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Tree mortality based fire severity classification for forest inventories: A Pacific Northwest national forests example

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ABSTRACT

Determining how the frequency, severity, and extent of forest fires are changing in response to changes in management and climate is a key concern in many regions where fire is an important natural disturbance. In the USA the only national-scale fire severity classification uses satellite image change-detection to produce maps for large (>400 ha) fires, and is generated by the Monitoring Trends in Burn Severity (MTBS) program. It is not clear how much forested area burns in smaller fires or whether ground-based fire severity estimates from a statistical sample of all forest lands might provide additional, useful information. We developed a tree mortality based fire severity classification using remeasured tree data from 10,008 plots in a probabilistic survey of National Forests System (NFS) lands in Oregon and Washington, using 8 tree mortality and abundance metrics. We estimate that 12.5% (±0.7% SE) of NFS forest lands in the region experienced a fire event during 1993–2007, with an annual rate of 0.96% (±0.05%). An estimated 6.5% of forest lands burned at High Severity or Moderate Severity; 2.1% burned at Very Low severity or only experienced surface or understory fire. A total of 358 of the 507 burned plots were within the MTBS perimeters, with ~45% having equivalent severity classifications; but for ~51% of the plots the MTBS classifications suggested lower severity than the tree-mortality based classes. Based on events recorded on plots and the inventory design, we estimate that 20.9% of the forested NFS lands experiencing fires, either wildfires or prescribed burns, were not in the MTBS maps. Tree mortality based fire severity classifications, combined with remotely-sensed and management information on timing and treatments, could be readily applied to nationally-consistent Forest Inventory and Analysis (FIA) data to provide improved monitoring of fire effects anywhere in the USA sampled by remeasured FIA inventories.

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1. Introduction

In the western United States considerable effort has gone into describing how the frequency, sizes, severity, and areal extent of wildfires have changed over the last century, and relating that information to land and fire management practices, and climate change (Agee, 1993; North and Hurteau, 2011; Giesen et al., 2008; Mitchell et al., 2009; Stephens et al., 2013). Analyses to characterize wildfires over large geographic areas are challenged by variability in the available data, over time, among data sources, area covered, and parameters measured. Older fire databases were developed and maintained by federal and state agencies, tending to cover only lands under their jurisdictions. Over time there has been an increase in interagency coordination of data management; see for example the primary data management section in Littell et al. (2009). Likewise greater availability of digital information (e.g., aerial photography, GIS mapping, satellite data) have improved the quality and completeness of wildfire databases.

Currently there are three primary sources of broad-scale wildfire data and severity classifications in the USA. The Burned Area Emergency Response (BAER) process is applied to large fires (generally >405 ha) on National Forest System (NFS) lands judged to have created potential for ecosystem or economic risks from damaging erosion or increased runoff (http://www.fs.fed.us/eng/rsac/baer/; http://www.fs.fed.us/biology/watershed/burnareas/). The BAER process includes developing fire severity classification and mapping, using on-the-ground assessment and aerial infrared photography (Parsons et al., 2010). To support its programmatic goals, the BAER classification is made as quickly as possible after

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the fire and emphasizes soil damage metrics. Because of BAER's prescriptive purpose for each fire, characteristics of the classes may vary among fires. Since 2007 as a companion assessment to BAER, the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) has used Landsat-TM satellite data taken within 30 days of the fire to assess post-fire vegetation conditions to prioritize vegetation management (http://www.fs.fed.us/postfirevegcondition/index.shtml).

Beginning in 2005, the national-scale interagency Monitoring Trends in Burn Severity program (MTBS; Eidenshink et al., 2007) has used Landsat-TM satellite data (back to 1984) to map burn severity for all fires >405 ha in the West and >202 ha in the East. MTBS uses spectra from Landsat bands 4 and 7 that detect changes in site moisture and chlorophyll, primarily for canopy vegetation, and have a pixel size of 30 × 30 m. These data are used to produce the normalized burn ratio (NBR), and the prefire and one-year postfire differenced NBR (dNBR) value for each pixel to create categorical severity maps, with category thresholds subjectively selected by image analysts using any available plot or image data (http://www.mtbs.gov/methods.html). MTBS also provides relativized dNBR (RdNBR) which removes biasing by prefire conditions (Miller and Thode, 2007; Miller et al., 2009a). Although MTBS does not provide fire severity class maps based on RdNBR, some researchers (e.g., Miller et al., 2009b, 2012; Dillon et al., 2011; Cansler and McKenzie, 2014; Prichard and Kennedy, 2014) have developed their own severity classifications, at regional scales, using those data. For example, Miller et al. (2012) developed severity classes for national forests in northwestern California, using RdNBR calibrated with plot-level Composite Burn Index (Key and Benson, 2006) ground-based measures from Miller et al. (2009b).

Although the Landsat-TM data are available nationwide, we are not aware of any west-wide fire severity classifications for fires <405 ha. There are a variety of individual agency fire mapping programs that include smaller fires, such as the California Department of Forestry and Fire Protection's (Cal Fire) Fire's Fire and Response Program data (http://frap.fire.ca.gov/projects/fire_data/fire_perimeters_index.php). However, these also have a variety of methods, and minimum fire sizes (e.g., ~4 ha for Cal Fire), and the data may not include prescribed burns.

Because existing national mapped annual fire severity classifications are limited to large fires, it has not been possible to make estimates that include all forested lands, or assess forest attributes that are not readily mapped with imagery. In this paper we propose that such statistical estimates can be developed, for all fire sizes and intensities across forest types and ownerships, using consistently collected on-the-ground, repeat tree measurement survey data, from representative samples of large areas. For most places in the western USA, those kinds of data have not been collected consistently in the past. However, in 2001 the U.S. Forest Service (USFS) began implementing the nationally standardized ("annual") Forest Inventory and Analysis (FIA) survey (Gillespie, 1999). FIA is a probability-based survey of all forested lands (all ownerships, all forest types) in the USA, in which 10% of the plots in the west are sampled each year over a 10-year resample cycle. Individual trees with diameter at breast height (DBH) > 2.5 cm are tagged and remeasured at each visit. Each year some of those plots will experience a fire event. We propose that the FIA tree mortality and plot disturbance data can be used to place those burned plots into fire severity classes, and that using the FIA plot sample density one can estimate, with known statistical confidence, how many forested hectares have experienced any class of fire, at various geographic scales. We focus on classes instead of continuous variables, similar to most existing fire severity methods, because fires affect different components of forest stands with different severity; even when single indices have been developed (e.g., Key and Benson, 2006), different weights have been applied to different forest components, depending on objectives.

