Relationships between bark beetle outbreaks and subsequent fire severity in the 2006 Tripod fire

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Abstract

Chi squared contingency tables were prepared to test for significantly increased fire severity in areas previously affected by outbreaks of mountain pine beetle (MPB; *Dendroctonus monticola*) or spruce beetle (SB; *Dendroctonus rufipennis*). Using a geographic information system (GIS), the locations of beetle presence determined by annual aerial surveys prior to the fire were overlaid onto maps of fire severity determined by Burned Area Reflectance Classification of the 2006 Tripod Fire in Washington state. Chi square contingency tables were developed to test for significance of overlapping cells. In contrast with other studies reviewed, 1-2 year old SB outbreaks had a high likelihood of being related to severe fire (P>99.9%; chi squared = 29.406), while earlier SB outbreaks had a moderate likelihood (P>90%). Outbreaks of MPB that were 1-2 years old were unrelated to subsequent severe fire (P<80%; chi squared = 0.327), as were outbreaks of MPB older than 5 years (P<85%; chi squared = 2.05). Interestingly 3-5 year old MPB outbreaks had a high likelihood of a spatial relationship (P>97.5%; chi squared = 5.25). These results indicate that the relationship of fire severity to prior beetle outbreaks is complex, and likely involves indirect factors, particularly fuel characteristics that that change from year to year. Potential indirect factors include the species of infected tree and its dominance and crown bulk density within the canopy, the timing of needle drop, the abundance of arboreal lichens, and the need to control for the influences of fire weather and fire-fighting activities. Future studies of the influence of bark beetles on wildfire should focus on fuel characteristics and field validation.

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Background

It is important for forest resource managers to have an understanding of the ecological processes and conditions that affect forest ecosystems (Veblen and Donnegan 2005). There is concern that coniferous forests in western North America are experiencing uncharacteristic outbreaks of bark beetles (*Dendroctonus* spp.) that will compromise the potential benefits from forest resources (Romme *et al.* 2006). There are concerns that beetle-killed trees will predispose those forests to wildfires (Hopkins 1909), with further consequences for fire control, forest health and economic losses. If wildfires are indeed being influenced by uncharacteristic beetle outbreaks, this has implications for the potential impacts of climate change on forest ecosystems as well.

This study was conducted to test for spatial and temporal relationships between bark beetle outbreaks recorded in yearly aerial surveys and subsequent fire effects determined by burn severity mapping within the perimeter of the 2006 Tripod Complex fire. The Tripod fire burned approximately 70,820 ha (175,000 acres) between July 4 and October 31, in the Okanogan Range of the North Cascades in North Central Washington. Much of the area burned at moderate to high elevations (> 1,500 m). At those elevations, the potential vegetation series are dominated by plant associations in the Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) series described by Williams and Lillybridge (1984). These plant associations extend far northward to the sub-boreal forests, where they are collectively grouped together as the Engelmann spruce-subalpine fir biogeoclimatic zone (Meidinger and Pojar (1991). Figure 2 shows a map of the plant associations (Almack et al. 1993). The spruce-fir zone is characterized by a high severity - moderate frequency (35-200 years between fires) fire regime (Agee 1993). This Tripod fire landscape experienced several large fires in the 1920s and 1930s that left behind a mosaic of younger stands of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) interspersed with older stands of spruce-fir.

Recent studies have challenged long-held assumptions that outbreaks of bark beetles increase the severity of subsequent fires. The relationship of mountain pine beetle (MPB, *Dendroctonus monticola* Hopk.) outbreaks on subsequent modeled fire behavior exhibited only slight or negative effects in studies by Tinker *et al.* (2009) and Simard *et al.* (2011) and these results were supported in retrospective studies (Kulakowski and Jarvis 2011, Prichard and Peterson 2009). Conversely, Lynch et al. (2006) did find a small but significant positive relationship between MPB outbreaks of 1972-75 with the Yellowstone fires of 1988. Schoennagel et al. (2012) also found a positive relationship between MPB and fire.

Available studies indicate that forests influenced by spruce beetle (SB, *Dendroctonus rufipennis* Kirby) outbreaks may behave differently during a fire. Bigler *et al.* (2005) found slight positive effects of SB on fire severity 60 years later, however Bebi and Kulakowski (2003) found no effects from SB outbreaks on severe fire 40 years later. The influence of more recent SB outbreaks to severe fire was investigated in a fire simulation study by DeRose and Long (2009) that found that killed stands of pure Engelmann spruce would be less like to experience active crown fire for 1 - 2 decades.

Other uncertainties remain about the relationship of fire to the character and timing of bark beetle pathology as well as the *risk* of ignition, rather than the *hazard* of subsequent fire. The interpretation of these relationships is further complicated by the interdependence of bark beetle outbreaks with other factors that can conceivably support severe fire behavior. Prichard and Peterson (2009) determined some of the important fire severity predictors in the Tripod fire included climate, landform, canopy cover and vegetation type, all of which are related to bark beetle outbreaks.

Bark beetles are suspected to affect potential fire risk and hazard through alterations in the arrangement and moisture content of canopy fuels moisture over time. Beetle outbreaks proceed through a temporal variation in their affect on fuels and potential fire behavior.

The Tripod fire provided an opportunity to study the role of both recent and older outbreaks of SB and MPB on fire severity, because both species of beetles were active in the area for at least a decade prior to the fire, and these outbreaks were mapped and ranked by severity in yearly aerial detection surveys

The objective of this study was to determine if the occurrence of severe fire effects in the Tripod fire was related to prior recorded outbreaks of MPB, SB or both, by period of occurrence.

Methods

Creation of the Burned Area Reflectance Classification (BARC) map layer

Fire severity within the Tripod fire perimeter was determined from the Burned Area Reflectance Classification (BARC) map layer available from the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al. 2007). A BARC is a raster dataset of post-fire spectral reflectance classified into four severity classes: high, moderate, low, and unburned. The cell values in BARC maps are derived from the ratio of the reflectance recorded in the mid- and near-infrared bands 4 and 7 of Landsat 30 m Thematic Mapper (TM) satellite images. These post-fire severity classes are also referred to as the Normalized Burn Ratio or NBR. The mid-infrared light reflectance is a measure of the amount of exposed rock and bare soil; the near-infrared light reflectance is a measure of chlorophyll that correlates with the presence of healthy vegetation, particularly with that of fast-growing, young vegetation and deciduous species.

Where pre-fire TM images are available, the post-fire NBR values can be subtracted from the pre-fire values to derive the delta NBR or dNBR (Key and Benson 2006). The relative differenced Normalized Burn Ratio (RdNBR) normalizes the dNBR by the square root of the pre-fire NBR to help correct for spatial variability in pre-fire forest cover (Miller and Thode 2007), however the results remain suboptimal for comparing forests to woodlands, shrublands and grasslands (Lentile *et al*. 2009).

The severity classes in the BARC map are related to the effects of fire on soils through combustion and mortality, as well as to the increased exposure of these soils through canopy reduction. Even though the BARC metadata refers to the map as a burn severity classification, measured BARC effects on soils are more appropriately referred to as *fire severity* effects, amongst a spectrum of broader ecosystem fire effects that the term *burn severity* increasingly refers to (Keeley 2009). In this study, references to fire severity refer to the rankings of the BARC.

The BARC map layer was processed for analysis by filling in interior offsite cells and assigning them as unburned areas (Figure 1). A polygon file was created from the BARC raster dataset and used to define and analyze the fire perimeter and map polygons of different fire severity.

