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Comparing changes in fuel loading, tree regeneration, and forest structure in once- and twice-burned mixed-conifer forests with a before-after-control-impact case study in the Bob Marshall Wilderness

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COMPARING CHANGES IN FUEL LOADING, TREE REGENERATION, AND FOREST STRUCTURE IN ONCE- AND TWICE-BURNED MIXED-CONIFER FORESTS WITH A BEFORE-AFTER-CONTROL-IMPACT CASE STUDY IN THE BOB MARSHALL WILDERNESS

By

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ABSTRACT

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Wildfires drive landscape character in the seasonally dry mixed-conifer forests of western North America. Forested landscapes in this region are a mosaic of overlapping burn perimeters, which span a wide gradient of severity and burn age. The goal of this study was to compare the effects of single and repeat wildfires on fuel loading and forest structure and composition. Our study site spans the east and west sides of the South Fork of Flathead River in the Bob Marshall Wilderness. The east side of the river burned in 2000 in the Helen Creek Fire. The west side of the river burned in 2003 in the Little Salmon Complex. Data was collected in 2011. In 2013, the east side of the river burned again, but the west side of the river did not burn a second time. In 2015, plots on both the east and west side of the river were resampled. Between 2011 and 2015, mean coarse woody debris load (>7.6 cm diameter) in twice-burned plots decreased by 23%, while once-burned plots increased by 76%. Total mean fine woody debris (<7.6 cm diameter) decreased by 30% in twice-burned plots and increased by 80% in once-burned plots. These changes in woody debris are the net outcome of inputs from standing dead trees that fell between 2011 and 2015 (including branch fall) and outputs from combustion and decomposition. For both once- and twice-burned plots, the density of live trees changed very little between measurements, but the density of dead trees significantly decreased. The density of dead western larch saplings and seedlings tended to be greater on twice-burned plots. The once- or twice-burned variable has a strong effect on surface fuels and tree regeneration, but a weak effect on forest structure and composition. The results of this study suggest that shorter fire return intervals lead to lower surface fuel load and more fire-tolerant forest structure and composition.

Contents

Introduction

Wildfire is a primary component of the disturbance regimes of many western forests (Arno 1980; Habeck and Mutch 1973). When unmanaged, the behavior of a wildfire is determined by weather, topography, and the abundance of consumable fuel. After many seasons of active fire, the perimeters of consecutive wildfires, and the gradient of disturbance severity they contain, begin to overlap (Figure 1). The severity of the composite disturbance generated by consecutive fire events, or ‘reburns’, depends on the severity of past fires and the time between consecutive fire disturbances (Parks, Miller, Nelson, and Holden 2014; Teske, Seielstad, and Queen 2012).

Figure 1. Example conditions in once-burned (left) and twice-burned landscapes (right) in the Bob Marshall Wilderness, Montana.

There is a significant amount of published research investigating the frequency and size of reburn events, but almost all of this work is based on satellite-derived measurements, with almost no field-based studies (Collins et al. 2009; Parks et al. 2014; Parks, Holsinger, Miller, and Nelson 2015; Teske et al. 2012; van Wagtendonk and Thode 2012). Wildfire management in wilderness areas is often limited, therefore studying wildfire in wilderness areas allows researchers to better isolate the impacts of past natural wildfire from the impacts of past landscape management (Keane et al. 2002; Lerifallom et al. 2011; Parks et al. 2015). Few case studies have been conducted on sites that lend themselves toward a control design, which contains distinct regions of once-burned and twice-burned plots within the same general area. The conclusions reached within wilderness areas have implications for fire managers in nonwilderness areas (Hopkins, Larson, and Belote 2014). Case studies such as this clarify the impact of manipulating confounding variables, such as time between consecutive fires and previous fire severity, on the ecological trajectory of fire-adapted ecosystems after reburn events.

The purpose of this study is to identify the impacts of consecutive wildfire events, or ‘reburns’, on surface fuels as well as forest structure and composition. This study is focused on three research questions.

1. Do twice-burned areas have less coarse woody debris and fine woody debris than once-burned plots?
2. How does the density and composition of overstory trees on once- and twice-burned plots compare?
3. How do seedling and sapling mortality rates on once- and twice-burned plots compare?

We predicted that twice-burned plots would have less surface fuel load, lower density of overstory trees, and a greater amount of regeneration (seedlings and saplings).

Methods

Study Site

The study site is located at the confluence of Little Salmon Creek and the South Fork of the Flathead River in the Bob Marshall Wilderness, Montana, USA (47.651397°N, -113.361699°W. All plots within the study site are on minimal slopes within 300 m of elevation of the valley floor, which is at approximately 1340 m of elevation. The forested areas throughout the study site are composed of Douglas-fir (*Pseudostuga menziesii*), lodgepole pine (*Pinus contorta),* western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa),* Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). The dominant overstory includes 200-700 year-old western larch.

The Bob Marshall Wilderness was designated a wilderness area in 1964 with the passage of the Wilderness Act. In 1981, fire managers began managing fires for resource benefit. Prior to this period, some fire suppression did occur, but resource limitations and the area's remoteness inhibited complete wildfire suppression historically. Based on personal communication with Seth Carbonari, the AFMO of Spotted Bear Ranger District, about half of wildfire ignitions annually are only passively managed. The active management practices of the district include a focused effort to defend historic structures locally and preserve main trail access throughout the season. Additionally, early season wildfire ignitions are monitored and even extinguished to limit the scale of fire events later in the season.