At this time only about 40% of the annual FIA survey plots on the west coast have tree remeasurement data (i.e., have second samples). However, the Pacific Northwest Region of the USFS did conduct a similar survey (the Current Vegetation Survey [CVS]) between 1993 and 2007 that included many of the design and tree measurement components used by FIA. The CVS measured more than 10,000 1-ha plots on National Forest System (NFS) lands, with remeasurement data on approximately 1 million live trees and snags. As a demonstration of how FIA data could be used in the future to assess fire occurrence and severity, we used the CVS remeasurement data in Oregon and Washington to: (1) develop a tree mortality based fire severity classification; (2) compare that classification with BAER and MTBS classes for subsets of CVS plots; and (3) use the CVS probability design to estimate the area of NFS forested land in the Pacific Northwest in each severity class in the 1993 to 2007 period. Our proposed fire severity classification is intended to supplement remote sensing based classifications, and not to replace them. Because of the historical importance of low-severity understory fire in many forest types in the western USA, our classification attempted to distinguish fire effects on different tree size classes and in relation to expected mortality rates in the absence of fire.

2. Methods

2.1. Field data

The CVS data used in this study were collected in Oregon and Washington by the U.S. Forest Service for an inventory of vegetation conditions on NFS lands in the Pacific Northwest (Max et al., 1996). The 10.0 million ha of NFS land in these states occur in a great variety of conditions, with annual precipitation ranging from 25 to over 350 cm, mean annual temperatures ranging from −1 °C to 12 °C, and elevations from 0 to 3,300 m above sea level (Franklin and Dyrness, 1973). We grouped the nineteen national forests into five zones to reflect regional variation in composition and productivity (Fig. 1). On average, vegetation west of the Cascade Mountains crest (western Oregon (WOR) and western Washington (WWA) zones) is more dense and productive than that east of the Cascades crest (Blue Mountains (BLUES), northeastern Washington (NEWA), and central Oregon (CEOR) zones). The climate west of the Cascades is more temperate (wetter with cooler summers and warmer winters) than on the east side.

Survey plots were located using a probability-based sample design (Olsen et al., 1999). The sample consisted of a systematic square grid with a 2.74 km spacing across all lands, except for designated Wilderness Areas which had a 5.74 km spacing, providing a sample density of one plot per 750 and 3000 ha, respectively. Plots were installed using the CVS design (Max et al., 1996) between 1993 and 1997 and remeasured between 1997 and 2007 in four spatially- and temporally-balanced panels. The CVS plot remeasurement period ranged from 1 to 14 years with a mean of 7.1 years. The same grid of plots was also measured with the FIA plot design starting in 2001 (Bechtold and Patterson, 2005). For this study, we used forest land plots with 2 CVS measurements and at least one live tree at the first sample.

The CVS plot design consisted of a cluster of five points within a 1-ha circle, with four points spaced 40.8 m in cardinal directions from the central point. At each point, crews measured live and standing dead trees of different sizes (2.5–7.6, 7.6–33.0, and >33 cm diameter at breast height (DBH; 1.37 m from the ground)) in nested circular subplots of 0.004, 0.020, and 0.076 ha, respectively. Trees >76 cm DBH east of the Cascades and >122 cm DBH

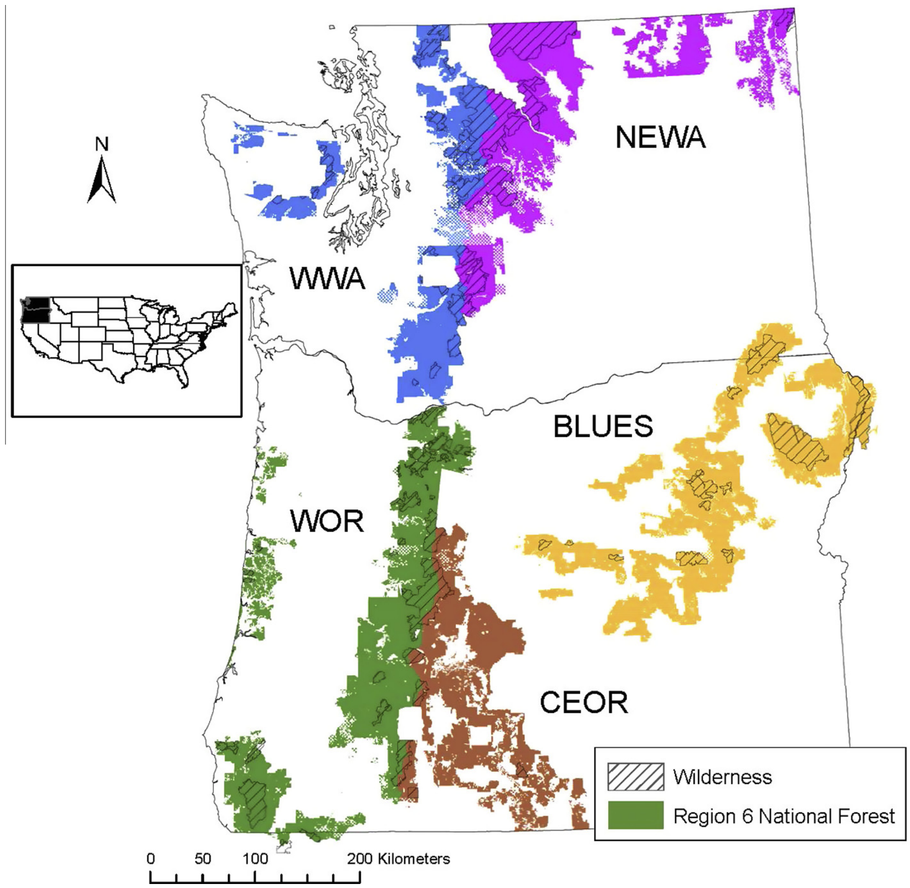

Fig. 1. Geographic zones within National Forest System forested lands in Oregon and Washington sampled between 1993 and 2007 (Gray and Whittier, 2014) BLUES = Northeastern Oregon, primarily Blue Mountains; CEOR = Central Oregon, east of Cascade Mountains crest; NEWA = Northeastern Washington, primarily northern Rockies ecoregion; WOR = Western Oregon, west of Cascade Mountains crest; WWA = Western Washington, primarily North Cascades and Coast Range ecoregions.

west of the Cascades were measured on the full 1-ha circle. Down wood, seedlings, saplings and non-tree vegetation were also sampled, but these data were not included in our fire severity classification. See Max et al. (1996), USDA Forest Service (2002) and Gray and Whittier (2014) for additional details on plot design, measurements and compilation.

2.2. Fire classification

We developed a classification of fire severity to identify whether tree mortality was elevated over that expected in the absence of fire, and to characterize levels of mortality of different size classes of trees. We initially identified burned plots from disturbance events recorded by FIA sample crews and by overlaying plot locations on GIS spatial layers of harvest and fire events maintained by the NFS, including MTBS (e.g., Eidenshink et al., 2007). For each initially-identified burn plot, we cross-checked disturbance codes, tree mortality data, and CVS and FIA field crews' written descriptions and maps of stand condition to confirm whether a fire event had occurred between sample visits. To develop our fire classification, we used data from the subset of trees (>2.5 cm DBH) that were alive at the first sample (time 1) and either alive or dead from non-human causes (i.e., had not been cut) at the second sample (time 2) on burned plots. Data used for each tree included time 1 size (DBH), time 2 status (live, standing dead or fallen dead), an expansion factor (number of trees per hectare (TPH) it represented), and a modeled annual natural mortality rate.

