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Assessment of Fire Effects Based on Forest Inventory and Analysis Data and a Long-Term Fire Mapping Data Set

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Integration of Forest Inventory and Analysis (FIA) plot data with Monitoring Trends in Burn Severity (MTBS) data can provide new information about fire effects on forests. This integration allowed broad-scale assessment of the cover types burned in large fires, the relationship between prefire stand conditions and fire severity, and postfire stand conditions. Of the 42.5 million acres burned in eight Interior West states since 1984, 41.4% was forestland. Forest types with the most burned acreage were ponderosa pine, lodgepole pine, and Douglas-fir. Nearly 35% of plots had no live basal area of trees $\geq$5 in. diameter remaining postfire, but 32% of plots had greater than 40 ft^2/ac of residual live basal area. Residual basal area appeared to decline slightly with time since fire, suggesting low mortality rates among survivor trees. Seedlings appeared to reach peak density 5–10 years postfire, and sapling density increased monotonically for at least 25 years postfire. Data from remeasured FIA plots indicate that the highest MTBS severity class is related to high prefire basal area. At a regional scale, MTBS severity classes represent significantly different levels of mean live basal area reductions, ranging from 4% for areas of very low fire severity to 89% for high-severity areas. Severity classes are less distinguishable for individual forest-type groups.

Keywords: forest monitoring, wildfire, fire severity, Monitoring Trends in Burn Severity (MTBS), Forest Inventory and Analysis (FIA), regeneration

Wildland fire is arguably the most important forest-related topic in the western United States today. Other disturbances, such as insect and disease outbreaks, may affect much larger areas than fire in a given year, but the urgency to protect lives, property, and natural resources from fire requires immediate and large expenditures. The average annual cost of fire suppression now exceeds $1.3 billion (US Department of Agriculture [USDA] Forest Service 2014). Although suppression costs and their impact on the budget of the USDA Forest Service are usually highlighted, many other costs can be included in the calculation of the "true cost" of wildfire (Western Forestry Leadership Coalition 2010). Such analyses take into account factors such as direct costs (e.g., damage to private property and utilities), indirect costs (e.g., loss of business and tax revenue), rehabilitation costs, and other costs, which include adverse health effects, loss of scenic values, and loss of ecosystem services (Western Forest Leadership Coalition 2010).

One component that is not well quantified is the direct effect on the forest resource itself. For example, in the estimates of total burned area reported annually by the National Interagency Fire Center (NIFC), there is no distinction between burned forest and burned grassland or shrubland. Furthermore, "fire use" acreage, i.e., fire of unintentional origin allowed to burn within an existing prescription, was only reported separately from wildfire acreage by NIFC during the period from 1998 to 2008. For most of the past several decades, there has been no record to distinguish between prescribed fire area, fire use area, and wildfire (i.e., uncontrolled fire, whether natural or human-caused). In a recent report on fire use, Melvin (2015) noted approximately 8.9 million acres of fire use for forestry purposes nationwide, with almost 2.5 million acres of that occurring in the western states. However,

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the report also states that rangeland burning is included in that total, leaving the amount of prescribed burning in forestland unknown. There is also no comprehensive program for monitoring fire effects in detail. Although fire effects monitoring methods and tools, such as FIREMON (Lutes et al. 2006) and FEAT/FIREMON Integrated (Lutes et al. 2009), are readily available, monitoring data are typically maintained separately by land management agencies or at land units within agencies. As a result, it is not possible to comprehensively estimate the variability of wildfire effects over space or time, nor is it possible to describe the effects of fire across the severity continuum that spans from low-intensity ground fires to high-intensity, stand-replacing crown fires.

The frequency and intensity of fire exert a formative influence on the structure and dynamics of forests in the western United States. In some forest types, such as ponderosa pine (*Pinus ponderosa* Laws.), low-intensity fire can maintain open stands and stimulate herbaceous understory vegetation (Laughlin et al. 2004). In other types, such as lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and aspen (*Populus tremuloides* Michx.), fire is an important factor in stand replacement and successful regeneration. In many parts of the Interior West, a century of fire suppression has led to a buildup of fuels and stand densification, which may lead to uncharacteristically intense fires (Reinhardt et al. 2008). Some areas that burn intensely may experience slow regeneration, but others may recover relatively quickly due to greater recruitment and/or survival. However, there has not been a plot-based system capable of producing unbiased, population-scale estimates of fire effects until recently.

The USDA Forest Service Forest Inventory and Analysis (FIA) program is designed to characterize the status and trends of the forests of the United States across all ownerships and forest types (Bechtold and Patterson 2005). With the implementation of the current annualized inventory (Gillespie 1999) in the late 1990s, the FIA program began to produce spatially and temporally balanced forest inventory data for most of the country. As the program was being phased in, this balance was present only at the level of individual states. Today, all of the contiguous 48 states are under annual inventory, and most western states are into a remeasurement cycle within this system. This allows analyses of forest trends that were not possible with the previous periodic approach to FIA inventories or even using annual inventories done as recently as 5 years ago.

To date, FIA data have been used on a limited basis for evaluation of fire effects. For example, a retrospective analysis using contemporary plot data shows that live tree volume per acre within the 1910 “Big Burn” area of Washington, Idaho, and Montana (Cohen and Miller 1978, Pyne 2008, Egan 2009) is about equal to that outside the fires, although the mean stand age is somewhat lower and the volume is generally distributed among smaller trees (Wilson et al. 2010). Such in-depth analysis of a single burned area was possible because the 1910 fire perimeter, which encompassed more than 3 million acres (USDA Forest Service 1978), included a relatively large number of FIA plot locations. Similar, single-fire analyses may also be possible for some of the recent, large fires in the Interior West, but individual analysis of the numerous, smaller fires is not feasible due to low data density. However, FIA plot data can be used to produce estimates of the cumulative effects of fire at state or regional scales. For example, Whittier and Gray (2016) produced an assessment of fire effects on national forests of the Pacific Northwest. Such analyses can place more localized conditions, for example, as revealed by postfire assessment of a specific watershed, in the context of the collective burned area, providing valuable information for managers who must prioritize the use of limited treatment resources.

At the same time, there has been development of other comprehensive resource data sets. The Monitoring Trends in Burn Severity (MTBS) program maps the perimeters and severities of wildland fires in the conterminous United States, Alaska, Hawaii, and Puerto Rico; minimum mapped fire size is 500 ac in the East and 1,000 ac in the West (Eidenshink et al. 2007, Finco et al. 2012). Fire boundaries are provided as vector data, whereas fire severity is mapped as a 30-m resolution raster product. The MTBS program develops data both forward and backward in time, i.e., following each new fire season and working backward in time through historic satellite imagery, with periodic revisions based on updated methodology.