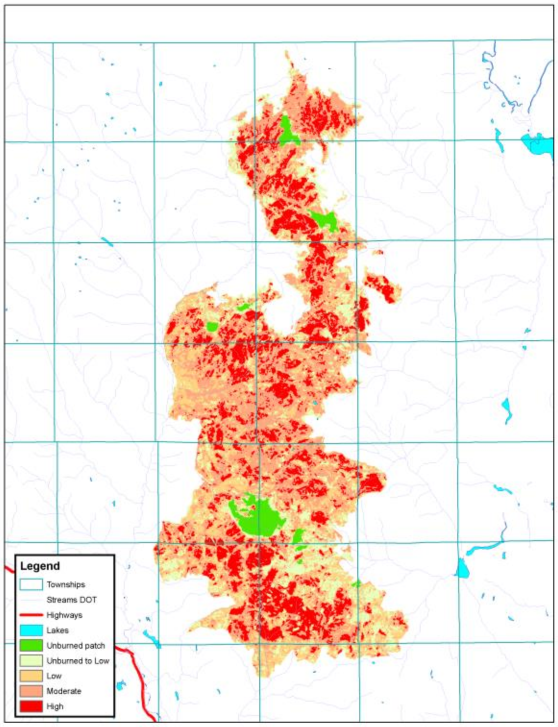
The area:perimeter ratio of the BARC map layer was analyzed to characterize the shape of the fire severity polygons (Figure 5).

Creation of a vegetation map layer

A map layer of forest vegetation cover types within the Tripod fire was developed from the vegetation map of Almack et al. (1993). The map of forest vegetation was used to create an analysis landscape containing only unlogged spruce-fir or lodgepole forests that had not experienced fire since 1970. The 57 m cells were aggregated using a 3 X 3 majority filter and then resampled to a cell size of 114 m. The raster dataset was converted to a polygon shapefile and overlaid onto satellite imagery to manually identify, digitize and exclude meadows, alpine areas, low elevation forests, lakes and logged areas.

For this study, it was necessary to exclude a limited area of salvage units logged within the northeast edge of the fire and visible in a 2009 Landsat image, because the dates when the logging occurred could not be ascertained from the 1998 orthophoto imagery. Also, areas located within 100 m of any of the 3 small lakes in the analysis area were excluded from analysis. The result of this classification is shown in Figure 2. The cover types in this classification are described in Table 1.

The vegetation cover type layer was clipped to the extent of the Tripod fire delineated by the BARC layer. Wherever the vegetation cover types overlapped unburned areas on the BARC layer or areas burned since 1970 on a map layer of historic fires, they were assigned as areas burned since 1970. A map of the analysis landscape containing only unlogged spruce-fir forests or areas burned since 1970 is shown in Figure 3.



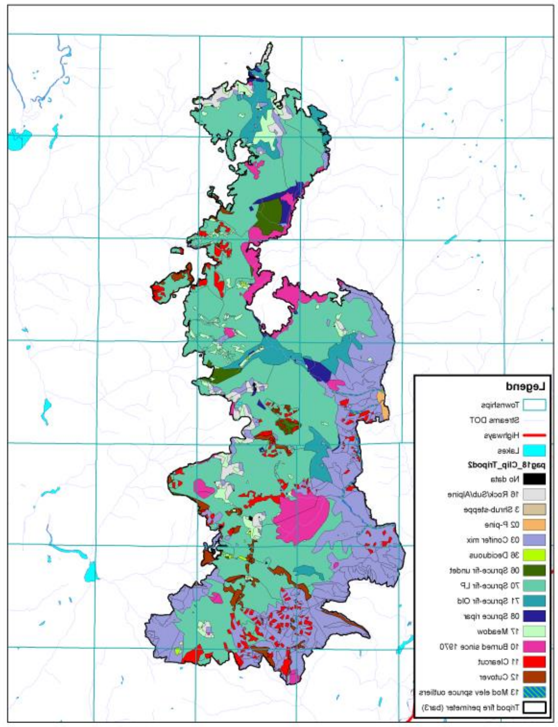


Figure 1 (left). The BARC fire severity layer within the 2006 Tripod fire perimeter. Figure 2 (right). Map of the landscape cover types within the 2006 Tripod Fire perimeter.

Table 1. Description of the landscape cover type classification, field codes and the area of each within the Tripod fire perimeter. "Griz1" and "Griz2" refer to the two sets of raster classifications in the original data from Almack *et al.* (1993); the numeric values are the cell values in the original data.

Field Code-description	**Cover type description**	**Area (ha)**
0-No data	No data	58.0
1-Rocky areas Subalpine and Alpine	Rock/Subalpine/Alpine; includes Griz2 values 16 (PIAL), 17 (LALY), 48 (Rock).	177.2
3-Shrub-steppe	Shrub-steppe; includes Griz2 values 18, 19, 20 (Shrub-steppe).	6.9
4-Ponderosa pine	Ponderosa pine; includes Griz2 value 2 (PIPO).	149.2
5-Conifer mix	Mixed conifer; includes Griz2 values 3 (PSME-PIPO), 4, 5 (PSME Mixed).	17789.2
6-Deciduous forest	Deciduous; includes Griz2 values 36, 38, 42, 44, 46 (Shrub, deciduous).	91.5
7-Spruce-fir undetermined	Spruce-fir with undetermined dominance (lodgepole or mixed conifer mature); includes Griz2 values 6, 7 (ABLA-PIEN-PICO).	1249.2
70-Spruce-fir LP	Spruce-fir (lodgepole dominated). These polygons indicate younger (<100-year old) stands dominated by lodgepole forests over a limited part of the landscape.	35039.1
71-Spruce-fir old	Spruce-fir (old forest). These polygons indicate older (>100 year old) stands dominated by spruce over a limited part of the landscape.	3647.9
8-Spruce riparian	Spruce riparian; includes Griz2 value 8 (PIEN Riparian).	991.3
9-Meadow	Meadows; includes Griz2 values 27, 29, 30, 32, 34 (subalpine, montane meadow and mosaic) and Griz1 value 8 (herbaceous meadow).	2221.8
10-Burn recent	Areas burned after 1970. These were digitized by merging with the layer of historic fires provided by the Forest Service.	4428.5
11-Clearcut	Clearcuts and overstory removal excluded from analysis. These were manually digitized using 1998 1 m digital orthophotos. This layer includes a limited area of salvage units logged within the northeast edge of the Tripod fire, digitized from 2009 Landsat images.	2619.7
12-Cutover	Cutover (partial and selectively logged) lands excluded from analysis. These were manually digitized using 1998 1 m digital orthophotos. This layer includes a limited area of salvage units logged within the northeast edge of the Tripod fire, digitized from 2009 Landsat images.	1728.3
13-Moderate elevation spruce outliers	Low to moderate elevation spruce dominated riparian zones excluded from analysis. These were manually digitized as KML export files using GoogleEarth satellite scenes, followed by importing the KML files back into ArcGIS for reattribution of the unioned overlays.	329.4
14-Lake	Areas within 100 m of a lake.	35.7
	TOTAL	70,562.9

Creation of a beetle outbreak map layer

Beetle outbreaks were mapped using the Washington Department of Natural Resources (DNR) geodatabase layer containing annual aerial surveys for forest disease and damage agents across Washington. The geodatabase contains fields for the agent or type of damage and for the year of the survey.

