OR. *Best Graduate Student Poster Award*. Flower, A., Gavin, D.G., Heyerdahl, E.K., and Parsons, R.A., 2010. Climate, Insect Outbreak, Fire, and Fuel Load Interactions in the Mixed Conifer Forests of Northeastern Oregon, Idaho, and Western Montana. Association of American Geographers. Washington, D.C.	
4 draft manuscripts for peer-reviewed journals	1) Cohn et al. Simulated western spruce budworm defoliation reduces torching and crowning potential: A sensitivity analysis using a physics-based fire model. 2) Flower et al. Drought-triggered western spruce budworm outbreaks in the Interior Pacific Northwest: a multi-century dendrochronological record 3) Flower et al. Synergism between fires and western spruce budworm outbreaks in Douglas-fir forests of the interior Pacific Northwest. 4) Parsons et al. Canopy structure and defoliation effects on vertical wind profile at a forest edge.	1) Submitted to *International Journal of Wildland Fire* 2) Draft close to complete for *Global Change Biology* 3) Draft nearly complete for *Ecology* 4) Draft in progress for *Forest Science*.
A general technical report with site-level information	Title to be determined.	Draft complete.
2 non-refereed publications for fire managers.	1) Cohn et al. "Isolating effects of western spruce budworm "*Fire, Fuel, and Smoke Science Program: 2012 Research Accomplishments.* 2) Cohn et al. "Studying insects, fire and climate at the stand scale "*Fire, Fuel, and Smoke Program Research Accomplishments: 2011 In Review.* 3) Gavin et al. Western spruce budworm is no firebug: fuel and fire behavior in budworm-affected forests of the Pacific Northwest. 4) Gavin et al. Northwest Fire Science Consortium Research Brief.	1&2) Complete 3&4) Drafts in preparation. Will submit after other papers pass peer review.

Fire and insect outbreak histories publicly archived on Gavin's website, International Multiproxy Paleofire Database, & RMRS archive	Data sets are being prepared for 1) International Tree-ring Data Bank (ncdc.noaa.gov/paleo/treering.html) and 2) International Multi-Proxy Fire History Database (ncdc.noaa.gov/paleo/impd/paleofire.html).	Data sets complete but not released until publication.
Permanently archived wood samples at the University of Oregon and eventually at the Laboratory of Tree-Ring Research in Tucson, AZ	Samples in storage at the University of Oregon.	Samples will be sent to Arizona following publication.
PhD Dissertation	Dissertation of Aquila Flower in preparation.	Defense scheduled in June 2013.

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