The combination of MTBS fire perimeter and severity data with FIA plot data potentially allows for novel analyses of fire effects and statistical estimation at large scales. The famous German soccer coach Josef “Sepp” Herberger said “Nach dem Spiel ist vor dem Spiel” [After the game is before the game], which Oregon State University Professor Klaus Puettmann has rephrased for forestry as “After the fire is before the fire” (pers. comm., March 30, 2015). Although this is a good characterization of any parcel of land in fire-prone ecosystems, it is also a good characterization of the role of FIA plots in long-term forest monitoring in these systems. All FIA plots sample the legacy of previous disturbances, with highly varying time intervals between the disturbances and the time of plot visits. These data provide a baseline against which to reference the effects of disturbances yet to come. In a fire-prone ecosystem, every FIA plot visit is before the fire and after the fire.

The objective of this study is to demonstrate the potential value of combining two publicly available data sets, i.e., plot data from the FIA program and fire perimeter and severity data from the MTBS program, to describe the effects of fire on forests in the interior western United States. Our approach is to analyze the properties of these two large data sets and illustrate some of the ecological questions to which they can be applied. The first question is somewhat basic but surprisingly unanswered, given the long history of recording wildland fire in the United States: of the total burned area

Management and Policy Implications

Local assessment of fire effects can lack context in terms of how prefire conditions, such as forest stand type proportions or stand density, relate to expected or actual postfire conditions. This study quantifies postfire conditions, such as variability of fire severity, residual BA, and regeneration, and relates them to prefire conditions across a wide geographic range. By understanding how postfire effects vary at a greater geographic scale, the results of local monitoring can be placed in the context of the broader forest population. This should help managers plan for expected forest responses to varying levels of fire severity, thereby providing a basis for planning the level of effort that may be needed to restore forest resources to their full potential.

mapped in the Interior West states, what proportion is forestland? The other questions relate to fire severity, as mapped by the MTBS program and measured on FIA plots. Separately, we analyze forest conditions preceding fire and the resulting effect on fire severity, using composition and density as independent variables, and then we assess the effects of fire on composition, density, and regeneration.

The data used to answer each of these vary, owing to the different metrics related to each question. Mapped fire perimeters, intersected by FIA plot locations, define the sample. MTBS severity classes, FIA plot-level data, and FIA condition (stand)-level data are analyzed separately or in combination. Furthermore, because both data sets are made up of time series data, the timing of observations between the data sets impacts the analysis approach and interpretation of results. Because of this and the complexity of the FIA data set in general, we have an additional goal of providing examples of potential application to prospective users of these data. Our results provide the first characterization of fire effects at this scale and level of detail.

Methods

This study encompasses eight western states: Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. MTBS fire perimeters and severity for the years 1984–2012 were obtained from the MTBS website (MTBS 2014). FIA plot data were queried from the public FIA database (O'Connell et al. 2015) and included observations from plots that were measured as part of FIA periodic and annual inventories between 1993 and 2013. The population of interest was thus defined as all areas within MTBS fire perimeters for 1984 to 2012, and the sample included FIA plots measured between 1993 and 2013 that were located within those perimeters. FIA plots that occurred outside the MTBS fire perimeters were not included in this study.

Because many FIA plot locations were carried over from periodic inventories (1993–2002) to annual inventory (2000–2013), a given plot location could have multiple visits, each of which could have a status as a pre- or postfire visit. Conceptually, a single plot visit could be characterized as postfire for one fire and prefire for another. Plot status was classified as prefire or postfire using a geometric intersection of MTBS fire perimeters and FIA plot locations. Actual plot coordinates were used to ensure that plots were correctly identified as being within or outside MTBS perimeters because geographic plot coordinates in the public FIA database are fuzzed (O'Connell et al. 2015).

The Identity function in ArcGIS (Environmental Systems Research Institute 2011) was used to assign actual FIA plot locations to MTBS perimeter polygons. The attributes (e.g., fire identifiers, fire date, and fire size) of multiple fires were assigned to plots that fell within overlapping fire perimeters (i.e., plots locations that burned more than once). Plots that fell within MTBS fire perimeters and were measured after any fire date were designated as postfire plots, whereas those that were measured before the earliest fire date were designated as prefire plots. Note that the prefire and postfire nomenclature only refers to the temporal relationship of a plot measurement with respect to the time of a fire, as indicated by its location inside an MTBS fire perimeter. It does not imply that the plots burned at any particular severity, and some plots may fall on unburned patches within fire perimeters.

We used a single raster data set, derived from all of the individual-year MTBS fire severity raster data sets, to assign fire severity data to FIA plot locations. The "collapsed" raster contained unique identifiers for cells or cell clusters that shared the common attributes of fire name, fire year, severity code, and land cover classification. Land cover classification is based on the National Land Cover Database (Homer et al. 2015). These identifiers were linked to a tabular file that contained the actual attribute values.

FIA plot data included measurement date, the proportion of each plot that met FIA's definition of forest (≥10% projected canopy cover of live or recently living trees), forest type and forest-type group, stand-level disturbance codes, tree-level variables (species, diameter, and live/dead status) for live trees at least 1 in. and dead trees at least 5 in. dbh for timber tree species or at rootcollar (drc) for woodland tree species (USDA Forest Service 2013), seedling-level variables (count and species), and appropriate expansion factors (O'Connell et al. 2015). Although the data from periodic and annual inventories are similar, numerous plot designs were used during the period of interest. Most periodic inventories used fixed-area and variable-radius designs, whereas all annual inventories and later parts of some periodic inventories used the nationally standardized, fixed-area, mapped-plot design.

The mapped-plot design allows for within-plot delineations, called "conditions" in FIA terminology (USDA Forest Service 2013), that correspond to stands that are commonly delineated in other inventory systems. Forest type, for example, is a condition-level variable. The area sampled by an individual plot may consist of a single forest or nonforest condition or two or more conditions, each of which may be classified as forest or nonforest. Thus, the number of conditions in any analysis of FIA data is always greater than or equal to the number of plots. Although it is possible for multicondition plots to have both burned and unburned conditions identified on one plot visit, the combination of MTBS spatial resolution and the positional accuracy of FIA plot locations does not allow for such precise delineations. Therefore, each condition was categorized based on the prefire or postfire status of the plot on which it occurs. In our description of each analysis, we state whether we use plots or conditions as the sample unit, as appropriate. Most periodic plots sampled only a single condition as part of the inventory design.