The insect and damage agent geodatabase was developed by DNR by manually digitizing polygons during yearly aerial surveys conducted since 1980. The digitizing process was conducted by overlapping a digitizing surface over a view of the flight scene, allowing the polygons to be accurately located. Each outbreak polygon was assigned a damage agent or species observed and ranked for incipient mortality in trees per acre of visibly damaged trees. Secondary and tertiary damage agents and their damage severity were also recorded wherever they occurred in the same polygon as a primary agent. Damage severity and incipient mortality was only recorded for the survey year; an attempt was made to exclude dead trees from prior years from the observations. Significant insect and fungal damage agents are listed in Table 2.

Each polygon in the insect and damage agent geodatabase was attributed with the year that the outbreak occurred. Polygons of any given year or any given damage agent could overlap any number or parts of any other polygons.

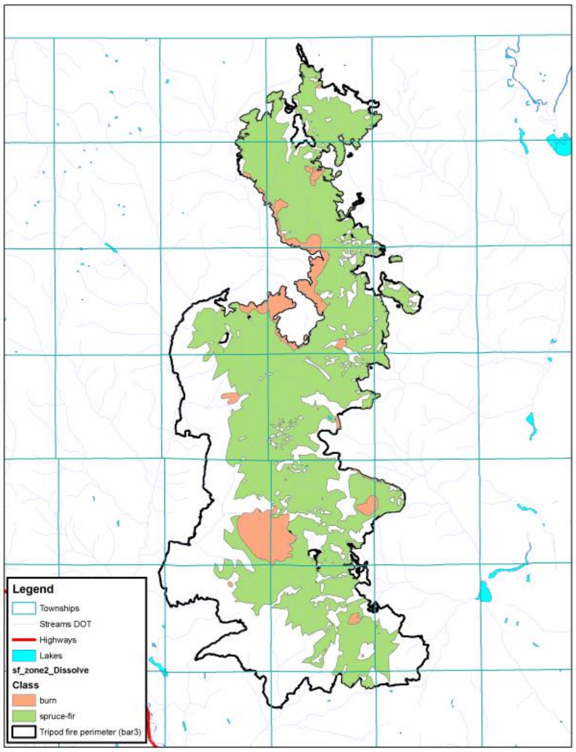
The insect and damage agent geodatabase was converted to a shapefile and clipped to the extent of the 2006 Tripod fire and all polygons recorded after the year 2005 were eliminated (Figure 4).

Gaps in the insect and damage agent shapefile were filled in and scored to indicate that they had no recorded insect or disease damage. This included some polygons classified as burned areas and a cluster of 10 polygons covering a relatively small area (< 10 ha) that were not coded for any agent or any year. Polygons where the primary damage agent was not SB or MPB were deleted, resulting in a map layer containing only polygons representing mortality from SB or MPB outbreaks.

Spatial correlation of overlapping beetle outbreaks was determined from the area of each polygon larger than 0.001 ha representing the combined overlap of all the beetle outbreak categories (n = 12,208 out of 12,644 records).

Table 2. Insect and fungal damage agents contained in the insect and damage agent geodatabase that have caused significant pathological effects in the Tripod fire area of the Okanogan Range. Abiotic agents and minor or non-pathological agents are not shown.

Code	Disease agent	Host
1	Douglas fir beetle (*Dendroctonus pseudotsugae*)	Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco)
2	Douglas fir engraver (*Scolytus unispinosus*)	Douglas fir
3	Spruce beetle (*Dendroctonus rufipennis*)	Engelmann spruce (*Picea engelmannii* Parry ex Engelm.)
4	Fir engraver (*Scolytus ventralis*)	Subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)
5	Western balsam bark beetle (*Dryocoetes confusus*)	Subalpine fir
6B	Mountain pine beetle (*Dendroctonus ponderosae*)	Whitebark pine (*Pinus albicaulis* Engelm.)
6L	Mountain pine beetle	Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.)
6P	Mountain pine beetle	Ponderosa pine (*Pinus ponderosa* Dougl.)
6W	Mountain pine beetle	Western white pine (*Pinus monticola* Dougl.)
7	Oregon pine engraver (*Ips pini*)	Ponderosa pine
8	Western pine beetle (*Dendroctonus brevicomis*)	Ponderosa pine
88	Western pine beetle	Ponderosa pine (in pole-sized trees)
AB	Balsam wooly adelgid (*Adelges piceae*)	Subalpine fir
BR	White pine blister rust (*Cronartium ribicola*)	Whitebark pine
BS	western spruce budworm (*Choristoneura occidentalis*)	Douglas fir, subalpine fir, Engelmann spruce
LC	lodgepole needle cast (*Davisomycella montana*)	Lodgepole pine
RC or ML	Larch needle cast (*Meria laricis* and *Hypodemella laricis*)	Western larch (*Larix occidentalis* Nutt.), Lyall's larch (*Larix lyallii* Parl.)
TM	Douglas fir tussock moth (*Orgyia pseudotsugata*)	Douglas fir



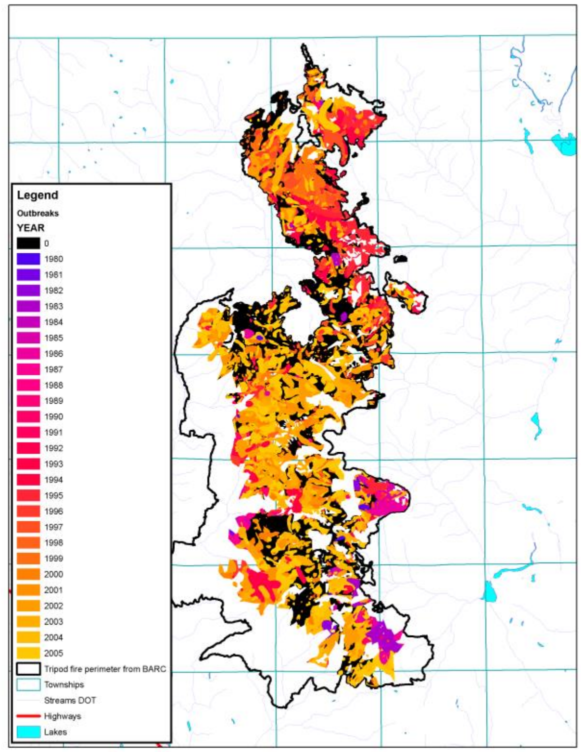


Figure 3 (left). The spruce-fir-lodgepole analysis landscape within the 2006 Tripod fire. Township grid lines are approximately 9.7 km on a side. Only areas classified within the spruce-fir plant association or burned since 1970 are shown (codes 7, 70, 71 and 8 in Table 1). Figure 4 (right). Forest disease and insect outbreaks observed on annual surveys between 1980 and 2005, clipped to the extent of the spruce-fir analysis landscape within the 2006 Tripod fire perimeter.

Analysis of the relationship of fire severity to beetle outbreaks

Analyses were made to determine whether occurrences of severe fire were related to prior outbreaks of MPB or SB. The summed damage severity from all agents was determined for each polygon in trees per acre (1ac = 0.4047 ha).

SB outbreak polygons were segregated from the other records in the beetle outbreak layer and all overlapping polygons were unioned with each other. The cumulative damage severity of all of the overlapping unioned polygons of SB outbreaks was then determined. The cumulative damage severity of the MPB outbreak polygons was determined separately in the same way. The cumulative damage for SB or MPB was exclusive to that species.