We developed an estimate of the natural "background" mortality rate in the absence of disturbance based on trees that were alive at time 1 and either alive, or dead from non-human causes at time 2, on plots that had not experienced major natural disturbance (i.e., excluding burned plots and plots coded in the field with severe insect or disease mortality) between samples. TPHs were summed for all live trees, and an annualized mortality TPH (i.e., TPH for mortality trees divided by the years between samples) was summed for mortality trees by various groupings across all plots. Mortality rate groups were based on species, tree size (generally, DBH less than or greater than 12.7 cm), crown ratio (<30, 30–60, >60%), and for widespread species which side of the Cascades the plot was on. For very common species that grow to large size we created additional large size groups. Some uncommon species with similar mortality rates were lumped together.

For each plot we developed a set of mortality metrics (e.g., percent of small trees that died) and abundance metrics (e.g., tally of small trees, TPH small trees). Because a fair number of burned plots had very low tree mortality rates (including zero), we calculated an observed mortality to background mortality ratio (O/B_{mort}) for each plot as:

$$O/B_{mort} = (\text{observed mortality} - \text{background mortality}) / \text{background mortality}$$

where observed mortality is the total TPH of trees that died, and background mortality is the sum of TPH * background mortality rate (for each tree) times the number of years between samples. Negative O/B_{mort} values (minimum = -1) indicate less mortality than expected for generally undisturbed plots.

To develop a fire severity classification that distinguished fire severity effects on mortality of different tree size classes, we examined mortality and abundance metric behavior on burned plots with at least 10 tally trees (trees alive at time 1 with DBH $\geqslant$ 2.5 cm counted on the appropriate subplots). We iteratively evaluated the effect of applying different thresholds to the metrics, on successfully grouping plot membership in a variety of meaningful fire severity classes. We developed a simpler rule set for plots with fewer than 10 tally trees. Because we wanted the classification to be tree-data driven we did not refer to the field notes and maps during the initial development process.

To evaluate our fire severity classification, we used box plots and the Tukey–Kramer multiple-comparison test on means of the proportion of TPH as mortality trees, and O/B_{mort} for small trees (DBH < 12.7 cm), for large trees (DBH $\geqslant$ 12.7 cm), and all trees in the classified burned plots, as well as the same data for unburned plots, for the entire study area and for the East side and the West side separately. We also calculated percent basal area lost to fires as the proportion of tree basal area in mortality in burned plots, for all trees, small trees, and large trees. We used the chi-square statistic to determine whether low severity fires were more likely to be detected or reported in the first few years post fire than after multiple years.

In addition, we evaluated three subsets of the CVS burned plots. First, the Forest Service measured CVS plots within the fire perimeters of 3 large fires one year post fire: the 2002 Biscuit Fire in southwestern Oregon, the 2003 B and B Fire in the central Oregon Cascades; and the 2003 Fawn Peak Complex in the North Cascades of Washington. These data included the standard CVS plot data plus additional fire measures (e.g., Campbell et al., 2007). A subset of these plots was sampled again 3 or 4 years later as the regular CVS time 2 sample. For this subset we compared the fire severity classification and tree mortality metrics calculated from the 1 year post fire sample with the CVS time 2 data, primarily to look for potential effects of delayed mortality on how plots were classified (i.e., from trees severely damaged by fire, and that have some green foliage in the first growing season after the fire, but die soon afterward). Second, we compared our fire severity classification with a classification of the Biscuit Fire plots as mapped by the BAER process. Third, we compared the MTBS severity classes with our classes for CVS plots within MTBS fire perimeters sampled before and after MTBS-assessed fires across the region. We used the median MTBS severity class value from the nine 30 $\times$ 30 m MTBS pixels that centered on the CVS plot center. On these plots, we also examined percent basal area lost by the tree mortality severity classes and the MTBS severity classes.

2.3. Estimation of area burned by severity class

Calculation of survey estimates differs from standard approaches commonly applied to designed studies (e.g., ANOVA). We calculated means and variances for all values using double-sampling for stratification based on sampled condition classes and their measurements (Cochran, 1977; Scott et al., 2005). The study area was divided into strata designed to capture the variation in vegetation attributes and sampling intensity in order to improve the precision of plot-based estimates and adjust for non-sampled forest land. Estimation units were defined by the area in each national forest in Wilderness and non-Wilderness designations to account for the different plot densities. Land cover classes from satellite imagery (Homer et al., 2004) were buffered into edge and internal classes and grouped to potentially differentiate forest from nonforest (Dunham et al., 2002). Plot locations were intersected with spatial layers and the numbers of pixels and plots were counted by strata and estimation unit. The ratios of the number of pixels in each stratum to the known area of sampled NFS lands in each estimation unit were used to calculate population means and variances (e.g., MacLean, 1972). Weights within strata for burned plots were adjusted to the total estimation unit based on the fire year, so that the population estimates for fires in particular years were based only on plots in the population that were remeasured after those fires occurred.

3. Results

Our fire severity classification data set comprised 759,832 live trees >2.5 cm DBH at time 1 and not cut at time 2, on 10,008 forest land plots on NFS lands in Oregon and Washington representing an estimated 9,007,719 ha (±31,150 SE) with 59.7% of the plots on the East side. A total of 507 plots (5.1%) had evidence of a fire event between the two sample visits; 30 burned plots had <10 live trees at time 1. As expected, fires were more common on East side plots than on West side plots (6.1% vs 3.5% respectively) during the 1993–2007 survey period. Approximately 64% of the West side burned plots were within the perimeter of the 2002 Biscuit Fire in southwestern Oregon, the largest forest fire on record in the state.

3.1. Fire severity classification

After examining candidate metric behavior on the burned plots, we settled on two rule sets that produced six fire severity classes, using eight metrics (Table 1). The rule sets were implemented as a series of if-then-else statements (Tables 2A and 2B). The primary rule set, applied to plots with $\geqslant$10 live tally trees at time 1, classified the two lowest mortality classes first, followed by the two highest mortality classes, and the intermediate classes last. This process simplified the decision rules. The secondary rule set was applied to plots with fewer than 10 tally trees at time 1.

The Very Low class ($\sim$18% of burned plots) comprised plots with mortality rates not different from the majority of non-burned plots (Fig. 2), as measured by both portion of TPH as mortality trees and by O/B_{mort}. We chose the 67th percentile (lower 2/3) of the O/B_{mort} values on non-burned plots as a reasonable characterization of the range of natural mortality and used these values in the primary rule set (Table 2A). Generally fires on these plots were surface fires that burned only ground vegetation or shrubs, or were low intensity fires that only encroached on a small portion of the plot. Because prescribed burns are used as a forest management tool to reduce fuel loads or thin the forest understory, we created an Underburn class ($\sim$5% of burned plots) that generally had low to moderate mortality (<50% TPH small trees) confined almost entirely to the understory, but higher overall tree mortality than Very Low severity plots (Fig. 2). A few plots contained only small trees (recent plantations or recent regeneration) and had high tree mortality; the classification rules placed those plots in other severity classes (below).