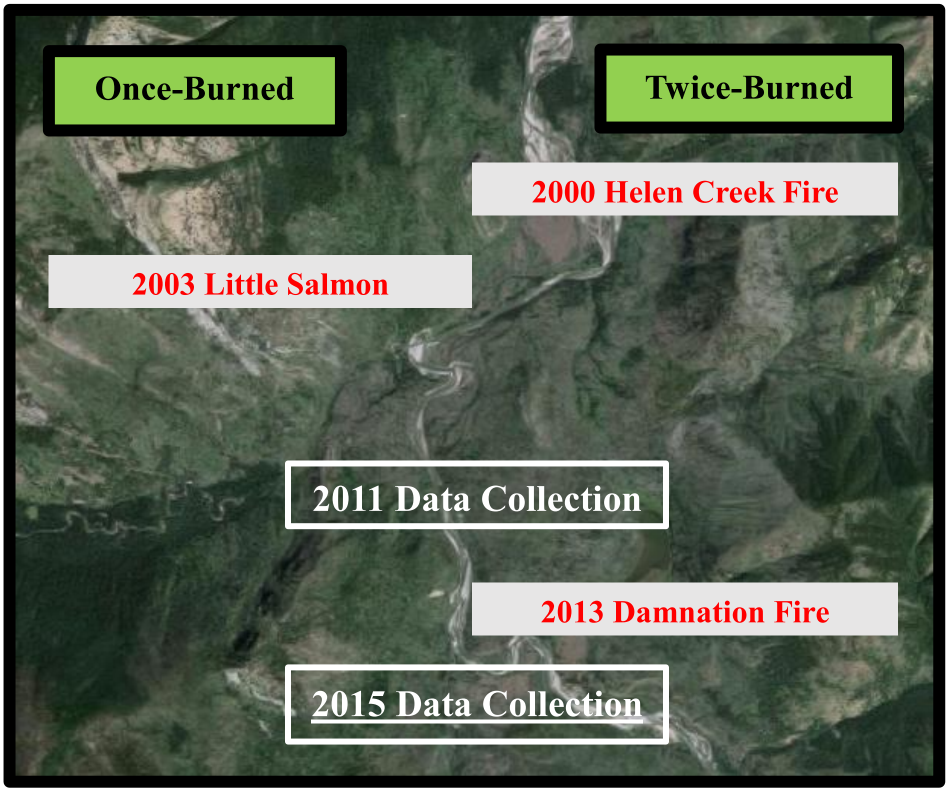

Figure 2. Map of fire events and data collection periods.

The west side of the South Fork of the Flathead corridor at the point of the Little Salmon Creek's confluence burned in 2003 during a fire event called the Little Salmon Complex. The east side of the corridor burned in 2000 in a fire event called the Helen Creek fire. Additionally, the area east of the South Fork of the Flathead burned again during the Damnation Fire in 2013, but the area west of the river did not burn a second time (Figure 2). Lightening ignited the 2000, 2003, and 2013 fires, and managers dealt with them both only passively.

In 2011, prior to the second fire event in the area, 10 plots were collected on each side of the river to characterize the severity of the 2000 and 2003 fires. In 2015, the plots were remeasured to compare the recently twice-burned area on the east side of the corridor to the still once-burned area on the west side of the corridor.

Field Sampling

In 2015, we relocated and remeasured the 20 plots recorded in 2011 using the GPS coordinates recorded at plot center in 2011. In 2011, we did not physically mark each plot center.

To inventory fine wood debris (FWD), we recorded fuels transects based on the planar intersect technique of Brown and Van Wagner (Brown 1971; Van Wagner 1968; Van Wagner 1982). Each plot had four transects which ran north, east, south, and west from plot center. Along the transects, we counted the number of intersections of 1 hr (0-1 cm) and 10 hr (1-3 cm) fuel particles along the transect from 3 m to 6 m from plot center. Likewise, we counted the number of intersections of 100 hr fuels from 3 m to 9 m from plot center. Furthermore, along each transect we measured duff and litter depths at 3 m and 9 m from plot center.

To inventory coarse woody debris (CWD; >7.6 cm diameter), we measured the large-end diameter, small-end diameter, and length of all woody debris particles within the perimeter of a 6 m radius subplot with its origin located at plot center. If a piece of woody debris tapered to a diameter less than 7.6 cm, the small end diameter and length would be measured only up to the point at which the debris still had a diameter greater than 7.6 cm. If a piece of woody debris crossed the boundary of the 6 m radius subplot, we record only the length of the particle within the boundaries of the subplot. For each particle, we also recorded an evaluation of species and decay class.

To inventory seedlings (<1.37 m tall), we recorded the height class (0-40 cm, 40-80 cm, or 80-137 cm) and species of stems within four 1 m radius subplots which were centered 6 m north, east, south, and west of plot center as well as a 1 m radius subplot at plot center.

To inventory saplings (>1.37 m tall and <20 cm diameter at breast height), we recorded the diameter class (0-5 cm, 5-10 cm, or 10-20 cm), status (alive or dead), and species of all saplings within 17.84 m of plot center.

Finally, to inventory trees greater than 20 cm in diameter at breast height (DBH), we recorded the species, diameter, tree type (live standing tree, dead standing tree, or uprooted and/or snapped below DBH but inferred standing at time of fire) within 17.84 m of plot center. Additionally, we recorded trees with a diameter at breast height greater than 80 cm within 47.3 m of plot center.

Data Reduction and Analysis

To expand the count of transect intersections into a metric of fuel load, we used the equation $W = (\frac{Gk}{L}) \sum d^2$(Van Wagner 1982) where G is specific gravity, k is a conversion constant equal to 1.234 Mg/ha, L is the length sampled by the transect, and d is diameter of intersected particle at point of intersection. The sampling length is a total of 12 m per plot for 1 hr and 10 hr fuels and 24 m per plot for 100 hr fuels.

To calculate the fuel load of CWD within the measured fixed-area plots, we first calculated each fuel particles volume using the equation $V = (\frac{\pi h}{3})(R^2 + Rr + r^2)$, where h is the length of the particle, R is the large-end radius, and r is the small-end radius. We used each particles estimated decay class and species to derive a density based on published values (Bisbing, Alaback, and DeLuca 2010; Harmon & Sexton 1996; Harmon, Woodall, Fasth, and Sexton 2008). The reference densities used for all decay classes of *Abies lasiocarpa* and *Pinus contorta* are gathered from Harmon et al. 1996. The reference densities for all classes of *Picea engelmannii* were gathered from Harmon et al. 2008. The densities for classes 1-4 of *Pseudotsuga menziesii* and *Larix occidentalis* were gathered from Bisbing 2010, and the 5th decay for both species were derived from extrapolation of a polynomial trendline based on decay classes 1-4. Finally, the average of the density of each species within the sample was used for the density of particles of ‘unknown’ species (See Appendix A for exact decay class densities). Using these reference densities, we converted the calculated volume into a mass value. Finally, we derived a plot-level fuel load estimate (Mg/ha) by dividing the derived mass value with the calculated area of our 6 m radius CWD subplot (0.011309734 ha).

Plot-level measurements of trees larger than 20 cm in DBH, as well as saplings 5-20 cm in DBH, were expanded to a trees per hectare density by dividing the tree count by the sample area of the 17.84 m radius plot, which has an area of 0.1 ha.

Plot-level measurements of seedlings were expanded to a trees per hectare density by dividing the tree count by the total sample area of all five 1 m radius subplots, which have a total area of 0.001570796 ha.