The SB outbreak layer then was segregated into two map layers containing polygons corresponding to the years 2004-5 (SB-late) or 1987-2003 (SB-early). The MPB outbreak layer was segregated into three separate layers corresponding to the years 2004-5 (MPB-late), 2001-3 (MPB-mid) or 1981-2000 (MPB-early). Each polygon in each of the SB and MPB outbreak periods was classified into the following cumulative damage of Low (SUM_TPA <= 5.0), Moderate (SUM_TPA > 5.0 and <= 20.0) or High (SUM_TPA > 20.0).

Each of the layers of outbreak periods SB-late, SB-early, MPB-late, MPB-mid and MPB-early were unioned with the polygons in the BARC fire severity layer. For segregation of analyses into Venn sets, a map layer was created containing unioned sets of polygons representing each of the SB and MPB outbreak periods.

Chi squared contingency analyses were developed from sets of 1000 to 8000 sample points placed randomly across a rectangle bounding the Tripod fire perimeter. A subset of random points was taken from those that overlapped the spruce-fir analysis landscape. These subsets of sample points were then intersected with the polygons representing the SB and MPB outbreak periods, so that each point contained the data for both fire severity and cumulative insect damage severity. In order to analyze effects of different combinations of outbreaks , the sample points also scored wherever they overlapped other beetle outbreak categories. The data in each of the analysis sets was used for chi squared contingency analyses.

Results

Fire severity mapping

The BARC polygon map was used to calculate the area of fire severity classes within the 2006 Tripod fire perimeter (Table 3).

There were 18,793 fire severity polygons in the BARC polygon shapefile. The fire severity represented by the polygons generated from the BARC layer was well distributed across the landscape in small to moderately sized patches. In contrast, the interior patches representing unburned areas in the Tripod fire that had been burned in older fires since 1970 were clumped. There were 98 polygons larger than 100 ha. Of these, only four polygons were larger than 1,000 ha. One of these with moderate severity was 10,512 ha in size; the size of the other 3 large polygons was 2076, 1472 and 1195 ha, with severities of 3, 4 and 0 (unburned patch), respectively. The 1,195 ha polygon was that of the 1970 Forks Burn.

Table 3. Fire severity within the Tripod fire determined by the BARC map layer.

Fire severity	Hectares	Percent
0 (unburned patch)	2,140	3.0
1	9,059	12.6
2	16,973	23.5
3	27,827	38.6
4	16,155	22.4
Total	72,154	100.1

Landscape cover types

The area covered by each of the landscape cover types are summarized in Table 4. The analysis landscape within the Tripod fire perimeter was limited to unlogged forests of spruce-fir or lodgepole pine (codes 7, 70, 71 and 8 above) that had not burned after 1970. The area of this landscape was determined to be 40,886 hectares (57% of the area within the Tripod fire perimeter including interior unburned patches). The next most common cover type within the fire perimeter was mixed conifer (25%).

Table 4. The area covered by each of the landscape cover types within the Tripod fire perimeter.

GRID CODE	Cover type	Hectares	Percent
0	No Data	58	0.1
1	Rock/Sub/Alpine	1,775	2.5
3	Shrub-steppe	7	0.0
4	Ponderosa pine	149	0.2
5	Mixed conifer	17,789	24.8
6	Deciduous	92	0.1
7	Spruce-fir undetermined	1,249	1.7
70	Spruce-fir (lodgepole)	35,063	48.8
71	Spruce-fir old forest	3,648	5.1
8	Spruce-fire riparian	1,001	1.4
9	Meadows	2,222	3.1
10	Burned since 1970	4,429	6.2
11	Clearcut	2,620	3.6
12	Cutover areas	1,728	2.4
13	Moderate elevation spruce outliers excluded	329	0.5
	TOTAL	**71,828.6**	**100.5**

Beetle outbreaks landscape

The outbreaks analysis landscape contained 51,658 polygons. The median size of the polygons in this shapefile was less than 1 ha. More than 99% of these polygons represented beetle outbreaks, with the remainder being primarily areas burned since 1970. There were 22 polygons over 100 ha in size, but only 2 of these (both approximately 100 ha in size) were scored as beetle outbreaks. This landscape overlaps areas where the fire perimeters mapped in polygon layers had slightly differently shapes than those of the BARC grid layer.

The map layer representing all overlapping SB outbreaks contained 5,559 polygons ranging in size up to 223.5 ha, with a mean size of 9.1 ha (SD = 20.5) and a median size of 1.8 ha (Figure 5). The summed overlapping damage severity in the spruce beetle polygons ranged from near zero to 88.0 tpa, with a mean of 25.2 tpa (SD=16.8) and a median of 25.0 tpa. Five Jenks natural breaks had breakpoints at 8.0, 18.0, 32.25, and 53.0.

The map layer representing all overlapping MPB outbreaks contained 39,698 polygons ranging in size up to 147.9 ha, with a mean size of 3.3 ha (SD=8.2) and a median size of 0.8 ha (Figure 5). The summed overlapping damage severity ranged from near zero to 81.13 tpa with a mean of 18.5 (SD=15.5) and a median of 13.7 tpa. Five Jenks natural breaks had breakpoints of 8.496, 17.562, 29.638 and 47.37.

The SB and MPB outbreak polygons were classified into 5 sets corresponding to the species and period of occurrence. The location of outbreaks within the unlogged spruce-fir zone of the Tripod fire are shown in Figure 5.