Table 1
Metrics used in the fire severity classification process.

Metric	Description
Mort Tally	Number of tallied[a] mortality trees
Large Mort Tally	Number of tallied[a] mortality trees >12.7 cm DBH
% Mort Total	% of trees per hectare that died after time 1
% Mort Small	% of trees per hectare <12.7 cm DBH that died after time 1
% Mort Large	% of trees per hectare >12.7 cm DBH that died after time 1
Plot O/B_{mort}	Observed to Background mortality ratio for all trees
Large O/B_{mort}	Observed to Background mortality ratio for trees >12.7 cm DBH
% Mort Tally[b]	Number of tallied * mortality trees/total tally trees

[a] Tally refers to the number of trees (DBH > 2.5 cm) counted on the plot rather than the expanded trees per hectare value. This value is useful on plots with few trees.
[b] Used only in the rule set for plots with fewer than 10 tally trees.

Table 2A
Fire severity classification rule set for burned plots with ⩾10 tally trees at Time 1. Rules were applied in order. Plots meeting a rule were classified and removed from further consideration. Metrics are defined in Table 1.

Severity class	Rule
Very Low	Plot O/B_{mort} < 0.33[a] OR Mort Tally ⩽ 2
Underburn	% Mort Total < 75 AND (Large O/B_{mort} < 0.19[a] OR Large Mort Tally < 2)
Severe	% Mort Large ⩾ 90 OR% Mort Total ⩾ 90
Moderately Severe	% Mort Large > 60
Low	% Mort Total < 50 AND (plot O/B_{mort} < 2 OR (% Mort Small < 25 AND% Mort Large < 25))
Moderate	All other plots

[a] Equal to 67th percentile (lower 2/3) of distribution of O/B_{mort} values for non-burned plots.

Table 2B
Fire severity classification rule set for plots with fewer than 10 tally trees.

Severity class	Rule
Very Low	No Mortality
Low	% Mort Tally < 25
Moderate	% Mort Tally < 60
Moderately Severe	% Mort Tally < 90
Severe	% Mort Tally ⩾ 90

The Severe and Moderately Severe classes (~31% and ~15% of burned plots) were based primarily on percent large tree mortality; >90% and 60–90% respectively (Tables 2A and 2B). Fires severe enough to produce those levels of large tree mortality also killed most small trees (Fig. 2). The Severe class rule also included high mortality plots with no large trees.

The Low severity class (~5% of burned plots) comprised plots with fairly low mortality of both small and large trees, selected as plots with total O/B_{mort} < 2 (approximately twice the background mortality rate), or TPH mortality <50%. The Low severity class plots were selected from the subset of plots remaining after Very Low and Underburn classes had been removed. The Moderate severity class (~25% of burned plots) comprised all plots not previously classified, and generally had large tree mortality in the 25–50% range and small tree mortality in the 40–90% range (Fig. 2). Not unexpectedly, mortality rates were higher for small trees than for large trees in all fire classes.

The patterns of mortality metrics by fire severity class shown in Fig. 2 were similar for East side and West side alone (not shown), except that the Underburn class on the West side had small tree TPH mortality significantly lower than the Low severity class and O/B_{mort} was not significantly different from the Very Low severity, Moderate severity and No Fire classes. This difference may reflect the greater use of prescribed burns as a management tool to reduce small-tree density on the East side, and is the type of fire effect the Underburn class was designed to detect. Percent basal area lost to fire (which was not used to classify severity) increased steadily across our severity classification (Fig. 3).

3.2. Delayed mortality

A total of 38 of the burned plots within the perimeters of three large fires were sampled 1 year post-fire (in the USFS special study) and sampled again 3 or 4 years post-fire by CVS; 33 in the Biscuit fire, 4 in the B and B fire, and 1 in the Fawn Peak complex. Seven of these plots (21%) increased fire severity class when classified with the 3 or 4 years post-fire mortality data compared with their classifications based on 1 year post-fire mortality data: one Very Low became Low, two Moderate fires became Moderately Severe and one became Severe, and three Moderately Severe fires became Severe. For all 38 plots, the change in% TPH mortality between the two sample times ranged from −2% to +16% (median = 5%) with the largest change in the Moderate and Moderately Severe classes. The negative change (one plot) was due to trees judged as dead 1 year post-fire being determined to be alive 3 years post-fire. The change in% TPH mortality was not significantly different for 3 and 4 years post-fire ($p = 0.70$).

3.3. Comparison with other classifications

The BAER classification for the Biscuit Fire comprised four severity classes, Unburned/Very Low, Low, Moderate and High (Azuma et al., 2004; Campbell et al., 2007), with a minimum mapped polygon size of approximately 20 ha. There were 93 CVS plots within the Biscuit fire perimeter with time 2 samples 1–3 years post-fire. The BAER process classified fire severity at 62% of these plots as Unburned/Very Low or Low (Table 3), the same proportion reported for the entire fire area by Campbell et al. (2007). The tree-mortality process only classified 18% of the Biscuit Burned plots in the 4 least severe classes. The tree-mortality fire severity classes agreed with the BAER classes at 34% of the plots (shaded cells Table 3), while at 61% of the plots the BAER severity classes were lower than the tree-mortality classes.

There were 360 CVS plots within MTBS fire perimeters sampled before and after the fires. The 30 × 30 m MTBS pixels were classed as Unburned/Unchanged, Low Severity, Moderate Severity, High Severity, and Increased Greening. There was low intra-plot variability among the 9 pixel classes; 25% of plots had one MTBS class, 44% had pixels that varied by one ordinal position. We chose to use the median pixel class to characterize the MTBS severity classes for our plots. A few Increased Greening pixels occurred at 15 Unburned and 4 Low Severity plots, and did not affect the median values.

In general, our tree-mortality based process classed plots as having experienced either similar severity fires (shaded cells Table 4; ~44% of plots) or more severe fires than did MTBS (below shaded cells; ~52%). We examined a variety of tree mortality and abundance metrics, and the number of years between the fire and the time 2 sample, to identify factors that might explain the unexpectedly high portion of plots in the lower left portion of Table 4. A higher proportion of plots had higher tree-mortality severity classes compared with MTBS classes for time 2 samples two or more years post-fire, than plots with time 2 samples within one year of the fire (58% vs 44%; Table 4), suggesting a possible effect of increased severity classification due to delayed mortality. Within tree-mortality classes, the mean number of years between the fire and time 2 generally decreased as MTBS severity increased, but was not significant ($p = 0.222$, 0.149, 0.080 for Moderate, Moderately Severe, and Severe classes, respectively) with no significant differences among MTBS classes (Tukey–Kramer test). For the tree-mortality Moderate class mean% mortality increased with increased MTBS severity class ($p < 0.001$). We found no other discernable patterns in the tree mortality and abundance metrics associated with differences between plot classifications.