Calculation of Area Proportions

For the first question, we wanted to know the proportions of forest versus nonforest within MTBS perimeters. For this analysis we used only annual inventory plots, because this subset of plots is spatially balanced. For the analysis of percent forest and nonforest, we used only plot measurements for the most recent evaluation to avoid double-counting plots measured multiple times during the annual inventory. Evaluations are aggregations of plots from multiple inventory years (2004–2013 in this case) that can be used to form population estimates (O'Connell et al. 2015). Nonsampled plots and nonsampled portions of plots were excluded from the analysis of forest versus nonforest area so that the proportion of forest and nonforest areas summed to 100% (per Bechtold and Patterson 2005). With respect to the FIA definition of forest, it is important to note that FIA does not immediately reclassify severely burned forest as nonforest (USDA Forest Service 2013). For example, if a fire causes 100% mortality on a previously forested plot, the field crew considers evidence of the prefire stand with respect to the definition of forest. Therefore, a plot's status as forest versus nonforest is not immediately affected by fire. Failure to regenerate adequately over a long period of time may result in a status change from forest to nonforest, but such a situation has not yet been identified in the Interior West states.

Calculation of Status, Change, and Severity Metrics

We addressed the remainder of our questions using a data set derived from the intersection of FIA plot locations, MTBS perimeter attributes, and the compressed MTBS raster data. FIA plot locations were represented in this data set by more than one observation in cases where more than one forested condition occurred on the plot. Therefore, we were able to analyze data at the plot and condition levels, as appropriate. Based on the timing of fires with respect to the dates of plot visits, plots fell into three general groupings: those with prefire measurements, those with postfire measurements, and those with both.

For typical reporting and analysis, FIA classifies forest types at the condition level using an algorithm (FORTYPCD; see Arner et al. 2001). However, crews also assess forest type in the field based on the current or former composition on the plot, as well as on evidence from the sampled condition that exists off-plot (FLDTYPCD; see USDA Forest Service 2013). Severely disturbed conditions are commonly classified as "nonstocked" forest type for lack of tally trees, because the algorithm requires a minimum level of stocking to classify conditions correctly. Because our analysis involves conditions that have high potential of being classified as nonstocked, we rely on the crews' assessments and use FLDTYPCD as the classification for postfire conditions.

For analysis of postfire forest attributes, we considered all measurements of annual inventory plots on the FIA base grid measured between 2000 and 2013, regardless of whether those plot measurements are used in current population estimates. Ideally, estimation of prefire to postfire change would be based on remeasurement of plots with at least one prefire and one postfire visit. However, true remeasurement data are sparse in the current state of the inventory because the annualized inventory started in 2000, uses a 10-year remeasurement period, and was phased in over a number of years. Instead, we utilized space-for-time substitution by using the MTBS perimeters collectively to establish the sampling frame and then compared plots that were measured prefire to plots measured postfire as two quasi-independent samples separated by the occurrence of fire.

We assessed basal area (BA) of live and dead trees and density of seedlings and saplings at postfire plots. Plot-level values were calculated on a per acre basis using the appropriate expansion factors for individual trees, saplings, and seedlings (O'Connell et al. 2015). Time since fire was calculated as the difference between measurement date and the most recent fire date. BA per acre of trees 5.0 in. or larger in diameter was computed separately for the live-tree and standing dead-tree components on each plot. We selected BA as the metric for large-tree density because it provides a familiar reference value by which to illustrate the relationships between FIA data and MTBS classification. Other common metrics may require one or more additional variables to be meaningful (e.g., combinations of stems per acre, stand density index, and mean stand diameter) or are more specific to certain kinds of assessments (e.g., aboveground carbon), so we elected to restrict the analysis to BA in the case of large trees. For seedlings and saplings, density was computed as number of stems per acre. FIA defines seedlings as trees with diameters less than 1.0 in. and at least 12.0 in. in height for hardwoods or 6.0 in. in height for softwoods; saplings are defined as trees with diameters of at least 1.0 in. but less than 5.0 in. (USDA Forest Service 2013).

Comparison of MTBS Severity Classes

Analysis of severity classes required prefire and postfire measurements of the same plots rather than the space-for-time substitution used in our estimates of postfire BA and stem density. There have not been enough annual inventory plots remeasured to permit this analysis using exclusively annual data, so we instead used data from annual inventory plots that were colocated with plots from the most recent periodic inventory. Although this data set represents prefire and postfire measurements of the same plots, it is not spatially representative of the distribution of forest types across the landscape (Goeking 2015). This is because there were geographic gaps in some periodic inventories, so the ability to use annual plots as postfire measurements is limited by the geographic distribution of periodic plots as prefire measurements. When annual plots are used for both pre- and postfire measurements, there will be no such spatial bias, and it will be possible to compare the proportions of forest types affected by fire with the proportions of forest types occurring in the general population.

MTBS severity classes include six possible values, but two of the classes, "increased greenness" and "nonprocessing area mask," are not severity classifications. Our analysis included only the four classes that are meaningful for interpreting fire severity. Severity classes range from 1 (unburned to very low severity) to 4 (high severity). The sample was constrained to the following: plots that were measured during FIA's most recent periodic inventory (1993–2002); plots that were measured again as part of the annual inventory between 2003 and 2012; and plots that burned after the initial measurement but before the second measurement. We assigned the maximum severity class among multiple fires to the postfire measurement for plots that burned more than once. Our reasoning for this was that the most severe event would probably be correlated with the level of change found when pre- and postfire conditions were compared. The number of forested conditions where this decision was made amounted to less than 3% of observations, so the effect of the severity assignment for these conditions on the results was assessed to be minimal.

Each plot was classified by the predominant forest-type group recorded during the prefire measurement (as opposed to the postfire measurement), and comparisons within forest-type groups were done only for the five major groups with sample sizes adequate for statistical analyses. These were, in decreasing order of sample size, the ponderosa pine group, the Douglas-fir group, the pinyon/juniper group, the fir/spruce/mountain hemlock group, and the lodgepole pine group.

The mean prefire total BA and mean prefire live BA were compared among severity classes to investigate a possible linkage between initial conditions and fire severity. Mean postfire reductions in live BA were also compared across severity classes. Each plot's live BA reduction was calculated as the difference between prefire and postfire live BA divided by prefire live BA. Variations in prefire total BA, prefire live BA, and percent reduction in live BA among severity classes were tested for statistical significance using PROC ANOVA (analysis of variance), both among major forest-type groups and for all groups; results were confirmed with the nonparametric Kruskal-Wallis test, although one-way ANOVA is considered to be robust even when the underlying assumptions are not met (SAS Institute, Inc. 2009). Differences among individual severity classes were identified using Tukey's honestly

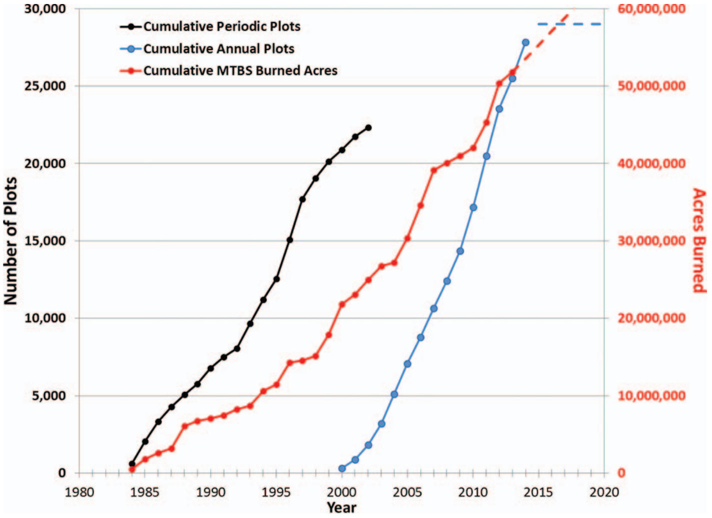

Figure 1. The numbers of periodic and annual FIA plots that sampled at least one forested condition, 1984–2014. The blue line represents the number of plots that will sample at least one forested condition at full implementation of annual inventory in all eight Interior West states. The red line shows the cumulative area inside MTBS polygons. From 2015 onward, approximately 29,000 forested FIA plots can potentially sample the continually increasing burned area.