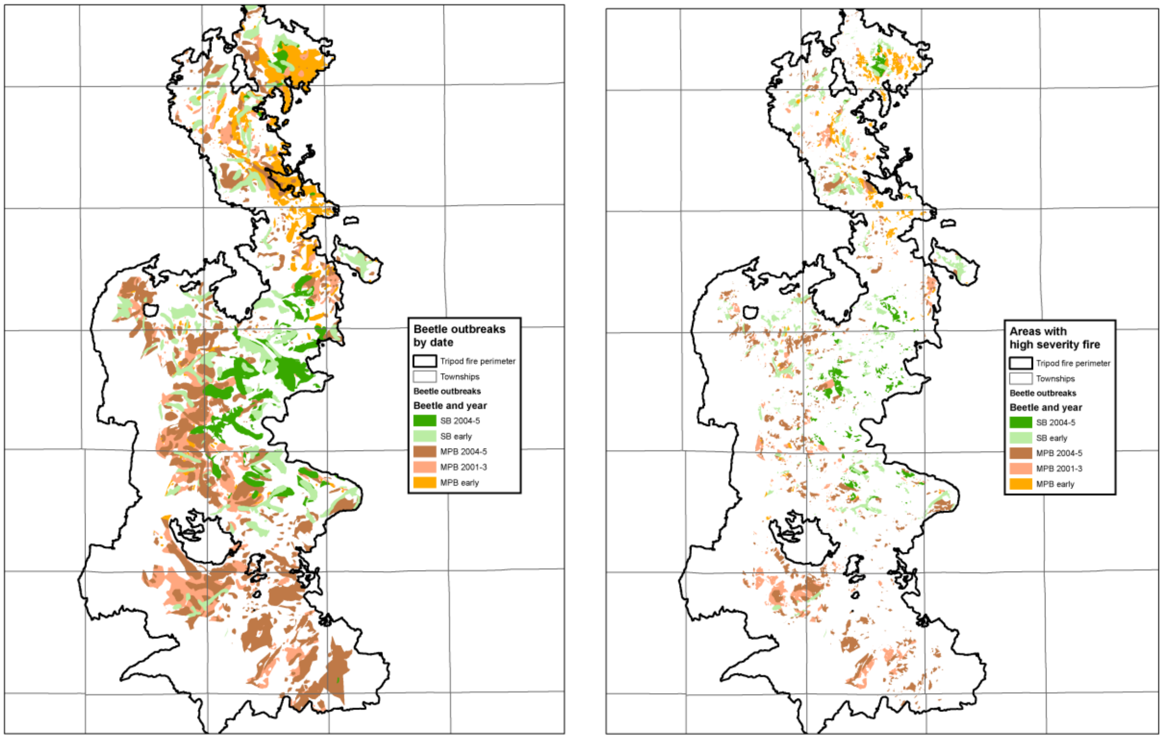


Figure 5. SB and MPB outbreak polygons classified by year of detection within the analysis landscape. (Right) all outbreak categories; (left) SB and MPB outbreaks showing only polygons that experienced high severity fire. In these figures, overlapping polygons are shown in the priority of SB-Late > SB early > MPB 2004-5 > MPB 2001-3 > MPB early. In the left image there is overlap of part of an outbreak into a burned area, due to differences in the maps of historic fire input layers. This was corrected by excluding those fires from both maps.

Demography of the beetle outbreaks

The insect and damage geodatabase was used to segregate SB and MPB outbreaks into time periods.

The MPB outbreaks occurred continuously across the landscape as individual stands of lodgepole reached stem diameters capable of successful invasion by MPB (Figure 6).

The SB outbreaks observed on aerial insect surveys began with a long latency period in the mid-1980s. Between 1987-1990, two outbreaks were detected between Tiffany Springs Campground and Roger Lake, each about 10 ha in size and each having about 10 infected trees. In the years 1995-7, six outbreaks were observed in the same area. In the years 1998-9, only one outbreak was observed in the area. In the years 2000-1, there were 6 large outbreaks observed in the area, although only one small outbreak was observed in the aerial surveys of Roger Lake Basin. During 2002-5, the observed outbreak spread across the landscape. The pattern of SB outbreak progression is shown in Figures 7 and 8.

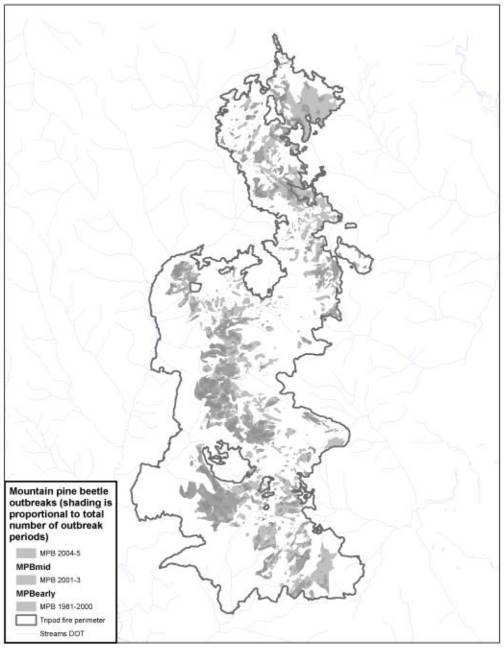


Figure 6. Cumulative MPB outbreaks observed in aerial flights across the spruce-fir landscape within the Tripod fire perimeter. The darkness of the shading represents the summed overlap of the three outbreak periods. Outbreaks that occurred in mixed-conifer forests dominated by Douglas fir are not shown.

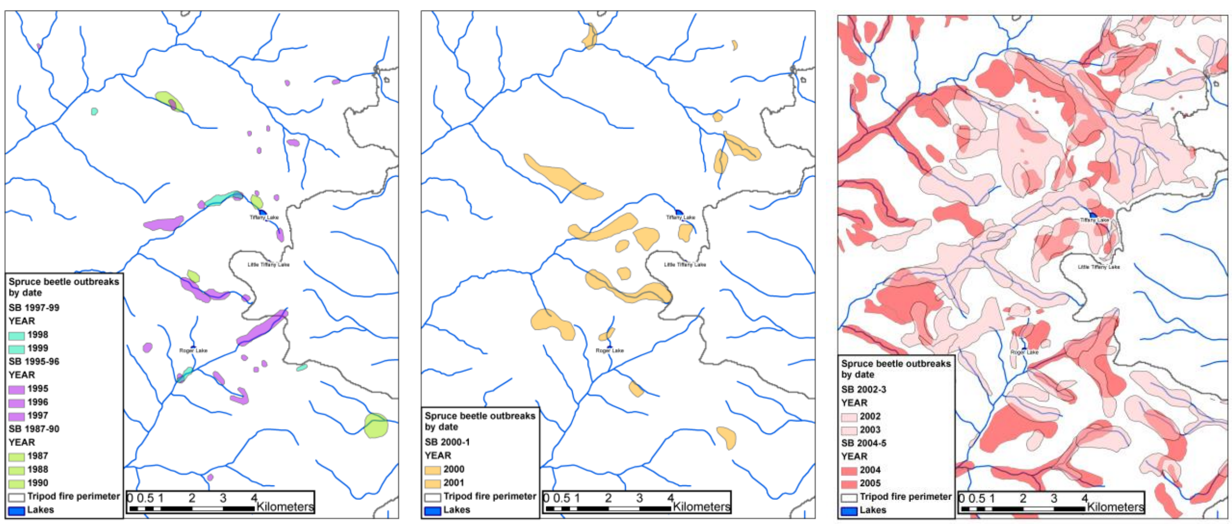


Figure 7. Spruce beetle outbreak progression observed in aerial flights above the area between Tiffany Springs Campground and Roger Lake; (left-right) 1987-1999, 2000-2001, 2002-5.

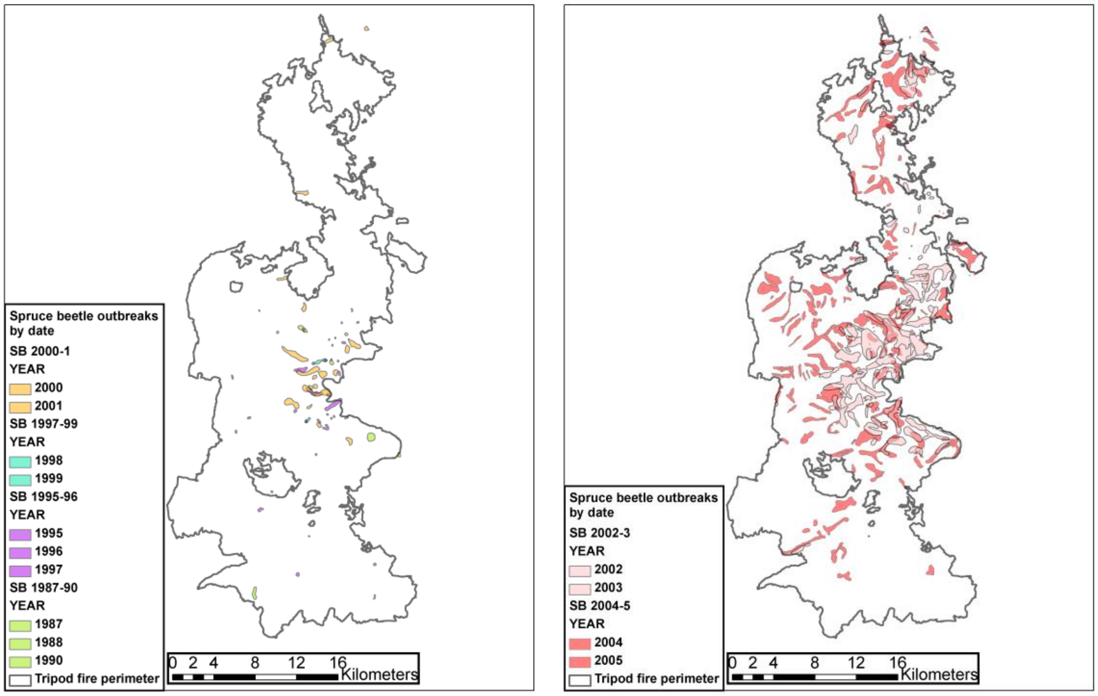


Figure 8. Spruce beetle outbreak progression observed in aerial flights across the Tripod fire landscape; (left-right) 1987-2001, 2002-5.