For the tree-mortality classification of CVS plots within the MTBS fire perimeters, percent basal area lost to fire increased with severity (Fig. 4). The interquartile ranges of the lowest 3 severity classes overlapped much more than for the full set of CVS burned plots. For the MTBS severity classes, percent basal area lost to fire also increased with severity, but with considerable interquartile range overlap.

3.4. Regional fire severity patterns

An estimated 12.5% (±0.7% SE) of all NFS forest lands in Oregon and Washington experienced a fire event during the 1993–2007

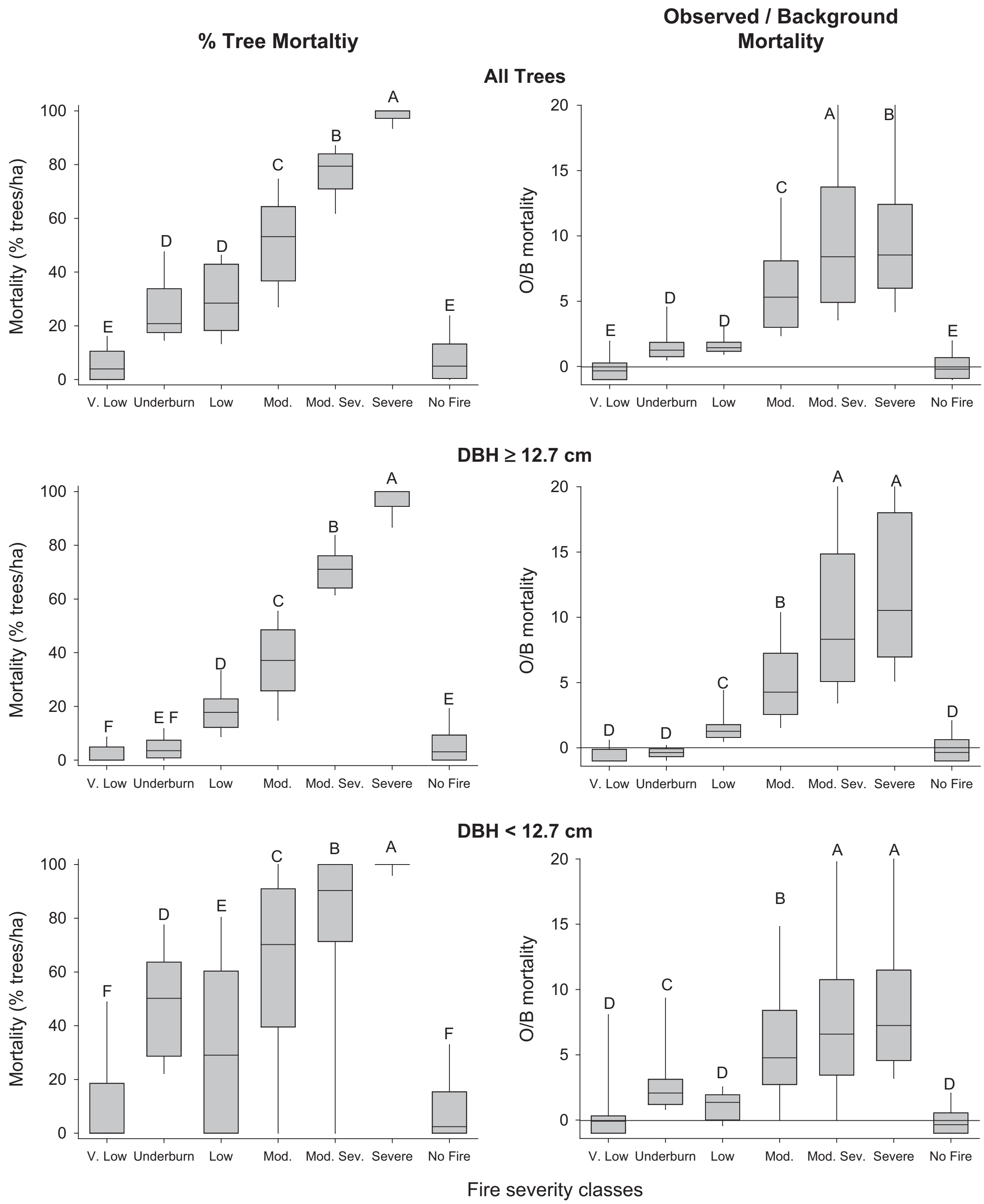

Fig. 2. Boxplots of the percentage of trees that died between the two sample dates (left side) and ratio of observed mortality to background mortality (O/B_{mort}; right side) classified by fire severity, for all trees, for large trees (DBH ⩾ 12.7 cm), and for small trees (2.5 cm < DBH < 12.7 cm) on 10,008 plots in Oregon and Washington. Boxes show interquartile range and median value, whiskers show 10th and 90th percentiles. Letters above the boxes indicate which fire class means are significantly different (identical letters = not different), based on the Tukey–Kramer multiple-comparison test on means.

CVS survey for an estimated annual rate of 0.96% (±0.05%) (Table 5). Fires were rare in the Western Washington zone (WWA). In the other four zones, fires occurred on an estimated 11.6–18.7% of NFS forest lands over the survey period. Severe and Moderately Severe classes dominated within the NFS forest lands experiencing fire events, accounting for an estimated 52.5% of the burned area region-wide, while Very Low severity fires and Underburn fires accounted for an estimated 17.1% of burned areas region-wide (Fig. 5 and Table A.1)

The similarity between the area burned in WOR and the 3 East side zones was somewhat unexpected. The WOR zone is generally wetter with more moderate temperature ranges than the east side. The high area burned in WOR was due primarily to the Biscuit fire which accounted for 77% of the WOR burn area. The Biscuit fire was located in the Klamath Mountains/California High North Coast Range ecoregion (U.S. EPA, 2014) which experiences more lightning strikes (Agee, 1993) and has generally warmer summers than the rest of WOR. The Biscuit fire alone burned an estimated 10% of

Fig. 3. Boxplots of percent of basal area lost to fires, by tree-mortality fire severity class for all CVS burned plots.

Table 3
Comparison of the Burn Area Emergency Rehabilitation (BAER) classification of 93 Biscuit burned plots with the tree-mortality based fire severity classification. Shaded cells mark approximately equivalent severity classes between the two systems.