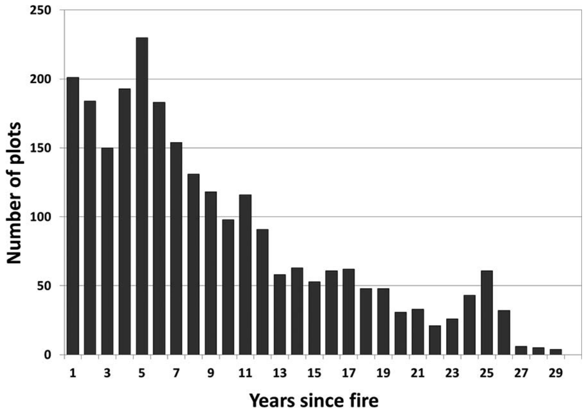

Figure 2. Number of years between fire and plot visit for postfire plots (n = 2,360 plots).

significant difference test for multiple comparisons (Zar 1996).

Results

Characteristics of the Data

The intersection of FIA plot locations and MTBS fire polygons creates a complex data set. Although MTBS mapping started with the 1984 fire season, with only 473,261 fire acres mapped in the Interior West states for that year, there were obviously many more cumulative acres burned in the preceding decades. However, because those fires have not been mapped by the MTBS program, there is no convenient way of knowing which FIA plots sampled postfire conditions for fires in the few decades before 1984 (Figure 1). Because of the timing of the periodic inventories, they serve primarily as prefire observations for most of the existing MTBS fire record. The probability of periodic inventory plots remaining as the most current prefire records has gradually diminished as annual inventory has been phased in. As of this writing, only about 1,000 of the approximately 29,000 plots that are likely to have at least one forested condition in the eight Interior West states remain to be measured under the annual inventory system. This means that approximately 96% of annual inventory plots have potential to provide pre- and postfire data for fires occurring from the present time. After 2020, any new fire that encompasses an FIA plot will have an annual inventory plot as a prefire measurement.

Within the eight Interior West states, the MTBS program delineated 6,170 burned area perimeters from 5,360 fires and fire complexes, 982 of which contained FIA postfire plot measurements. Of the 31,152 FIA plot measurements from 2000 to 2013, 28,502 fell outside MTBS perimeters and thus were not included in our analyses of prefire versus postfire stands, 859 plots were measured within MTBS perimeters before fired occurred, and 2,360 were postfire plots (Figure 2). The number of plot locations with pre- and postfire observations is 735. The number of available paired pre- and postfire observations will increase over time, as new fires occur, as additional periodic plots are verified as being colocated with the annual locations, and as annual plots are remeasured. After full implementation of annual inventory, the maximum time between a fire and the first measurement afterward will be 10 years or less for plots measured in their scheduled year.

As this study was an exploratory analysis of the combination of FIA and MTBS data, we did not intend to critique the accuracy of MTBS severity classifications. Using the different burn ratio calculations on which MTBS severity classes are based, Kolden et al. (2015) noted that different thresholds could be found for burn severity classes in different regions and that there were varying degrees of overlap in the burn ratios among adjacent severity classes. For our own assessment, we used a subset of 726 annual plot locations. The MTBS classifications for these locations were as follows: unburned/low = 165, low = 218, moderate = 183, and high = 160. We then ranked the postfire BA changes from highest (positive BA change) value to lowest (negative BA change) and used the same class breakpoints as represented in the MTBS severity classifications (Figure 3).

In a perfect correlation, severity classes would coincide with the ranked BA loss; i.e., we would expect all of our plots with positive to neutral BA change to be classified as unburned/low and all of the plots with the highest mortality (i.e., ~100% BA loss) to be classified as high severity. We found that high severity was classified most "correctly," with 65% of the highest-mortality plots being classified as high severity. The proportions of correct classifications decreased in the lower mortality ranges, with correct classifications ranging from 37 to 44%. In the group of plots that experienced positive to neutral BA change, there were actually more "low" MTBS classifications than the expected "unburned/low" classifications, suggesting that there is poor separation of the lower two MTBS classes in forest areas.

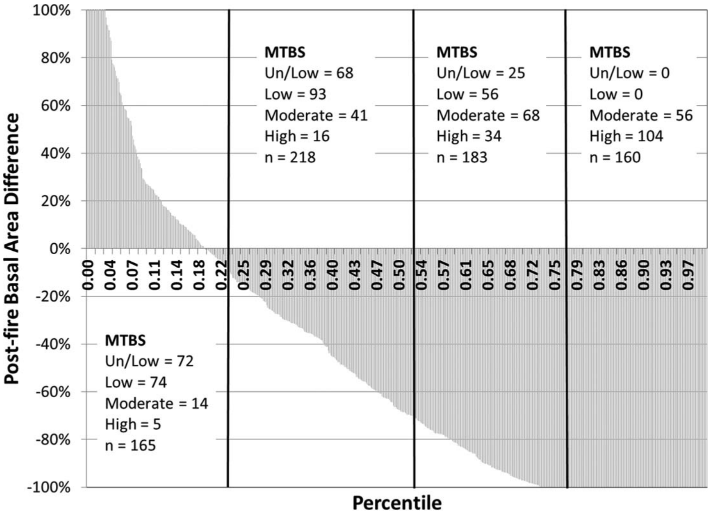

Figure 3. Ranked BA percent changes for conditions with prefire and postfire measurements. Percentile breakpoints are set at the percentiles of MTBS severity classes for the same conditions. Inset numbers are counts of FIA plots by the MTBS severity classes within each percentile range. A perfect rank correlation would have all 165 MTBS "unburned/low" conditions in the lowest group, all MTBS "high" conditions in the highest group, and so on. The graph has been truncated at 100% increase (doubling of BA) for clarity.