Plot centers were not physically marked in 2011, therefore the 2015 measurements are not remeasurements of the 2011 plots. Instead, the mean of the 10 plots collected in 2011 and in 2015 are compared rather than 2011 and 2015 measurements of individual plots that have the same general location. Due to the heterogeneity of fire disturbance and the number of plots in the sample, the range of variability of the sample is a considerable proportion of the mean. However, the effect size of the twice-burned variable is large enough that comparing the mean of the sample is still significant in some instances. Furthermore, in addition to being a measure of error, the variability of the sample is a reliable measure of the stochasticity of fire disturbance.

Results

Surface Fuels

FWD

In general, for once-burned plots there was an increase in fine woody debris (FWD), fuel particles less than 7.6 cm in diameter, between the 2011 and 2015 measurements (Figure 3). Oppositely, there was generally a decrease in the load of FWD for twice-burned plots between 2011 and 2015 (Figure 3).

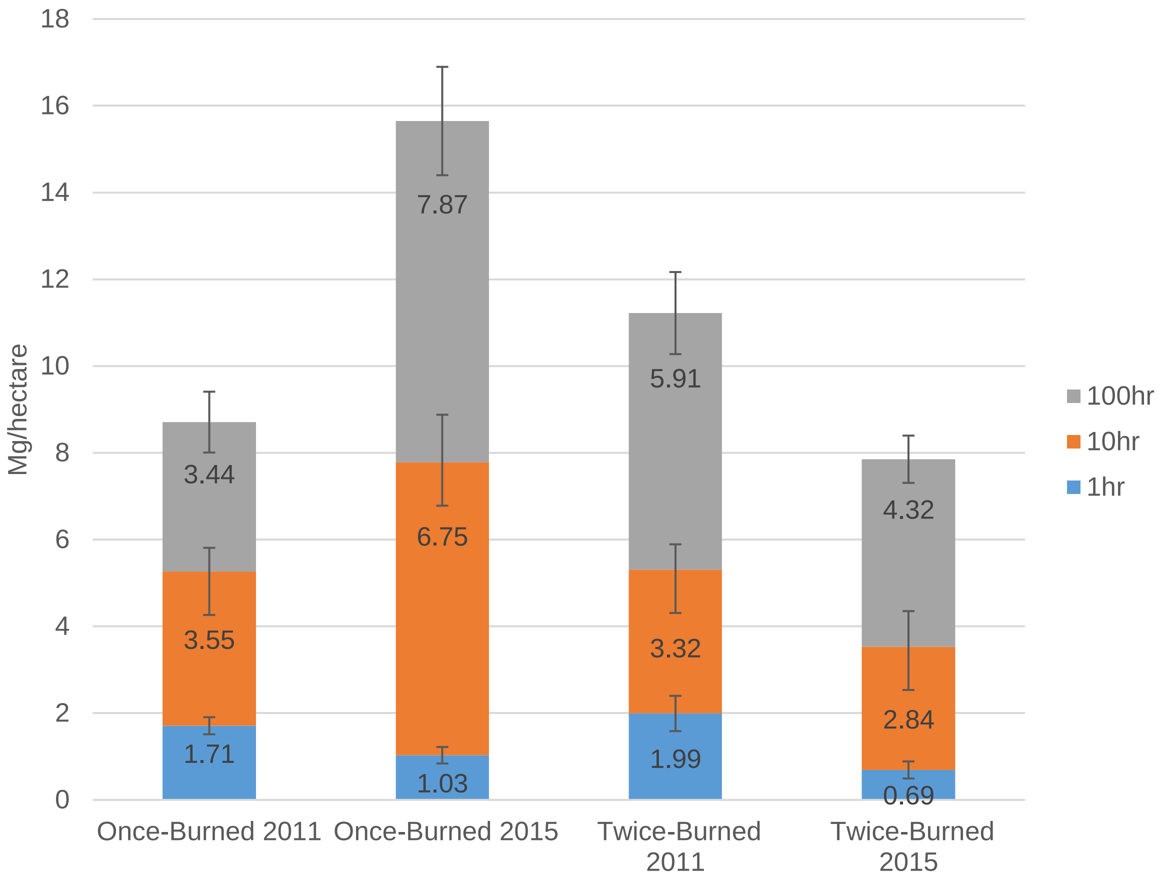

Figure 3. Fuel load (Mg/ha) of fine woody debris for once- and twice-burned areas, separated by the contribution of 1 hr, 10 hr, and 100 hr fuel particles.

The mean load for 100 hr fuels in the once-burned area increased 129% (from 3.44 Mg/hectare to 7.87 Mg/ha) between 2011 and 2015, whereas the mean load for 100 hr fuels decreased 27% (from 5.91 Mg/ha to 4.32 Mg/ha) in the twice-burned area. Similarly, the mean load of 10 hr fuels on once-burned plots increased 90% (from 3.55 Mg/ha to 6.75 Mg/ha), while on twice-burned plots the mean load decreased by 14.5% (from 3.32 Mg/ha to 2.84 Mg/ha). However, the mean load of 1 hr fuels on once-burned plots decrease 40% (from 1.72 Mg/ha to 1.03 Mg/ha), more closely mirroring the 65% decrease in mean 1 hr fuel load (from 1.99 Mg/ha to 0.69 Mg/ha) on twice-burned plots.

CWD

In general for once-burned plots there was an increase in the mean load of coarse woody debris (CWD), fuel particles greater than 7.6 cm in diameter, between the 2011 and 2015 measurements (Figure 4). Oppositely, there was a decrease in the mean load of CWD for twice-burned plots between 2011 and 2015 (Figure 4). The mean load of CWD on once-burned plots increased 76%, whereas the mean load decreased 21% on twice-burned plots. The standard error of each mean is between of 19% and 25% of the mean.