Tree mortality severity class	BAER severity class				Total
	Unburned/very low	Low	Moderate	High	
No Fire	1	1	–	–	2
Very Low	2	1	1	–	4
Underburn	4	4	–	–	8
Low	2	2	–	–	4
Moderate	9	13	5	1	28
Moderately Severe	6	7	5	–	18
Severe	1	5	9	14	29
Total	25	33	20	15	93

WOR NFS forest lands, with 52% of burned area in Severe or Moderately Severe classes and 13% of burned area in Very Low Severity fires or Underburn classes. All the other fires in WOR burned an estimated 3.5% of NFS forest lands (exclusive of the Biscuit fire area), with 42% of burned area in Severe or Moderately Severe fires,

Table 4
MTBS fire severity classes and the tree-mortality based severity classes for CVS plots within MTBS fire perimeters, sampled by CVS within 1 year of the fire, and 2 or more years after the fire. MTBS classes are the median class for the nine 30 × 30 m pixels centered on the CVS plot center. Shaded cells mark approximately equivalent severity classes between the two systems. The No Fire class is based on the Time 2 field crew notes and maps.

Tree mortality severity class	MTBS severity classes				Total
	Unburned/ unchanged	Low	Moderate	High	
CVS sample within 1 year of fire					
No Fire	5	1	–	–	6
Very Low	3	3	–	–	6
Underburn	1	1	2	1	5
Low	3	4	–	–	7
Moderate	7	23	8	2	40
Moderately Severe	2	13	8	7	30
Severe	1	5	14	42	62
Total	22	50	32	52	156
CVS sample 2 or more years after fire					
No Fire	5	–	–	–	5
Very Low	6	3	1	–	10
Underburn	5	–	–	–	5
Low	3	2	–	–	5
Moderate	20	24	8	1	53
Moderately Severe	3	17	13	–	33
Severe	4	15	28	46	93
Total	46	61	50	47	204

and 15% of burned area in Very Low Severity fires or Underburn fires. The WOR annual burned rate drops from 1.03% to 0.28% when the Biscuit fire is excluded, becoming more similar to the WWA annual rate of 0.05%.

An estimated 234,472 ha (20.9%) of NFS forested lands that burned had fires too small to be included in the MTBS analyses (Table 6). Not unexpectedly, the non-MTBS fires were primarily in the least severe fire classes (60.6% Very Low severity and Underburn vs 6.2% in Moderately Severe and Severe) (Table 6). In contrast, MTBS fires were dominated by the most severe fires (64.6% in Moderately Severe and Severe fires vs 6.9% in Very Low severity and Underburn fires). For the non-MTBS fires we estimate that 28.7% of burned area was in prescribed post-harvest or other stand management fires. Because we did not make an exhaustive review of field notes, we suspect this is an underestimate.

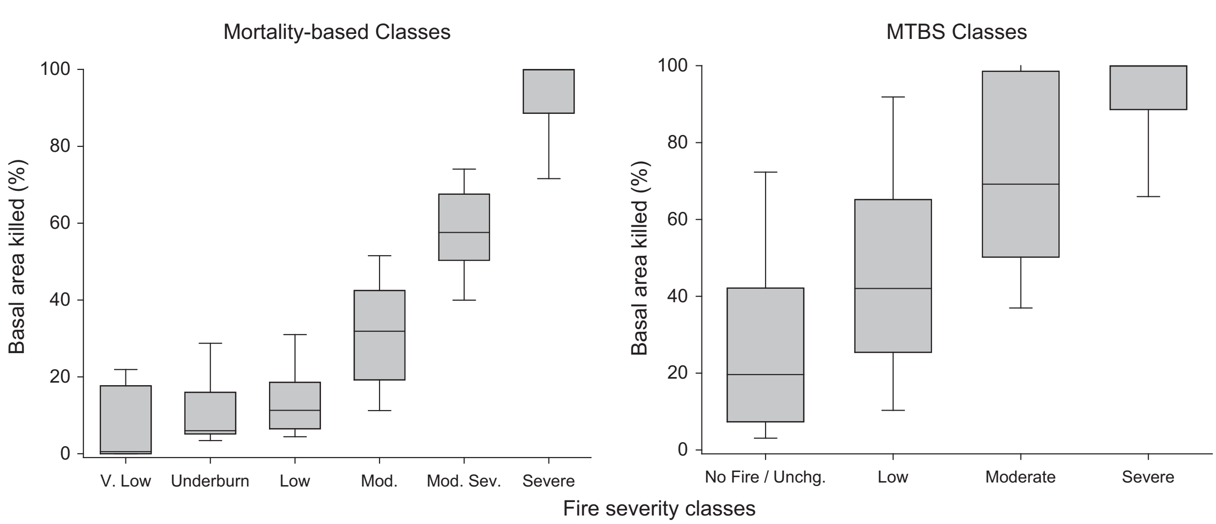

Fig. 4. Boxplots of percent basal area killed for CVS burned plots within MTBS fire perimeters, by tree-mortality fire severity classes (left) and by MTBS fire severity classes (right).

Table 5
Estimates and standard errors of area (hectares) and percent of area burned in Oregon and Washington National Forests System (NFS) lands (1993–2007) by geographic zone. Zones: BLUES = Northeastern Oregon, primarily Blue Mountains; CEOR = Central Oregon, east of Cascade Mountains crest; NEWA = Northeastern Washington, primarily northern Rockies ecoregion; WOR = Western Oregon, west of Cascade Mountains crest; WWA = Western Washington, primarily North Cascades and Coast Range ecoregions.

	Area (1000 ha)	SE	Portion	SE
OR and WA NFS lands				
Forested land	9008	31,150		
Forest burned	1123	63	12.5%	0.70%
Burned/year (average)	86.4	4.8	0.96%	0.05%
BLUES				
Forested lands	2069	16		
Burned total	301	31	14.5%	1.5%
Burned/year (average)			1.12%	0.12%
CEOR				
Forested lands	1451	8.1		
Burned total	168	24	11.6%	1.7%
Burned/year (average)			0.89%	0.13%
NEWA				
Forested lands	1780	21		
Burned total	332	40	18.7%	2.3%
Burned/year (average)			1.44%	0.17%
WWA				
Forested lands	1354	13		
Burned total	8.1	8.0	0.6%	0.6%
Burned/year (average)			0.05%	0.05%
WOR				
Forested lands	2354	11		
Burned total	314	27	13.3%	1.1%
Burned/year (average)			1.03%	0.09%
WOR excluding Biscuit Fire				
Forested lands	2118	20		
Burned total	71	10	3.5%	0.5%
Burned/year (average)			0.28%	0.04%

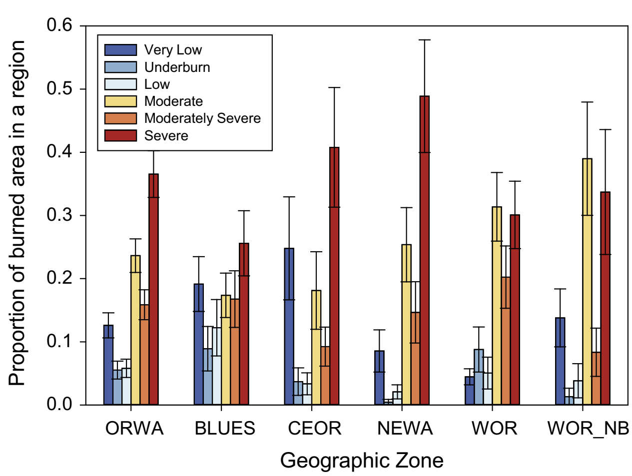

Fig. 5. Estimates and standard errors of proportion of burned area by tree-mortality severity class, and geographic zone in Oregon and Washington National Forests System (NFS) lands (1993–2007). ORWA = Oregon and Washington combined; BLUES = Northeastern Oregon, primarily Blue Mountains; CEOR = Central Oregon, east of Cascade Mountains crest; NEWA = Northeastern Washington, primarily northern Rockies ecoregion; WOR = Western Oregon, west of Cascade Mountains crest; WOR_NB = Western Oregon without Biscuit fire. Western Washington (WWA) not included due very low area burned.