Spatial correlation of beetle outbreaks

Table 5 contains a cross-tabulation of the area of overlapping beetle outbreak categories within the unlogged spruce-fir zone of the Tripod fire. The percentage of area overlap of the categories of beetle outbreaks within the unlogged spruce-fir zone of the Tripod fire is shown in Table 6.

Table 5. A cross-tabulation of the area (ha) of overlapping beetle outbreak categories in shapefile outbreaks_singlep.shp within the unlogged spruce-fir zone of the Tripod fire. This analysis includes a small amount of overlap into areas that may have burned after 1970 where the clipping polygon sf_zone2_Dissolve.shp contained fire polygons with slightly differently shapes than those of the BARC grid layer bar3.

Area (ha)	SB-Late	SB-Early	MPB-Late	MPB-Mid	MPB-Early
SB-Late	**5083**	1397	572	948	1170
SB-Early	1397	**5348**	509	521	674
MPB-Late	572	509	**11430**	4900	3887
MPB-Mid	948	521	4900	**10146**	5233
MPB-Early	1170	674	3887	5233	**11058**

Table 6. The percentage of area overlap of the categories of beetle outbreaks in shapefile outbreaks_singlep.shp within the unlogged spruce-fir zone of the Tripod fire. The top-right cells contain the percentage of the cross-product with the diagonals to the left; the bottom left cells contain the percentage of the cross-product with the diagonals to the right.

Area (ha)	SB-Late	SB-Early	MPB-Late	MPB-Mid	MPB-Early
SB-Late	**100**	27.5	11.3	18.7	23.0
SB-Early	26.1	**100**	9.5	9.7	12.6
MPB-Late	5.0	4.5	**100**	42.9	34.0
MPB-Mid	9.3	5.1	48.3	**100**	51.6
MPB-Early	10.6	6.1	35.2	47.3	**100**

Testing the relationship of fire severity to beetle outbreaks

Contingency tables in a 2x2 matrix were used to test for significance of the co-occurrence of severe fire and severe beetle outbreaks. Chi squared test statistics were determined for each of the high-severity SB and MPB outbreaks periods. These statistics were created by intersecting random sample points that overlapped areas of unlogged spruce-fir forests with the BARC severity layer and with each of the 5 categories of outbreak polygons in turn. The occurrence of severe fire effects following outbreaks of MPB or SB by period of occurrence was determined in combination with prior outbreak occurrences (Table 7) as well as in cases that had only a single outbreak occurrence (Table 8).

Table 7. Outbreak category refers to samples that overlapped the indicated outbreak category and no other category. SB early refers to outbreaks that occurred during the period 1987-2003; MPB early refers to the period 1981-2000; MPB 2001-3 refers to the period of 2001-3, MPB recent or SB recent refer to the period 2004-5. N (set) is the number of points included in the 2x2 chi square analysis for the specified species and outbreak period. N(test) indicates the number of points that had both severe fire and moderate-severe insect mortality that was tested with the chi squared statistic. These statistics were created by intersecting random sample points that overlapped areas of unlogged spruce-fir forests, sf_zone3.shp, with the BARC severity layer, bar7poly.shp.

Outbreak category	N (set)	Moderate-high beetle severity (%)	% severe fire in moderate-high beetle outbreaks	Chi squared	P()
SB-late	1132	14.2%	49.1%	29.406	>99.9%
SB-early	712	11.7%	31.3%	2.989	>90%
MPB-late	761	17.3%	20.5%	0.327	<50%

MPB-mid	674	6.7%	37.8%	5.250	>97.5%
MPB-early	1200	3.3%	17.9%	2.050	<85%

Table 8. Overlap indicates that the sample point overlapped the indicated outbreak category(ies) and no other categories.

Outbreak category	**Overlapping outbreak categories**	**N(set)**	**N(test)**	**Chi squared**	**P()**
SB-late	any period of moderate-severe MPB	1294	31	0.300	<40%
SB-early	any period of moderate-severe MPB	596	6	0.476	<75%
MPB-late	moderate-severe MPB-mid or moderate-severe MPB-late	440	67	0.409	<50%
MPB-mid	MPB-early	185	38	6.227	>97.5%

Influence of riparian areas

In order to consider whether the effects of fire and insects might be related to the ecology of riparian zones, a map was made of SB outbreaks overlaid by a map of streams (Figure 9).

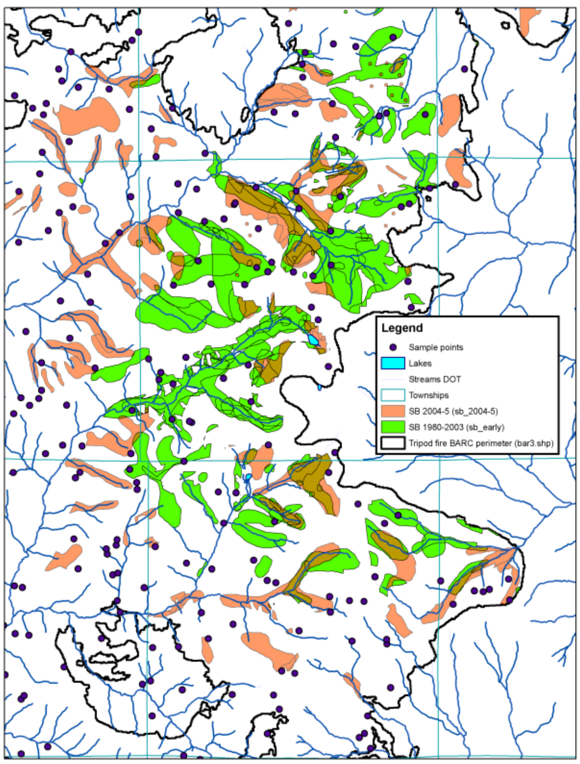


Figure 9. Map of spruce beetle outbreaks within the Tripod fire perimeter showing their relationship to riparian areas.

Discussion

Fire severity

Within the 72,154 ha Tripod fire of 2006, high severity fires covered 22.4% of the study landscape. This study was limited to the spruce-fir zone of the Tripod fire, which in the pre-fire landscape consisted of continuous canopy spruce-fir forests with only two dominant overstory species: Engelmann spruce and lodgepole pine. Subalpine fir was present, but not well represented.

Within the 2006 Tripod fire, high severity fire was distributed across the landscape in patches ranging up to 1,472 ha in size (Figure 1). There was a trend toward greater perimeter:area ratio with increasing fire severity (Figure 5).