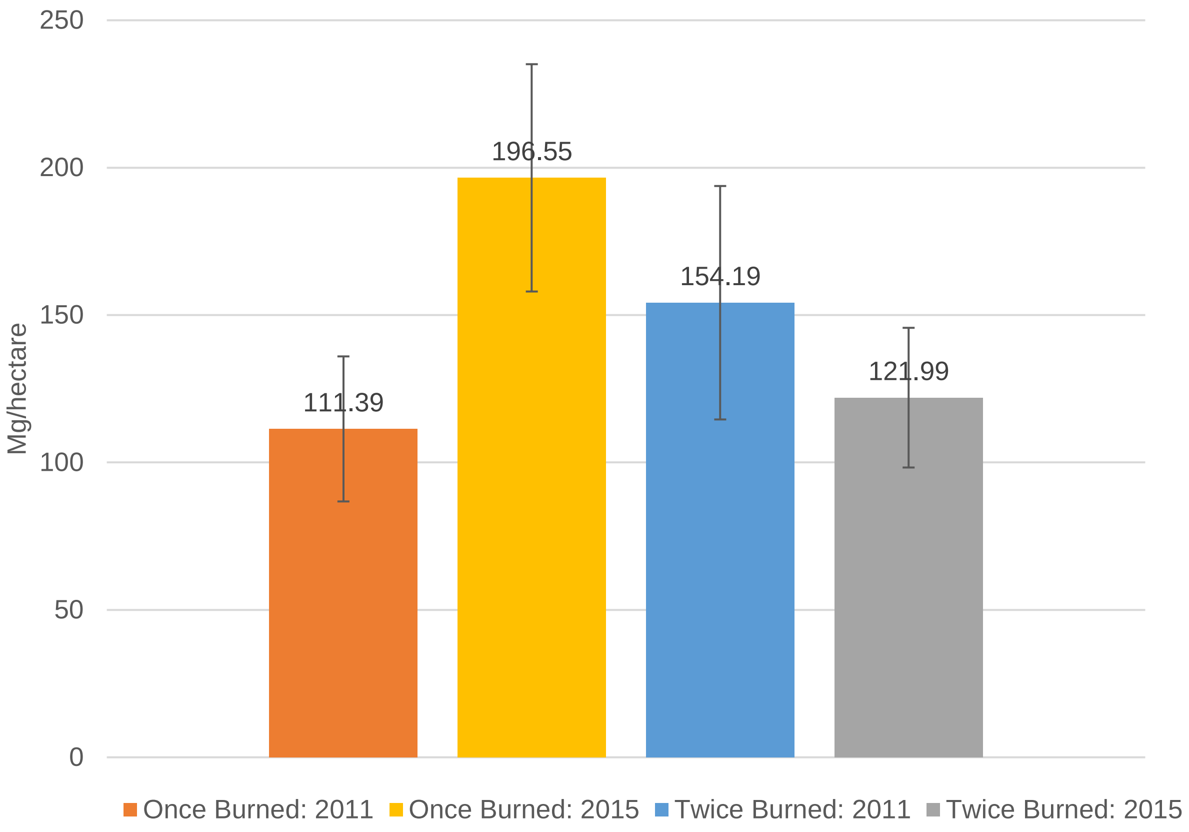

Figure 4. Fuel load (Mg/ha) of coarse woody debris for once- and twice-burned areas.

Forest Structure and Composition

Large Stems

Considering trees of all species, both alive and dead, there is no significant difference in the density of stems recorded on once-burned and twice-burned plots (Figure 5). Between the 2011 and 2015 measurements period, on average there is a decrease in the number of stems recorded on once- and twice burned plots, in nearly all size classes, with the largest decrease found in the density of the smaller size classes, 20-35 cm and 35-55 cm. The decrease in the average total stem density is most closely associated with a decrease in the number of dead tress per hectare (Figure 5).

The composition of live trees on both once- and twice-burned plots is largely composed of Douglas-fir (*Pseudostuga menziesii*) and western larch (*Larix occidentalis*), with a minor Engelmann spruce (*Picea engelmannii*) component (Figure 6). Furthermore, fire-intolerant species such as lodgepole pine (*Pinus contorta)*, and subalpine fir (*Abies lasiocarpa*) are very scarce within the sample, even within the subsample of dead trees. In general, western larch is a larger portion of the species composition of both live and dead trees of the once-burned sample, than it is within the twice-burned sample. Conversely, Douglas-fir (*Pseudostuga menziesii*) is largest portion of the species composition of both live and dead trees within the twice-burned sample.