3.5. Investigation of potential data anomalies

The chi-square analysis showed about 17% more plots (75 vs 64) in the two highest severity classes were sampled 1 year after the fire event than expected from a random distribution. This difference may have resulted from planned sampling being delayed because of the fire itself, or in the case of the three largest fires, CVS sample dates may have been moved forward to accommodate the special post-fire surveys. Twice as many (16 vs 8) Very Low severity plots were sampled less than one year after the fire event, than expected. The tree sample data showed that most of these plots had relatively few trees, particularly small trees, at time 1, in addition to very low mortality. There was no clear pattern in the deviations for other time frames for the Very Low severity class and for the Underburn and Low severity classes. This led us to conclude that field crews are not failing to detect or report older low severity fires.

Table 6
Tree-mortality severity classes for large fires (>405 ha) on Oregon and Washington NFS lands included in the MTBS compared with smaller fires not assessed by MTBS. Values are estimates and standard errors of area burned (hectares) and percent of burned area.

	Area	SE	Portion	SE
Fires within MTBS fire perimeters				
Burned total	887,736			
Very Low	25,121	9154	2.8%	1.0%
Underburn	36,182	13,289	4.1%	1.5%
Low	40,721	14,278	4.6%	1.6%
Moderate	211,847	27,902	23.9%	3.1%
Moderately Severe	168,678	26,419	19.0%	3.0%
Severe	405,187	41,289	45.6%	4.7%
Fires outside MTBS fire perimeters				
Burned total	234,472			
Very Low	116,403	20,383	49.6%	8.7%
Underburn	25,804	8708	11.0%	3.7%
Low	24,427	7786	10.4%	3.3%
Moderate	53,402	10,544	22.8%	4.5%
Moderately Severe	9382	3020	4.0%	1.3%
Severe	5053	3093	2.2%	1.3%

The examination of Very Low severity plots indicated that there were fewer small trees (DBH < 12.7 cm) on the Very Low severity plots than plots in the other classes (Fig. 6). There also tended to be fewer large trees in the Very Low severity plots and in the Underburn plots. It seems likely that many of these plots lacked sufficient fuel to support hot fires. However, some of the highest small tree densities were on Underburn plots, although the differences are not statistically significant.

4. Discussion

Our goal in this study was to develop a fire severity classification based on tree mortality data collected in repeat-measurement surveys, from which statistical estimates can be made of the areas and proportions of forest lands experiencing the full range of fire severities, over a range of geographic scales. The numerous existing fire severity classifications each have their own data needs, advantages and disadvantages, appropriate research and management uses and geographic scales. Here we discuss our classification process in terms of some of these issues, and the assessment gaps we believe they can fill. This study is a proof-of-concept assessment of a process that we expect can be applied to the ongoing national FIA survey of all forest lands in the USA. Thus, much of the following is framed in terms of future applications by FIA.

4.1. Data issues

A primary advantage of our classification process is that the individual tree data (size and mortality status) and some of the plot disturbance data we used are being collected by an ongoing,

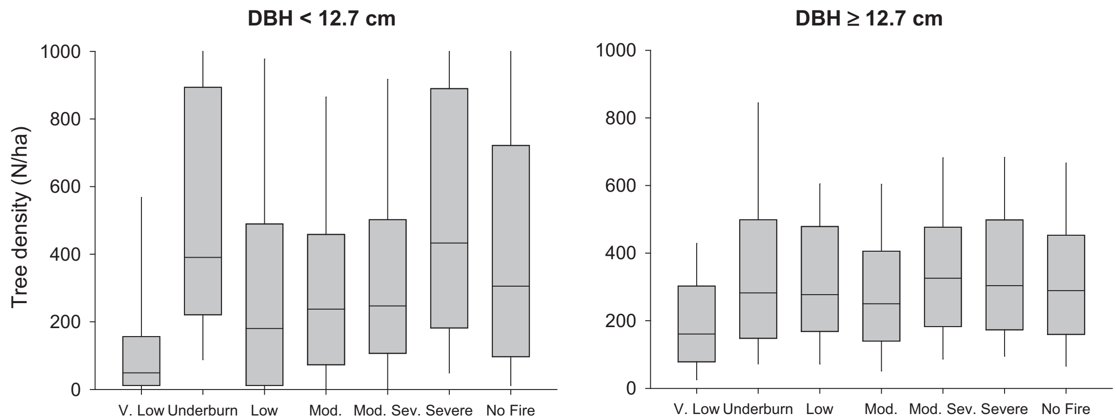

Fig. 6. Boxplots of time 1 tree density (TPH) for small tree (DBH < 12.7 cm; left side) and large trees (right side) by fire severity class. Boxplots and letters above the boxes as in Fig. 2, except that some of the 90th percentile whiskers have been truncated to emphasize differences in the central tendencies.

nationally standardized survey of all forest lands, on a regular remeasurement cycle. Another advantage is that the abundance and mortality metrics are intuitive and easy to calculate, as is the classification itself. However, before this process can be applied to the FIA data, it will be necessary to calculate regionally appropriate background tree mortality rates.

A disadvantage in the FIA data collection, for fire severity assessments specifically, is that commonly-used fire effects measures such as tree bole scorch height and forest floor consumption are not currently being collected on FIA plots except for specialized post-fire studies. However, it is not clear that those fire effect measures would maintain their usefulness and accuracy when measured several years after a fire event. Another limitation is that due to the FIA field methods and 10 year western remeasurement cycle our process only assesses trees with DBH > 2.5 cm. Smaller trees are not individually tracked, so it would be difficult to use their abundance to determine fire severity up to 10 years post fire, or on plots that have no trees with DBH > 2.5 cm at time 1. For completeness it may be useful to create a separate class for these burns.