Forest versus Nonforest Burned Area

Based on the sum of the areas of all MTBS burned-area perimeters, fires burned a total of 50,366,800 acres between 1984 and 2012. This acreage represents a simple sum of all burned areas; in actuality, some areas burned multiple times during the years covered by the MTBS data set. Accounting for overlapping fire perimeters, the total unique area that burned between 1984 and 2012 is 42,504,834 ac (Table 1). Within the total area of all MTBS fire perimeters, the percentage that was classified by FIA as forestland varied considerably by state, from a minimum of 10.1% in Nevada to a maximum of 64.9% in Montana. Based on FIA plot data, 41.4% of the area within MTBS fire perimeters in our eight-state study area was forest (Table 1).

Effect of Forest Type on Fire Severity

The sample of remeasured plots that burned between their periodic and annual inventory measurements consisted of 735 plots (Table 2). The distribution of remeasured plots by MTBS fire severity class is approximately equal, with each class representing between 22% (class 4, high severity) and 31% (class 2, low severity) of all remeasured plots. Most forest-type groups burned in proportion to their abundance across our eight-state study region, although the Douglas-fir and ponderosa pine groups are proportionally overrepresented and the pinyon/juniper group is underrepresented, compared with their proportional regional abundance (Table 2). This pattern mirrors the forest-type biases of the periodic inventory sample demonstrated by Goeking (2015), where periodic inventories sometimes sampled forest types in proportions different from the proportions that exist across all forests.

Prefire BA and Fire Severity Class

When prefire density (BA per acre) was compared with MTBS severity classes, only severity class 4 (high) had a significantly different density from those of all other classes (Figure 4). Of the five forest-type groups tested for the effect of initial BA, only the ponderosa pine and Douglas-fir groups had any significant differences in density among lower-severity classes (not shown). This suggests that for some types, up to a certain threshold of stand density there may not be a substantial difference in the resulting fire severity. However, because stands of a given density can, for example, burn with different intensities under different weather or fuel conditions, a larger sample and more detailed analysis will probably be required to separate the effects of multiple factors on fire severity.

Postfire Live and Dead BA

Although there were few differences in fire severity classification in relationship to prefire BA, many significant differences were found among severity classes for tests of prefire versus postfire BA change (Figure 5; Table 3). This is an expected result, of course, because MTBS severity classifications are based on changes in spectral signatures. However, this analysis also provides a potential explanation of some of the mismatches

Table 1. Summary of FIA and MTBS data used for this study.

State	Plot measurements within burned perimeters[1]	% nonforest	% forest	Total amount burned (ac)	No. of prefire forest plots	No. of postfire forest plots
Arizona	788	45.9	54.1	4,837,906	237	361
Colorado	211	39.5	60.5	1,460,609	45	136
Idaho	1,726	56.8	43.2	10,562,802	209	569
Montana	967	35.1	64.9	6,050,826	170	589
Nevada	1,390	89.9	10.1	8,138,978	27	131
New Mexico	617	56.7	43.3	4,510,332	51	234
Utah	503	57.6	42.4	3,332,783	119	227
Wyoming	170	44.9	55.1	3,610,600	1	113
Total	6,372	58.6	41.4	42,504,834	859	2,360

The percent forest and percent nonforest are based on the proportions of sampled forest and nonforest conditions on FIA plots within MTBS fire perimeters and thus represent the distribution of forest and nonforest within fire perimeters. The total acreage burned represents the combined area, or geographic union, of all MTBS fire perimeters in each state over the period of the study; areas that burned multiple times were not counted twice. The number of prefire forest plots includes all FIA plots that fall within MTBS perimeters but were measured before a fire occurrence and contained at least one forest condition. Postfire plots are those within MTBS fire perimeters that were measured after a fire occurred and contained at least one forest condition.

[1] Plots included in this summary are those from the most recent evaluation group for each state (EVALID; see O'Connell et al. 2015).

Table 2. Distribution of forest-type groups among the eight-state area, among remeasured FIA plots ($n = 735$) within MTBS perimeters where fires burned between plot measurements (measurement periods were 1993–2002 and 2003–2012), and among MTBS fire severity classes.

Prefire forest-type group[1]	Proportion of total forest land area in 8-state study area[2]	Percentage of remeasured plots in MTBS fire perimeters	No. of remeasured plots in burned areas	Percentage of remeasuredplots, by forest-type group, in each fire severity class			
				1	2	3	4
Aspen/birch	5	2	12	0	25	50	25
Douglas-fir	13	20	148	24	24	28	24
Fir/spruce/mountain hemlock	16	15	113	14	20	22	43
Lodgepole pine	8	8	57	32	23	14	32
Other western softwoods	2	3	20	20	35	25	20
Pinyon/juniper	37	20	145	26	37	25	12
Ponderosa pine	9	23	172	23	38	25	14
Western larch	1	1	5	20	20	40	20
Woodland hardwoods	10	9	63	24	37	30	10
All groups	100	100	735	23	31	25	22

[1] Not shown: forest-type groups that occur in Interior West states but did not occur at T1 at remeasured plots.

[2] Total forest land area by forest-type group was obtained from FIA's online EVALIDator estimation tool (apps.fs.fed.us/Evalidator/evalidator.jsp).

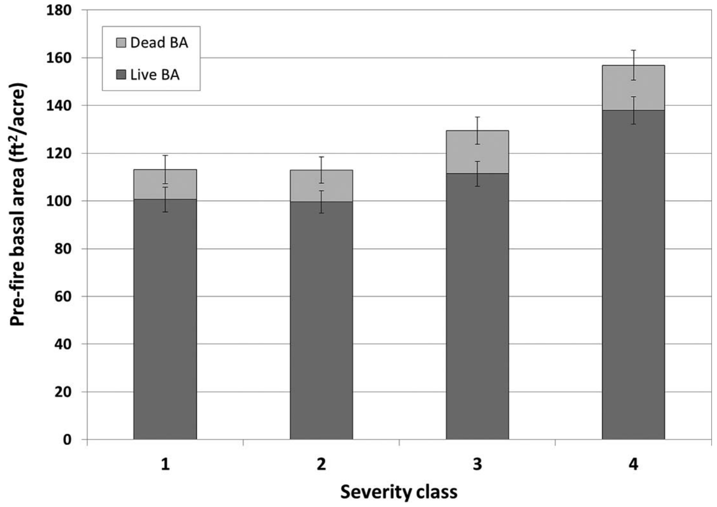

Figure 4. Mean prefire total and live BA at FIA plots ($n = 735$) that burned between measurements by MTBS fire severity class. Prefire measurements occurred between 1993 and 2002. Only the high-severity class (4) was significantly different from the other classes (prefire live BA, $df = 3$, $F = 11.03$, $P < 0.0001$; prefire total BA, $df = 3$, $F = 11.63$, $P < 0.0001$). Error bars are ±1 SEM live and total BA.

shown in Figure 3. For all forest-type groups combined, there was a significant and relatively regular progression of BA decrease with increasing severity class. However, when major forest-type groups were considered individually, severity classes 3 and 4 were not significantly different in terms of live BA reduction even though most groups did show qualitative differences. The ability to statistically distinguish between classes 1 and 2 and also between classes 2 and 3 varied among the major forest-type groups (Table 3).