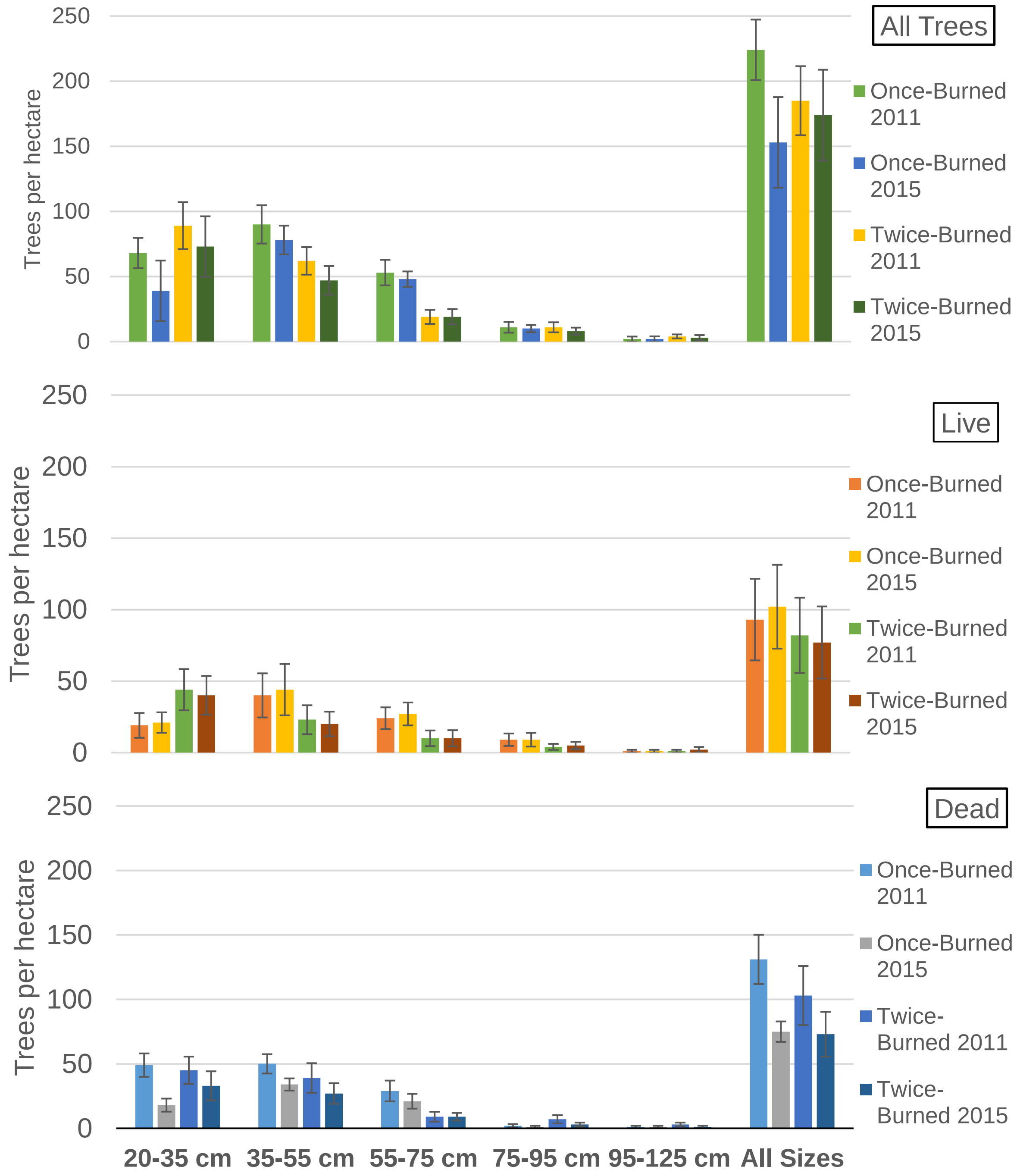

Figure 5. Density (trees per hectare) of stems greater than 20 cm in diameter at breast height. Summary of all trees, as well as live and dead trees separately. Diameter size class bins are the same for each figure and are labeled on axis of bottom figure.

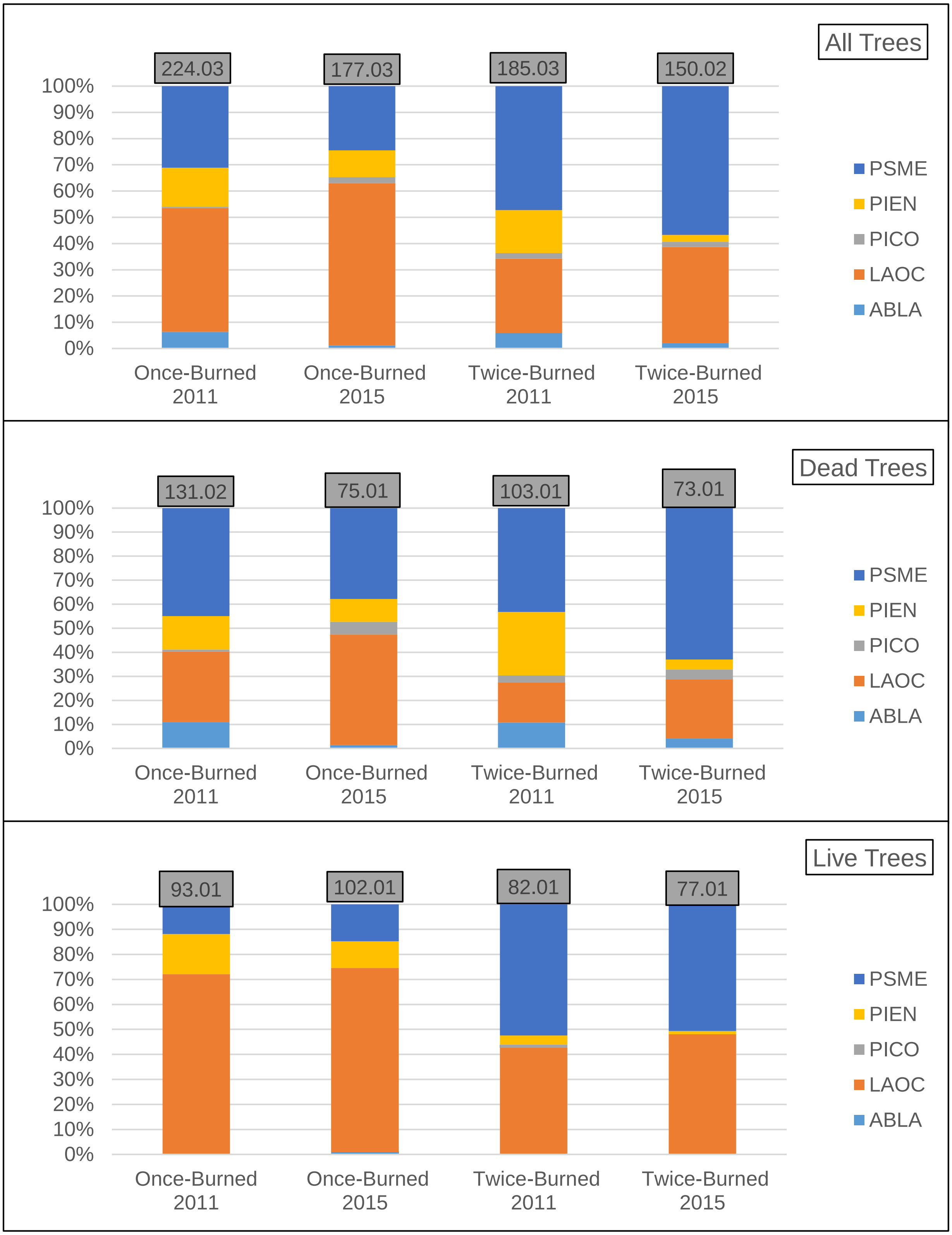

Figure 6. Species composition of all trees greater than 20 cm DBH, as well as all live and dead trees separately. The mean total trees per hectare of each treatment is displayed at the top of the stacked columns.

Saplings

There are more dead western larch saplings, in all size classes, on twice-burned plots than there are on once-burned plots (Figure 7). For all species other than western larch, between 2011 and 2015, there was an increase in the number of dead saplings on twice-burned plots, whereas there was a decrease in the number of dead saplings on once-burned plots (Figure 7). In addition, during the first measurement period in 2011, there were almost no dead saplings present. Furthermore, between 2011 and 2015, there was a significant decrease in the number of saplings on twice-burned plots, whereas there was a slight increase in the number of saplings on once-burned plots (Figure 7).