Figure 1 and Table 3 show that the fire severity polygons of all classes were well distributed across the landscape, except for areas that burned prior to the Tripod fire since 1970 that were excluded from these analyses. The perimeter:area ratio of the fire severity polygons shown in Figure 5 demonstrates that most polygons have wavy edges and these appear to become more so with increasing fire severity. A perfect circle would have a ratio of 35.4 while a perfect square would have a ratio of 40

In this study, fire severity was modeled using a BARC map. It should be noted that tree mortality is another widely used measure of fire severity. A widely accepted standard for high severity fire using this metric is a 75% mortality threshold (Morrison and Swanson 1990; Agee 1993; FRCC 2005). Since this study was primarily a test for relationships, we did not measure the accuracy of the BARC map classification with field measurements, however this is recommended for future studies.

Keeley (2009) cautioned that the relationship of burn severity to conifer mortality needs to be carefully evaluated in consideration of the species affected. The NBR is influenced by pre-fire reference conditions wherever the satellite data covers variable bare ground cover or chlorophyll-rich vegetation. In order for NBR mortality rankings to be consistent across different landscapes, Safford *et al*. (2008) recommended that mortality analyses assess the *RdNBR*, a relative index derived by dividing the dNBR by that of the pre-fire image. However, for this study, that method would be complicated because of widespread spatial and temporal variation in the onset of dead and dying beetle-killed trees that would influence the dNBR differentially in the infected stands (Figure 4). The issue of pre-fire canopy variability was addressed by delineating the spruce-fir analysis landscape to exclude non-forested areas, cutover areas and recent burns. This produced a pre-fire landscape of remarkably even canopy cover ranging from ca 60-90%, and containing only two main stand ages of ca 90 and 200 years, dominated respectively by either lodgepole or Engelmann spruce.

Demography of the SB outbreak

The observed SB outbreaks began with a few scattered outbreaks beginning in 1987, that appeared to have subsided by 1999 (Figure 7). This period represents the lag phase of a lag-log outbreak progression. Observed activity began to show log phase growth during 2000-1. Beginning in 2002, rapid expansion of SB was observed across the study area, lasting until it was interrupted by the 2006 Tripod fire (Figures 7, 8).

The transition from lag-phase to log-phase growth of the SB outbreaks appears to have actually occurred 2 years earlier than when it was detected by aerial surveys, in the year 2000 or possibly 1999. During the years 1987 to 2005, aerial surveys recorded high- and moderate-severity SB outbreaks within the fire perimeter covering only 3,711ha (9,166 ac). This represents only a fraction of the area of spruce-fir forests within the study area that actually did withstand stand-level loss of spruce (author's personal observation). But even if the aerial surveys underestimate the actual extent of the SB outbreak, the available data should strengthen the value of a chi squared contingency analysis by restricting the positive mortality records to those that are clearly due to SB.

One source of observational error during the aerial flights is that the time for a tree to become mortally infected and its initial visibility in an aerial overflight is often shorter than one year. When these trees are detected during the aerial surveys, the protocol excludes counting trees considered to have died previously on the assumption that they were already been recorded.

The Forest Service first became aware of the extent of the SB outbreak in this study area in August 2000, following a survey by entomologist Paul Flanagan on the ridge between Tiffany and

Roger Lakes, a year or so after they were first reported in the Tiffany Lake area. He noted that the majority of large Engelmann spruce in this watershed > 25 cm DBH would be expected to be killed during this outbreak. His projection began to be borne out by the end of 2002, when essentially all of the large spruce in Roger Lake Basin were dead, and the outbreak had spread both north and east about at a rate of about 8 km per year.

In an August 2000 letter to the Methow District, entomologist Paul Flanagan noted that the annual aerial survey flight did not provide an accurate estimate of the total area affected. This was also confirmed by a demographic study of outbreak progression in two stands of trees near Roger Lake that were undetected through 2001.

SB mortality begins with a barely perceptible reddening in the upper crown of the tree, while the lower branches remain green. In the early course of this outbreak, trees that were mortally infected with high numbers of SB showed only a slight reddening of the upper needles during the fall and spring that may not have exceeded the damage threshold observed on the aerial flights.

This early outbreak in the years just prior to 2000 resulted in rapid and total mortality of all the needles on infected trees within a single season. The method of scoring insect damage during aerial detection surveys could have contributed to detection errors because trees that are already dead are not scored for the year, under the presumption that they would have been scored the previous year. During the early part of the lag-log transition, the only trees visible may have been either all green or all red, neither of which would have been scored.

The insect and damage surveys did show some early outbreaks in that area. There were two outbreaks identified between Tiffany Springs Campground and Roger Lake between 1987-1990, each about 10 ha in size and each having about 10 infected trees. In the years 1995-1997, there were 6 infestations in the same area. In the years 1998-1999 there was only one infestation observed. In the years 2000-1 the outbreak exploded into 6 large outbreaks in the Tiffany Basin, although only one small outbreak was observed in the Roger Lake Basin. Yet Flanagan's survey and another by the author of this study confirmed that by 2001, the infestation had spread to about 90% of the large diameter trees in Roger Lake Basin, even though it was only visible as faint reddening in the upper crowns.

The low aerial detection rate was also demonstrated in two areas of near total mortality in 2002, in two study plots of spruce beetle demographics near Roger Lake. The southern plot had no aerial detection of any spruce beetle mortality by 2002 and the other plot showed only a small infestation in a nearby area during that time period. Yet on the ground, it was clear that almost all of the large spruce between these two plots had already become mortally infected. The areal surveys first noted this infestation in 2002, by which time essentially all the trees > 25 cm diameter at breast height (DBH) in these stands had died. The SB outbreak was recorded in aerial surveys to have spread to the remaining nearby stands during 2004-5, when most of the trees that died in 2002 had no spruce beetles at all, since those trees were no longer a food source for the beetles.

Other types of stand-level disturbances may complicate the determination of beetle outbreaks. During the years between 1987 to 2000, there were 3 windthrow events that affected Tiffany Springs Campground. The first event occurred in approximately 1990 and primarily affected exposed trees along the road, although the storm did knock down a few trees in the campground. The second event occurred in the mid-1990s. It affected the higher ridges and blew over a number of lodgepole pines in the campground. These were salvaged in a small sale primarily designed to protect visitor safety. The third windthrow event occurred a year or two after the first. It toppled more of the remaining larger standing trees that were left after the salvage operation in the campground.

Despite these sources of error, it is now clear that large areas of Engelmann spruce died during an outbreak of SB in the Cascades of northeast Washington. The progression of the outbreak was observed and recorded by areal surveys in a way that made it possible to use chi-squared analysis to test for spatial correlation between the outbreaks and fire severity.

It is worth noting that the initial outbreak appears to have been favored by early onset of warm weather in the spring. A University of

Washington demographic study of spruce beetles in the Roger Lake Research Natural Area began in 2001, timed for expected emergence in July. But when the trees were inspected on July 1, the broods had already begun to leave the trees, 2-3 weeks earlier than expected by entomologists. By the end of 2001, all of these trees had red needles in the upper crown, and by the end of 2002, all of the needles (and spruce trees in this cohort) were dead. The demography of this outbreak apparently involved a change from univoltine life cycle to a semivoltine life cycle, due in part to an earlier onset of warm weather suitable for brood emergence.