A wide range of live BA was found on postfire plots ($n = 2{,}360$); 35% of plots had zero live BA and only 22% had more than 60 ft^2/ac (Figure 6). Because the calculated BA includes only trees ≥5.0 in. in diameter and most major tree species in this region grow too slowly to reach the 5-in. size class within 20 years (Burns and Honkala 1990a, 1990b), postfire BA is probably composed almost entirely of trees that survived fire rather than new growth and thus represents residual BA. We defined stand-replacing fire as plots with no live trees ≥5.0 in. in diameter. Although this high threshold appears conservative (i.e., resulting in a minimal area of stand-replacing fire), we should note that the FIA footprint samples are only ⅙ ac. At larger sampling footprints, the same sampling locations would undoubtedly capture live residuals under some conditions. Because of the small scale of the plot design, we do not know whether a plot with 100% mortality at the plot scale represents a high-severity patch within a variable severity fire or a typical part of a large, high-severity patch. This distinction could be made through additional spatial analysis of MTBS severity products and FIA plot locations.

At a regional scale, postfire plots that burned fewer than 5 years before measurement have about 41% of the live BA observed at unburned plots (Figure 6). Postfire dead BA is about three times the dead BA at unburned plots, and it then gradually decreases with time since fire. However, even at plots that burned 25 years or more before measurement, dead BA is nearly half that observed at recently burned plots (<5 years postfire). For a more detailed example of snag analysis using FIA data, see Ganey and Witt (2017). Although some latent mortality may generate additional dead BA, the large amount of dead BA present in all time intervals suggests that most of it was present just after the fire. In the Interior West, postdisturbance standing dead volume does not reach its minimum until regenerating stands reach ages between 30 and 60 years, according to a chronosequence analysis by Garbarino et al. (2015). The downward trend in standing dead BA is consistent with that trajectory, depending on when new standing dead trees are produced by postfire regeneration.

Postfire Regeneration

Both seedling and sapling demographic classes show the expected immediate decrease after fire (0–5 years), followed by expected increases (Figure 7). Seedling density peaks 5–10 years after fire and then declines after 25 years postfire, as seedlings self-thin

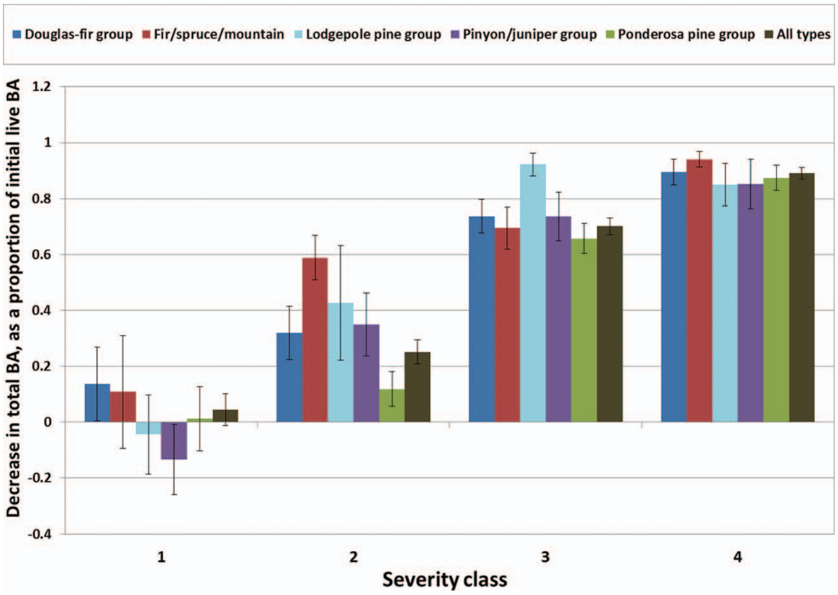

Figure 5. Mean percent decreases of prefire live BA after fire among the five most widespread forest-type groups and for all forest-type groups by MTBS fire severity class (1 = unburned to very low; 2 = low; 3 = moderate; 4 = severe). Mean prefire and postfire BAs are based on measurements of the same plots (*n* = 735), as measured during the periodic (1993–2002) and annual (2003–2012) inventory. Error bars are ±1 SEM; see Table 3 for statistically significant differences among severity classes.

or move into the sapling size class. In contrast, sapling density increases over a much longer period, and even at plots that burned more than 25 years before measurement sapling density continues to increase with time since fire. Thus, this data set captures the peak of regeneration in terms of seedling density but does not capture the peak of sapling density. Instead, it illustrates that the peak of postfire recruitment into the sapling size class may occur more than 25 years after fire and also reinforces the assumption that most postfire live BA consists of residual BA, or survivor trees for at least 25 years after fire.

Postfire Forest Type Changes

In previous results we have shown fire-induced reductions in BA and general patterns of recruitment. Although these metrics provide some insight into stand-level change, they do not give a complete picture of potential future stand development. Using the data set with pre- and postfire observations of forest-type group we constructed a change matrix (Table 4). Across the sample, pyrogenic groups such as aspen (DeByle 1985), lodgepole pine (Lotan et al. 1985), and western larch (Schmidt and Shearer 1995) showed net gains, whereas pinyon/juniper, Douglas-fir, ponderosa pine, and spruce/fir/hemlock groups showed net losses. In the cases of pinyon/juniper and ponderosa pine, much of the net loss came from changes to woodland hardwoods.

Discussion

Data Characteristics

Unlike most experimental studies or even typical observational studies, we had no way of knowing the characteristics of the analysis data set until we started our analysis. With a nonoverlapping area of 42.5 million burned acres, we would expect to have more than 7,000 FIA plots in the sample, based on the area represented by one plot. With the complement of annual inventory plots still incomplete (lacking mostly in Wyoming), we found 6,372 plot locations inside MTBS perimeters, which was about as expected. However, because there was no available estimate of burned area by land cover type (i.e., forest cover types versus nonforest cover), it was impossible to estimate how many plots would sample burned forestland in advance of our analysis. MTBS data include National Land Cover Database land cover classifications (Homer et al. 2015), but summing different combinations of cover classes (i.e., adding obvious forest classes and marginal classes such as dwarf scrub and shrub/scrub) would not add up to the amount of forest area estimated by FIA plots. Therefore, the finding of burned area of forest versus nonforest (and the number of associated plots) was result on its own, and information we do not believe has ever been published.