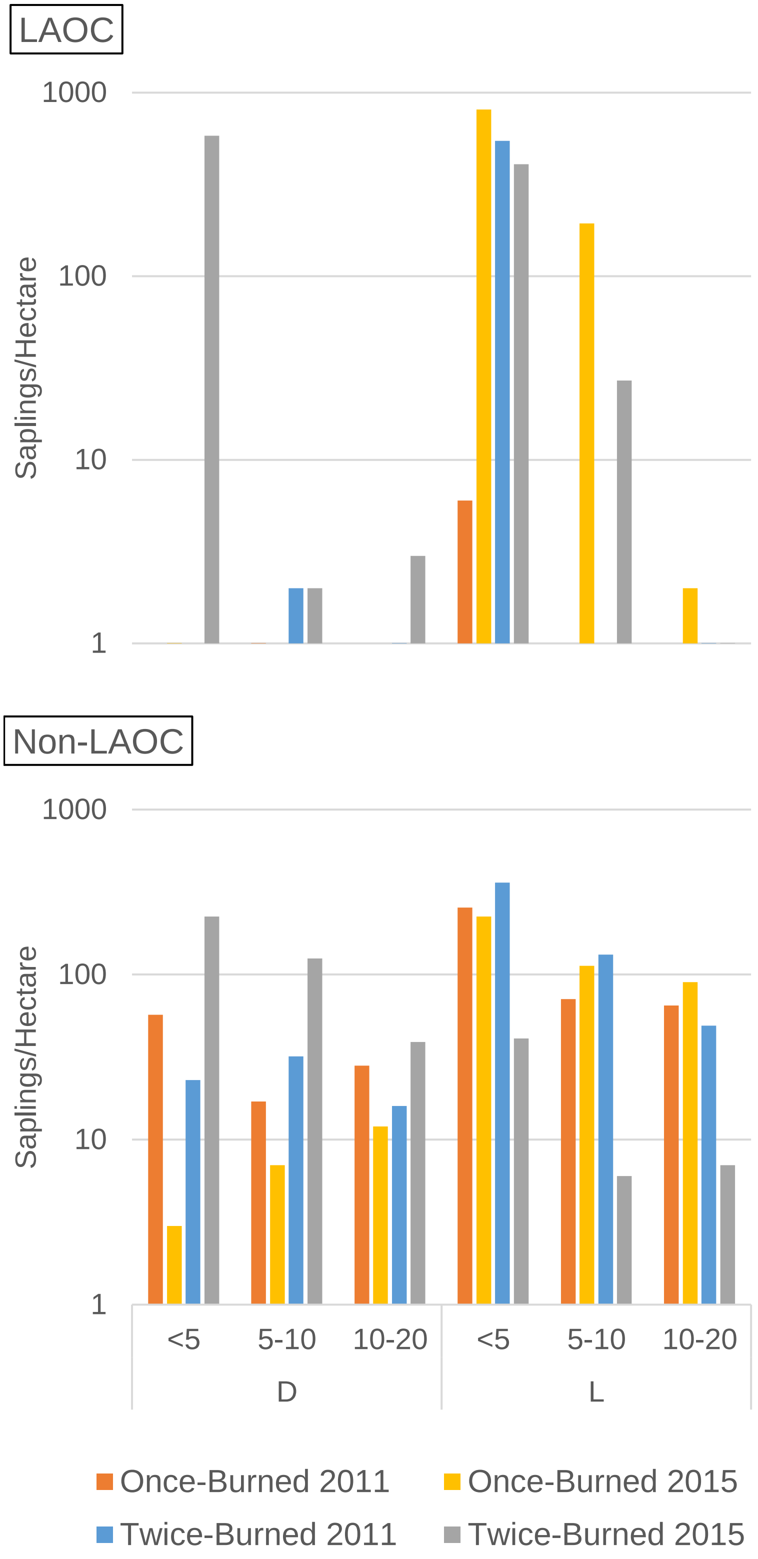

Figure 7. Density of both live and dead saplings (stems with height greater than 1.37 m) for each diameter size class (<5 cm, 5-10 cm, 10-20 cm).

Seedlings

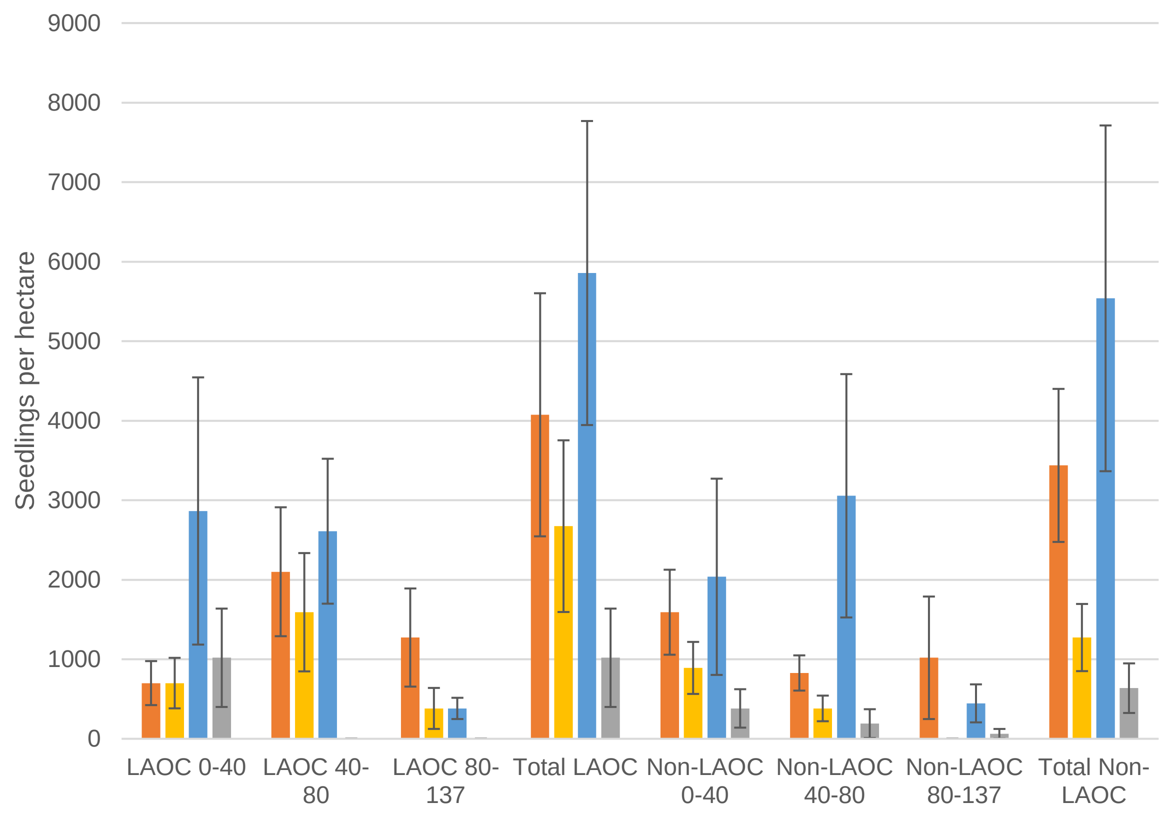

Figure 8. LAOC and non-LAOC seedlings per hectare by size class (0-40 cm, 40-80 cm, 80-137 cm) and in total.