Relationship of fire severity to beetle outbreaks

This study found that there does appear to be a positive relationship between fire severity and prior beetle outbreaks, but it is complex, and likely involves indirect factors, particularly fuel characteristics that that change from year to year.

Over half of the area of the 2006 Tripod fire burned through unlogged spruce-fir and lodgepole pine dominated forests (Table 4). The spruce-fir forests in the study area occur in two age classes, one dominated by lodgepole pine dating from extensive fires in the 1920s and 30s, and the other a 200-year age class dominated by large spruce trees that survived the fires of the 1920s. In the 3 decades prior to the Tripod fire, both of these age classes of spruce-fir forests were attacked across a broad landscape by two insect pathogens. These insects were MPB, that primarily attacks the largest lodgepole pines over 10 cm in diameter within a stand (Cole and Amman 1980), and SB, that primarily attacks spruce over 10 cm DBH (Figure 5).

The observed MPB outbreaks began in lodgepole forests during the 1980s and continued in large patches until the 2006 Tripod fire burned through the area (Figure 6). The SB outbreak began in the 1990s.

The likelihood of significant spatial correlation of severe fire effects following outbreaks of MPB or SB by period of occurrence was determined using a chi-squared analysis both separately and in combination with prior outbreak occurrences. SB outbreak periods were categorized as SB-late (2004-5) or SB-early (1987-2003). MPB outbreak periods was categorized as MPB-late (2004-5), MPB-mid (2001-3) or MPB-early (1981-2000). Severity of the SB and MPB outbreak periods was classified by the cumulative number of damaged trees as Low (SUM_TPA <= 5.0), Moderate (SUM_TPA > 5.0 and <= 20.0) or High (SUM_TPA > 20.0).

In contrast to several other studies, this study found that 1-2 year old SB outbreaks had a high likelihood of being related to severe fire (P>99.9%; chi squared = 29.406), while earlier SB outbreaks had a moderate likelihood of a relationship (P>90%). Nearly half of the samples that were ranked to have moderate to high SB outbreak severity also had subsequent severe fire.

This study was in agreement with most other studies in the case of 1-2 year old MPB outbreaks which were unlikely to have a relationship to severe fire (P<50%; chi squared = 0.327), whereas MPB outbreaks older than 5 years were unlikely to have a relationship (P<85%; chi squared = 2.05). Strangely, 3-5 year old MPB outbreaks had a high likelihood of a relationship (P>97.5%; chi squared = 5.25), indicating either the data is inaccurate or there are indirect factors operating in that class of outbreak period.

Using this same fire severity data set, Prichard and Peterson (2009) investigated a number of predictors for fire severity including MPB outbreaks determined by the enhanced wetness difference index (EWDI) from Landsat 5 TM imagery between August 18, 2003 to August 8, 2005 (EWDI, Wulder *et al*. 2006). They found only weak relationships between MPB and subsequent severe fire.

Other results of the chi squared analysis performed for this study were as follows:

1. SB-late had high correlation with severe fire whether overlapping areas with high or moderate MPB outbreaks were included or not.
2. SB-early had moderate correlation with severe fire, but when overlapping areas with high or moderate MPB outbreaks were included the correlation significance decreased.
3. MPB-late did not correlate with high fire severity regardless of whether areas with

overlapping MPB-early or MPB-mid outbreaks were included.

4. MPB-mid had moderate correlation with high fire severity, but when overlapping areas with MPB-early outbreaks were included, the correlation became very high.
5. MPB-early not having any other types of overlapping outbreaks had only moderate correlation with high fire severity.

All of the above results indicate that significant relationships likely exist between bark beetles and subsequent severe fire, but they are complicated by indirect effects. Indirect effects can be segregated into those due to the biology of the insects and those due to fire behavior, particularly fuel characteristics.

For instance, the fire severity following insect outbreaks was reversed between early and late dates for the two insect species. There are host structural differences in the pathogenicity of these two species, that could partly explain this reversal. Because the recorded observations used to measure insect severity landscapes were mutually exclusive between species, our analysis may have underrepresented the presence of beetle mortality in stands where both beetles were active.

Another potential indirect effect of insect outbreaks depends on the timing of needle drop following an outbreak. Following a disturbance such as fire, needles may remain on trees for a number of years (Wooten et al. 1997+). Fire behavior studies indicate dead needles contribute to fine fuels and raise crown bulk density, and that this in turn should increase crown fire potential for while the needles remain on the trees. If so, then the crown potential should drop when the needles drop (Cruz et al. 2010).

Over the course of its spread, the SB outbreak resulted in widespread spruce mortality across the landscape. By 2005, the year before the fire, nearly all large spruce trees near Tiffany Lake and Roger Lake were dead. Most of these were likely still standing when the fire burned through. Engelmann spruce has dense crowns that support heavy accumulations of lichens, notably *Bryoria fremontii* (Tuck.) Brodo & D. Hawksw. Crowns adorned with lichens are speculated to contribute to fire behavior (Agee et al. 2002). The branches of Engelmann spruce maintains these accumulated lichens and needles for years after an outbreak, and this provides conditions that increase crown fire potential. In contrast to Engelmann spruce, the crowns of lodgepole pine are shorter and narrower and have a high crown base and only half the crown bulk density of Engelmann spruce (Cruz et al. 2003).

Another indirect effect on severe fire behavior may have involved high severity plume-dominated fire spreading, which may be somewhat independent of crown-to-crown spreading. An analysis of topographic relationships is needed to determine whether the relationship of topography to fire is dominating the fire severity. Fire behavior may be indirectly affected by fire fighting techniques, including back burning large areas in a way that would not occur naturally, and severe fire weather days where fire spreading is driven by weather instead of fuels.

Another factor influencing the results is the close association of Engelmann spruce with riparian areas, unlike lodgepole pine, which is facultative. Figure 9 indicates that spruce-beetle outbreaks tended to occur in riparian areas. Whether this is due to the demographics of the outbreak or of the ecology of spruce is irrelevant, because the influence of riparian areas on fire behavior is well acknowledged.

Riparian areas influence and attenuate wildfire. The lower temperatures and moist soils may allow for partial survival of stands as wildfires move from uplands into the riparian zone. In any case, the following observations indicate that riparian areas affected the dynamics of the beetle outbreaks. The sequence of early (pre-2004) and later (2005-5) SB outbreaks tended to occur in adjacent polygons, rather than directly overlapping polygons. This indicates that the effect is likely due at least in part to the demographics of the outbreak itself, as it radiated outward from its initial center near Roger Lake. Wherever a SB outbreak erupted in stands in this area, it invariably caused total mortality in the size class > 20 cm DBH. Early outbreaks tended to consume all of the available food source, excluding those stands from future outbreaks and likely affecting their predicted fire behavior.

The relationship of high severity fire to insect outbreaks will continue to be an important issue for managers who must grapple with the problems of managing ecosystems for fire, insects and people. Recommendations for future studies are to include field-based sampling methods, in order to improve the quantification and timing of bark beetle outbreaks and fire severity. Potential indirect factors to include in studies are the species of infected tree and its dominance and crown bulk density within the canopy, the timing of needle drop, the abundance of arboreal lichens, and the need to control for the influences of fire weather and fire-fighting activities. Future studies of the influence of bark beetles on wildfire should focus fuel characteristics.

In considering these results and in light of other studies that have found effects of beetle outbreaks on fire behavior ranging from strong to none, caution to consider a wide range of potential variables is recommended before making any broad conclusions.

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