We noted the "misclassifications" of MTBS severity compared with postfire effects measured on FIA plots but did not alter our analysis based on them. For several reasons, we did not treat this analysis as a validation exercise; rather it was a form of blind check comparison. One reason to expect some classification error was the choice to do single-cell intersections of MTBS data with FIA plot locations. This was necessary for preserving the ordinal classifications for comparison purposes as opposed to developing a continuous severity scale with complex properties (e.g., differing variances for equal mean severities). One alternative approach is to average the severity ratings, e.g., in a 3 × 3 block of cells centered on the FIA plot

Table 3. Summary of differences in mean percentage decrease in live BA among MTBS fire severity classes, for all forest-type groups (*n* = 735) and for five major forest-type groups.

Variable	Forest-type group	Results of ANOVA		Statistical differences among severity classes			
		df, *F*-statistic	*P* value	1	2	3	4
% decrease in live BA	All groups	3,84.75	<0.0001	a	b	c	d
% decrease in live BA	Douglas-fir	3,15.87	<0.0001	a	a	b	b
% decrease in live BA	Fir/spruce/mountain hemlock	3,17.70	<0.0001	a	b	bc	c
% decrease in live BA	Lodgepole pine	3,10.90	<0.0001	a	b	bc	c
% decrease in live BA	Pinyon/juniper	3,12.73	<0.0001	a	b	bc	c
% decrease in live BA	Ponderosa pine	3,25.87	<0.0001	a	a	b	b

Statistical differences among severity classes are based on the Tukey test for multiple comparisons (Zar 1996); severity classes with the same letter are not significantly different.

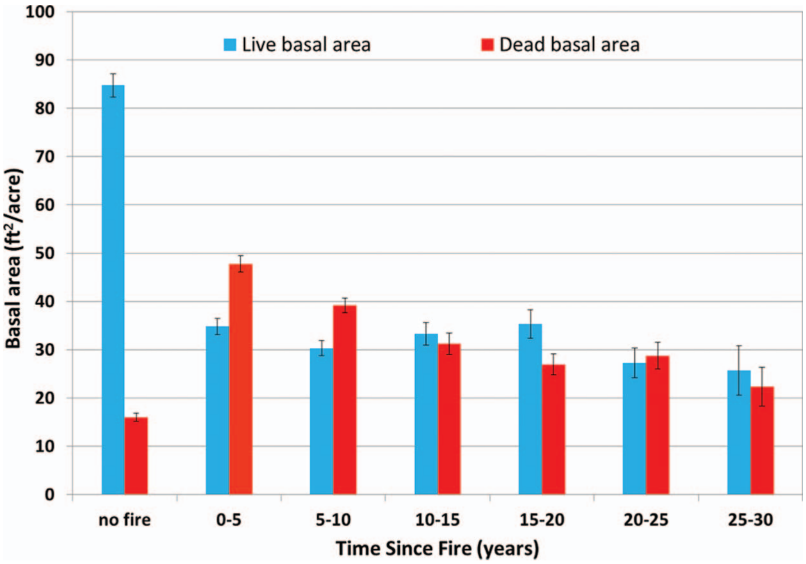

Figure 6. Chronosequence of mean live and dead BAs for prefire (n = 859 plots) and postfire (n = 2,360 plots) plots, with data from postfire plots shown by 5-year postfire intervals. Error bars are ±1 SEM.

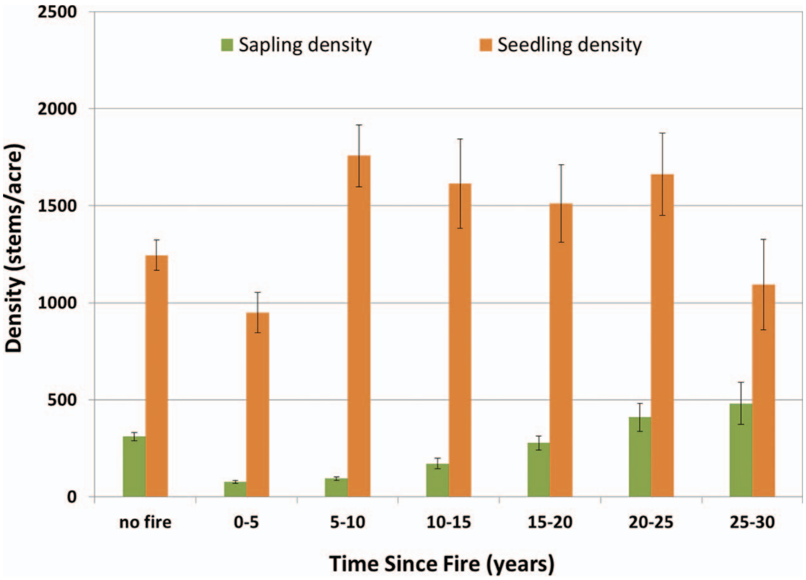

Figure 7. Chronosequence of mean sapling and seedling density for prefire (n = 859 plots) and postfire (n = 2,360 plots) plots, with data from postfire plots shown by 5-year postfire intervals. Error bars are ±1 SEM.

location. This would have required analysis of all 30 annual severity data sets, which was beyond the scope of this project. Another alternative, suggested by C.A. Kolden (pers. comm., Sept. 25, 2015), is to drop MTBS severity classes in favor of using the burn ratio data used to derive severity classes. This approach has the advantage of relating two sets of continuous variables (i.e., burn ratios and computed FIA variables). Both approaches merit future investigations and are currently in development.

At full implementation, annual FIA data provide a spatially and temporally balanced sample of forestland. However, although annual inventory was started in 2000 in the Interior West, annual inventory implementation was phased in from 2000 to 2011. In fact, 2014 was the first year that the annual sample was spatially balanced across all eight Interior West states. At this time, seven of the eight states have entered a cycle of annual inventory remeasurement. As a result, although the patchy history of FIA inventory in the Interior West has imposed limitations on the current analysis, future analyses have potential to be much more straightforward and informative.

Effects of Prefire Conditions on Severity and Postfire Residuals, Regeneration, and Forest Type Change

Our analysis examines the effect of stand density and forest type on fire, and the effects of fire severity on stand residual structure, composition, and regeneration. The purpose of these analyses was not specific hypothesis testing. Rather it was an exploration of the potential usefulness of the combination of two large, geographically comprehensive data sets.

Our analysis of the effect of prefire BA on fire severity showed that fire in higher-density stands tended to result in higher severity classifications, whereas there was poor separation between adjacent classes and no difference at all between the two lowest classes. Although this might be an indication of a threshold effect, we must also consider the part of our analysis that showed relatively poor separation of severity classification in the BA change ranking analysis (Figure 4). Perhaps improvements in severity classification procedures can result in better alignment of MTBS severity classes and plot-based observations of change, thereby providing greater separation of change among severity classes.