Between 2011 and 2015, there was a decrease in the numbered of seedlings measured on both once- and twice- burned plots (Figure 8). In general, there is a larger decrease in the number of seedlings measured for twice-burned plots (Figure 8).

Discussion

In general, twice-burned plots had less CWD and FWD than once-burned plots. The density of dead larch saplings and seedlings tended to be greater on twice-burned plots. For both once- and twice-burned plots, the density of live trees changed very little between measurements, but the density of dead trees significantly decreased. The once- or twice-burned variable has a strong effect on surface fuels, but a weak effect on forest structure and composition.

Surface Fuels

For once-burned plots, mean CWD increased 76% and mean FWD increased 80%. Conversely, for twice-burned plots, mean CWD load decreased by 21% and mean FWD decreased 30%. It is probable that the second fire in 2013 consumed a significant proportion of the fuel associated with the long-standing, dead trees which fell in the two-year period between the first measurement and the second fire. In addition, the second fire consumed the fuel associated with trees which fell prior to the first measurement period, and were therefore recorded as a CWD and FWD by the first measurement, resulting in a measured net reduction in surface fuel load. Furthermore, the effect size of the once- and twice-burned variable is strongest in the 100 hr fuel class and weakest in the 1hr fuel class. The difference in the effect size of the once- or twice-burned variable on each fuel particle class likely relates to the inverse relationship between 1) particles size and decomposition and 2) particle size and fuel consumption by wildfire.

Decomposition acts as an output for surface fuel, decreasing the number of small-diameter, easily decomposed particles at a faster rate than large-diameter logs. This relationship explains the dissimilarity between the large increase (+129%) in mean load of 100 hr fuel in once-burned areas and the moderate decrease (40%) in the mean load of 1hr fuel in once-burned areas. During the four-year period between measurements, a greater number of the small diameter particles decomposed than did large diameter particles. This relates to the sampling method directly, because even if a small amount of a large diameter particle decomposed, it could still be easily recognized and measured as a particle, whereas if a small amount of small diameter particle decomposed it would likely make the particle unnoticeable and unmeasurable.

The inverse relationship between decomposition and particle size mirrors the consumption pattern of fuel particles in a wildfire, where small particles are consumed at a faster rate than larger particles. This relationship explains the dissimilarity between the small decrease (-27%) in mean load of 100 hr fuel in twice-burned areas and the moderate decrease (-65%) in the mean load of 1 hr fuel in twice-burned areas. Due to differences in particle surface-area-to-volume ratio and moisture damping coefficient (Rothermel 1972), small diameter fuels are dried very quickly and can be completely consumed in seconds, whereas large diameter fuels are less responsive to short-term changes in weather and additionally take longer to be fully consumed.

Forest Structure and Composition

The effect of the once-burned/twice-burned variable on the density of stems greater than 20 cm DBH is negligible between the 2011 and 2015 measurements, however this similarity can be explained by tree species composition and species specific adaptations to fire. On average there is a decrease in the density of dead trees greater than 20 cm DBH, but there is no significant difference in the degree of this change over time between once-burned and twice-burned plots (Figure 5). A mechanism which could explain this effect is that the first fire killed a significant portion of the fire-intolerant trees, therefore additional fire disturbance did not significantly affect the mortality rate in twice-burned areas, because the residual live trees following the first fire are tolerant to the impacts of fire disturbance. The data supports this explanatory model, in that on both sides of the fire there were almost no live lodgepole pine or subalpine fir. In fact, there was only one live subalpine fir recorded and one live lodgepole pine recorded in the entire study.

The largest change between the measurement periods for both once- and twice-burned plots was the decrease in the density of dead trees (Figure 5). The density of live trees changed very little on both sides of the river (Figure 5). The decreasing trend of dead tree density could be the result of the delayed effects of fire mortality. Extending the theoretical model outlined above, it is probably that a significant portion of the dead standing trees fell over during the four-year period between measurements. In short, the biomass measured in 2011 as an overstory tree, was measured a second time in 2015 as woody debris.

This explanatory model is supported by Belote et al. (2015) who found that fire intolerant species experienced greater rates of mortality, with western larch having the lowest mortality rate following fire and Douglas-fir having the next highest tolerance to fire disturbance (Belote et al. 2015). Western larch and Douglas-fir comprise the vast majority of the live trees on both once- and twice-burned plots (Figure 6). Additionally, Belote et al. (2015), using the 2011 of overstory data of this study in part, found that the highest rates of mortality in Douglas-fir were found in the largest size classes, with 100 percent mortality in trees greater than 70 cm DBH (Table 2). Belote et al. (2015) suggest that the larger-sized Douglas-fir are more susceptible to bark beetles, which preferentially attack larger diameter stems.

The decrease in the number of seedlings measured on both once- and twice-burned plots could in part be due to the natural growth of seedlings which were present in 2011 out of the seedlings size cut-off in 2015 (height of <1.37m). In general, there is a larger decrease in the number of seedlings measured for twice-burned plots, suggesting that a significant amount of the decrease in the density of seedlings on twice-burned plots can be attributed to actual seedling mortality rather than growth out of the seedling size class.

Additionally, there are more dead western larch saplings of every size class on twice-burned plots, than on once-burned plots. The same trend can be found in the sample of non-larch species, where once-burned plots generally decreased in dead sapling density, and twice-burned plots generally increased in dead sapling density. Likely, the thirteen-year period between the first and second fire was too short for saplings to develop traits that confer resistance to fire, especially the thick, insulating bark characteristic of large, old, western larch.

Given the size of the sample and its variability, it is difficult to quantify the effect size of the once-burned, twice-burned variable in all instances. However, some qualitative trends within the sample are significant. In addition, the standard error of the sample is not simply a measurement of error, but rather suggests that the impacts of fire are spatially heterogeneous (Figure 9).

Figure 9. Image characterizing the fire effects within the 2013 reburn of the area initially burned in 2000. Both the mortality of the overstory and the success of the regenerating understory are spatially heterogeneous. Both the live (left) and dead (right) larch seedlings established after the 2000 fire.

Management Implications

Fire effects within a mixed-severity fire regime are difficult to predict and are highly contigent upon time-since-last-fire, previous fire intensity, and both short- and long-term weather. Many of these variables which are difficult to measure and nearly impossible to control, especially within wilderness areas. However, general qualitative trends in the ecological trajectory of fire disturbance are both tractable and well-supported by this study. It is probable that within a significant portion of the fire-adapted ecosystems of the Bob Marshall Wilderness, and even more probably within the location of focus of this study, the phenomenon of consecutive fire disturbances, or reburns, tends to alleviate the input of woody debris which follows the initial reintroduction of fire to an area which has experienced infrequent fire. At the same time, the reduction in surface fuel is not correlated with addition woody debris input, because the residual overstory after the first fire is composed primarily of tree species which can tolerate fire disturbance.