In contrast to the generalized approach of looking at all burned plots in aggregate, stratification of data by prefire forest-type groups revealed differences across the range of MTBS severity classes (Figure 5). Interestingly, within the highest two severity classes the amount of BA change as a proportion of prefire BA was very similar among the major forest-type groups. The exception to this pattern was for lodgepole pine, which experienced similar rates of mortality in the moderate and severe MTBS classes. This raises the question of whether the data reflect a tendency for lodgepole pine stands to be similarly affected across a range of fire severity or whether MTBS procedures do not adequately separate areas of moderate and high severity in lodgepole pine stands. On the surface that question would seem to be circular because severity classification is based on spectral signature change, but there may be other factors that make lodgepole pine the exception among the types we analyzed. Given that the other four types show relatively clear separation between the proportional BA change in moderate and severe classes, the lack of a difference in lodgepole pine merits a closer look. Within the two lowest severity classes, the differences among forest types appear greater, but there are few

Table 4. Prefire/postfire forest-type group change matrix ($n = 735$ plots).

Prefire forest-type group (*n*)	Postfire forest-type group								
	Aspen/birch	Douglas-fir	Fir/spruce/mountain hemlock	Lodgepole pine	Other western softwoods	Pinyon/juniper	Ponderosa pine	Western larch	Woodland hardwoods
Aspen/birch (12)	7		1	1		1	2		
Douglas-fir (148)	8	101	7	7	1		12	4	8
Fir/spruce/mountain hemlock (113)	13	10	54	30	2		1	1	1
Lodgepole pine (57)	2	1	3	49	1	1			
Other western softwoods (20)	1	1	5	3	5	1	1		3
Pinyon/juniper (145)	2	7	2	1		92	4		36
Ponderosa pine (172)	2	8				20	108		33
Western larch (5)				1				4	
Woodland hardwoods (63)			1			8	3		51
Total (gain/loss)	35 (+23)	128 (−20)	73 (−40)	92 (+35)	9 (−11)	123 (−22)	131 (−41)	9 (+5)	132 (+69)

Some minor forest-type groups have been omitted, so prefire and postfire totals do not match.

cases for which the differences are significant. However, for each forest type, the differences in the proportional changes between the unburned/low and low classes tended to be significant. This result suggests that some of the misclassifications found in the ranked change analysis may be related to certain forest types.

Our analysis of postfire BA shows that total mortality occurs on a minority of burned forest acres. This is somewhat expected, because even in the large and severe fires of recent years, there is a mixture of fire effects. What is not well known, however, is how the proportions of severity class have been changing over time. The currently available approach is to rely on MTBS classifications (e.g., Dillon et al. 2011), but this methodology carries forward any MTBS classification errors. There are open questions regarding the limitations inherent in MTBS classifications (Kolden et al. 2015). FIA data can serve as a consistent source of ground-truth information and will characterize fire effects in greater detail than is possible using spectral signatures.

For example, our analysis characterizes the distribution of postfire residual BA of both the live and standing dead stand components. Based on seedling and stand origin records associated with these conditions, about half of the area classified as severe appears to be regenerating naturally. This is likely to be a conservative estimate because errors of commission in seedling counts are rare, but it is common to have regeneration recorded in crew notes when none is tallied on the microplots. The regeneration status of such plots will only be determined as remeasurement progresses and seedlings cross the size threshold (5 in. dbh/drc) to be captured on the subplots. In the majority of burned forest area, a live tree component, frequently accounting for substantial BA, remains after fire and appears to persist. This suggests that the residual component has the opportunity to contribute to understory reinitiation (Oliver 1981) in a large fraction of burned forest. Our generalized view of stand dynamics after fire shows that this is occurring, with the expected postfire increase of seedling-sized trees occurring up to 10–20 years after fire, and subsequent graduation into the sapling size class, which peaks at least 25 years after fire. The next cycle of measurements will provide valuable information on the trajectories of stands burned during the past 30 years, which may include regeneration failures in addition to the documented successes. These detailed observations are important in the context of severity classification, because one of the major concerns about large areas of severely burned forestland is the extent to which they will adequately regenerate. The systematic sample provided by FIA provides a framework for monitoring regeneration success.

Beyond the simple issue of recording regeneration, a major goal of the FIA program is to capture changes in the makeup of future forests. From an ecological perspective, the story is complex: high-severity fires in forest types such as lodgepole pine and aspen tend to favor these types (DeByle 1985, Lotan et al. 1985), whereas in pinyon/juniper and spruce-fir, high-severity fire generally favors earlier successional states. We found evidence of this using the limited set of remeasured plots from which a forest-type group change matrix was derived (Table 4). Across the sample, pyrogenic species such as aspen (DeByle 1985), lodgepole pine (Lotan et al. 1985), and western larch (Schmidt and Shearer 1995) showed net gains, whereas pinyon/juniper, Douglas-fir, ponderosa pine, and spruce/fir/hemlock groups showed net losses. In the cases of pinyon/juniper and ponderosa pine, much of the net loss came from changes to woodland hardwoods. This might be expected because these types tend to include a component of species that sprout after fire, such as Gambel oak (*Quercus gambelii* Nutt.) (Harper et al. 1985). In these cases, the sprouting species could account for the majority of the live component for many years after severe fire and would be recognized by field crews as the dominant species. Over all types, more than one-third of stands sampled before fire changed type after fire. What has yet to be assessed is whether these changes are expected as parts of successional cycles, or if some are state changes that are possibly related to fire severity and other factors, such as climate. Again, the increasing body of data provided by continuous monitoring will allow many of these questions to be answered.

Although this analysis has produced interesting and perhaps encouraging results with respect to future forests, we caution that this is a preliminary analysis, given the limited set of remeasurement plots available. Fortunately, as of the 2015 field season, seven of the eight Interior West states will be in a remeasurement cycle, so remeasurement data will accumulate rapidly. In the Interior West states, remeasurement will occur at the rate of approximately 3,000 forested conditions per year, with about one-third of those occurring in areas that have burned within the past 25 years. Equally important are the two-thirds of plots in the yet-unburned portion of Interior West forests, because they will serve as an unburned baseline for future fires. As burned area accumulates in the future, this baseline will allow further analysis of postfire conditions in the context of prefire conditions, providing direction for future management.

These analyses were done at a large regional scale, so there is much opportunity for dissection of the results at smaller scales. In addition, we expect that the use of ancillary variables (e.g., stand density, composition, vertical structure, understory and dead woody fuel loadings, and climate data) could further inform some of our analyses, such as the effects of predisposing conditions on fire severity. Although many of these characteristics have been examined in other studies, FIA's continuous monitoring allows analysis and inference to population scales. Despite the fact that much remains unknown, our widespread systematic sample allows some generalizations about fire effects in the Interior West states. Different forest types have different proportions of area in each fire severity class. These proportions can be referenced to existing studies on historic fire severity and can be used as baseline values for comparison in the future.

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