This case study shows that reburns tend to have a stabilizing effect on surface fuels, while maintaining the overall fire-tolerance of the residual overstory. This trend loosely describes the middle of all possible ecological trajectories, and as many wilderness managers already know, the behavior and effects of wildfires in reality are wild (Figure 10).

Figure 10. An area that burned initially and during the second fire at high severity.

Conclusions

This study was designed to characterize the effect of consecutive fires on the surface fuel and forest structure and composition. Our most important finding is that the overstory of once- and twice-burned plots have similar mortality rates and species composition, even though twice-burned plots have significantly lower surface fuel load. This finding is important because it suggests that ‘reburns’ minimize the spike in surface fuel load associated with the input of overstory trees killed by the first fire, without significantly increasing the overall mortality or species composition of the residual overstory.

References

Arno, S. F. (1980). Forest fire history in the northern rockies. *Journal of Forestry, 78*(8), 460-465.

Belote, R. T., Larson, A. J., & Dietz, M. S. (2015). Tree survival scales to community-level effects following mixed-severity fire in a mixed-conifer forest. *Forest Ecology and Management, 353*, 221-231.

Bisbing, S., Alaback, P., & DeLuca, T. (2010). Carbon storage in old-growth and second growth fire-dependent western larch (larix occidentalis nutt.) forests of the inland northwest, USA. *Forest Ecology and Management, 259*(5), 1041-1049.

Brown, J. K. (1971). A planar intersect method for sampling fuel volume and surface area. *Forest Science, 17*(1), 96-102.

Collins, B. M., Miller, J. D., Thode, A. E., Kelly, M., Van Wagtendonk, J. W., & Stephens, S. L. (2009). Interactions among wildland fires in a long-established sierra nevada natural fire area. *Ecosystems, 12*(1), 114-128.

Habeck, J. R., & Mutch, R. W. (1973). Fire-dependent forests in the northern rocky mountains. *Quaternary Research, 3*(3), 408-424.

Harmon, M. E., & Sexton, J. (1996). *Guidelines for measurements of woody detritus in forest ecosystems* US LTER Network Office Seattle (WA).

Harmon, M. E., Woodall, C. W., Fasth, B., & Sexton, J. (2008). Woody detritus density and density reduction factors for tree species in the United States: A synthesis.

Hopkins, T., Larson, A. J., & Belote, R. T. (2014). Contrasting effects of wildfire and ecological restoration in old-growth western larch forests. *Forest Science, 60*(5), 1005-1013.

Keane, R. E., Ryan, K. C., Veblen, T. T., Allen, C. D., Logan, J. A., Hawkes, B., & Barron, J. (2002). The cascading effects of fire exclusion in rocky mountain ecosystems. *Rocky Mountain Futures: An Ecological Perspective*, , 133-152.

Leirfallom, Signe B., Robert E. Keane, and Rocky Mountain Research Station. *Six-Year Post-Fire Mortality and Health of Relict Ponderosa Pines in the Bob Marshall Wilderness Area, Montana*. RN-42 Vol. Fort Collins, CO: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, 2011. Print. Research Note RMRS .

Parks, S. A., Holsinger, L. M., Miller, C., & Nelson, C. R. (2015). Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. *Ecological Applications, 25*(6), 1478-1492.

Parks, S. A., Miller, C., Nelson, C. R., & Holden, Z. A. (2014). Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems, 17*(1), 29-42.

Parks, S. A., Miller, C., Parisien, M., Holsinger, L. M., Dobrowski, S. Z., & Abatzoglou, J. (2015). Wildland fire deficit and surplus in the western United States, 1984–2012. Ecosphere, 6(12), 1-13.

Rothermel, R. C. (1972). A mathematical model for predicting fire spread in wildland fuels.

Teske, C. C., Seielstad, C. A., & Queen, L. (2012). Characterizing fire-on-fire interactions in three large wilderness areas. *Fire Ecology, 8*(2), 82-106.

Van Wagner, C. (1968). The line intersect method in forest fuel sampling. *Forest Science, 14*(1), 20-26.

Van Wagner, C. (1982). *Practical aspects of the line intersect method* Petawawa National Forestry Institute Chalk River, Canada.

van Wagtendonk, J. W., van Wagtendonk, K. A., & Thode, A. E. (2012). Factors associated with the severity of intersecting fires in yosemite national park, California, USA. *Fire Ecology, 8*(1), 11-31.

Appendix A

Table 1. Reference densities by decay class and species used to calculate fuel load.

Species	Decay Class	Density (g/cm3)
PSME	1	0.462
PSME	2	0.356
PSME	3	0.288
PSME	4	0.22
PSME	5	0.1805
LAOC	1	0.463
LAOC	2	0.356
LAOC	3	0.269
LAOC	4	0.215
LAOC	5	0.1873
ABLA	1	0.414
ABLA	2	0.238
ABLA	3	0.25
ABLA	4	0.177
ABLA	5	0.139
PICO	1	0.405
PICO	2	0.405
PICO	3	0.37
PICO	4	0.176
PICO	5	0.175
PIEN	1	0.393
PIEN	2	0.258
PIEN	3	0.28
PIEN	4	0.117
PIEN	5	0.129
UNKN	1	0.4274
UNKN	2	0.3226
UNKN	3	0.2914
UNKN	4	0.181
UNKN	5	0.16216

Appendix B

Table 2. Diameter at breast height of Douglas-fir.

Year	Burned	Trees L/D	Mean D (cm)	Δ	StanDev	Δ	StanErr	Δ	Largest Stem	Δ
2011	Once	D	45.59		14.02		0.24		73.40	
2011	Twice	D	37.67		11.28		0.26		90.40	
2011	Once	L	33.11		9.00		0.82		54.40	
2011	Twice	L	30.58		6.52		0.15		47.50	
2015	Once	D	50.24	4.65	12.69	-1.33	0.45	0.21	74.60	1.20
2015	Twice	D	33.57	-4.10	8.88	-2.40	0.19	-0.06	57.30	-33.10
2015	Once	L	34.37	1.26	9.52	0.52	0.63	-0.18	52.90	-1.50
2015	Twice	L	31.41	0.83	5.46	-1.06	0.14	-0.01	41.00	-6.50