Another need for improving plot-based assessments of fire severity is for standardized, reconciled plot-level disturbance and management activity data. We used a variety of unreconciled data sources to determine the nature and timing of fire events. Often field crews can only estimate when a fire or a management activity occurred and whether, for example, a ground fire was a natural fire or a prescribed burn or whether tree cutting occurred before or after a fire. Thus, an additional process similar to the one we used to evaluate various sources of disturbance data, or that includes investigation of timing of multiple events in the field protocols, would help produce a final reconciled burned plot data set. While FIA is legally precluded from releasing exact plot locations, options for external fire researchers to associate remotely-sensed attributes with FIA plots include having FIA scientists doing simple overlays and providing attributes, and external researchers conducting overlays and analyses at FIA facilities (http://www.fia.fs.fed.us/tools-data/spatial/index.php). For more extensive analyses, researchers may enter into formal collaborations with FIA scientists that guarantee that they meet confidentiality requirements and assume full legal responsibility for any misuse or disclosure of the data.

4.2. Design issues

A key feature of the FIA probability-based survey design is that disturbances such as fire are detected proportionally to their occurrence on the landscape. That is, there is no bias toward or away from particular forest types, landowners, fire sizes, or severities. Thus, FIA will be able to estimate, with known statistical confidence, the total area (or proportion of area) of forest lands that experience fire events in each severity class. To our knowledge, our study is the first to characterize fire severity and extent for large geographic areas in this way.

The statistical estimates of area or proportion of area burned such as we developed can be made for any "population of interest". Populations of interest can be defined broadly (e.g., severe fires on all forested lands in the 12 western states between 2002 and 2012) or narrowly (e.g., underburns on ponderosa pine forests on private industrial land in eastern Oregon in 2012). The estimates for these two examples will be equally valid, but the confidence interval around the former will be smaller (more precise) than the latter. Finally, sample surveys, such as CVS and FIA, are not intended to address questions of numbers or sizes of individual fires, nor for in-depth analyses of processes and patterns on individual plots. Sample survey data can be very useful in providing the broad-scale context for those kinds of assessments.

4.3. Fire severity classes

Most of the fire severity classifications that we have seen use four classes, generally low, moderate and severe, with an implicit or explicit no fire/unchanged class. Here, we describe the reasoning behind our choice to use seven severity classes. We were partially motivated by a desire to provide better understanding of the regional extent of the smaller and less intense fires, and of prescribed burns. First, it is useful to have an explicit No Fire class because most plots in broad-scale sample surveys will not experience a fire event between samples, and some areas within large fire perimeters will not burn at all. Field crew assessments are critical to distinguish No Fire from Very Low severity ground fires. The Very Low severity class plots have explicitly experienced a fire event, but the direct mortality effect on trees (larger than seedlings) on these plots is zero or indistinguishable from the natural background mortality. This does not imply that there have been no ecological effects. In addition, for some prescribed burns the management goal is limited to reducing ground fuels, producing the same (tree mortality) effect as natural Very Low severity fires. An estimated 32% of the NFS forested land area that burned in Very Low severity fires was in prescribed burns (39% of Very Low in non-MTBS fires). In other cases, prescribed burn goals also include killing potential ladder fuels including saplings (DBH < 12.5 cm). Our Underburn and Low severity classes were the least common (lowest areas burned) severity classes in the CVS survey; 5.5% (±1.4%) and 5.8% (±1.4%) of burned area respectively. We estimate that 4.9% of the area in Underburn fires (11.7% in non-MTBS fires) and 10.9% of the area burned in Low severity fires (29.0% in non-MTBS fires) was in prescribed burns. Combined these two classes are generally equivalent to the low severity classes in most other classifications. However, it seems useful to be able to distinguish low intensity fires which only kill understory trees from those that also kill a portion of the overstory canopy. The Moderately Severe class (generally 60–90% large tree mortality) allows additional resolution at the high fire severity end of the spectrum.

The CVS data appear to confirm the often unstated assumption that very large fires are generally more severe than smaller fires. For MTBS fires (>405 ha) nearly half of the burned area was in our Severe class which was more the twice the area in Moderately Severe fires. In the smaller non-MTBS fires, Severe fires were the least common class (3.9% of burned area), with nearly twice as much area burned in Moderately Severe fires. The portion of burned area in Moderate severity burns was similar for MTBS and non-MTBS fires.

4.4. Other issues and concerns

Before the FIA tree-mortality and plot disturbance data can be used to characterize fire extent and severity as we did here, and to assess trends in those data, an adjustment for the effect of delayed mortality will improve comparisons among plots measured over the remeasurement cycle. Our limited assessment of delayed mortality found 21% of plots changed severity classes and up to a 16% increase in% TPH mortality (median = 5%) 3 or 4 years post-fire compared with 1 year post-fire. The FIA field-data collection is more explicit about causes of tree mortality than was the CVS data, which may help distinguish delayed mortality due to secondary causes (e.g., insects). Although it may be possible to develop statistical models to adjust for delayed mortality using the basic FIA data alone, we expect that additional targeted field studies, or implementing post-fire measurements, will be useful.

Salvage logging can further complicate use of survey-based tree mortality to classify fire severity. On National Forest lands, salvage logging is often limited to cutting dead or dying trees, so one could potentially include cut trees with the other fire killed trees in the classification data. Although we did not do this due to issues discussed above, we made a qualitative review of field notes for burned plots that had trees cut, apparently post-fire. That review indicated that including cut trees as fire mortality could change about half of the Moderate severity classifications (on plots with cuts) to a higher severity class. Very few other burned and cut plots were likely to change fire severity classes; salvage logging was not done on plots with lower intensity fires. However, on private forest lands salvage logging may include harvest of merchantable trees within one or two years of the fire. Determining fire severity on these plots would require either field surveys soon after a fire (prior to logging) or substitution of other fire severity classification data.

Perhaps the most unexpected result for us was the high proportion of plots for which both the BAER and the MTBS fire severity classifications were distinctly less severe than the tree-mortality based severity classification. Given the smaller area of Landsat pixels (30 × 30 m) compared to the CVS plot footprint (1 ha), the frequency of high and low severity classes should be greater than on plots, where any patchiness in severity would be averaged across the sample area. Some of these differences may be due to the delayed mortality effect described above, where fire severity apparently increased over time on some of the plots. However the size of this effect does not seem sufficient to explain how MTBS classified fires in 53% of the plots with 60–90% large tree mortality (Moderately Severe) as Low severity or Unburned/Unchanged, and 43% of the fires in plots with >90% tree mortality as Moderate severity, Low severity or Unburned/Unchanged. These differences were supported by the distributions of the percent basal area lost to fire, which ranged much higher in the less severe MTBS classes than we expected. For example, half of the plots with a median MTBS class of No Fire/Unchanged lost more than 20% of basal area and a quarter of those plots lost more than 40% of basal area (Fig. 4). Similarly half of the MTBS Low severity plots lost more than 40% of basal area and a quarter of those plots lost more the 60%.

It is likely that a portion of the differences between classifications is due to the fact that the largest trees are the least likely to die in a fire and can still have a substantial amount of green cover from above, potentially masking high mortality of shorter trees. As we described in the introduction, other investigators studying fire severity trends have chosen not to use the MTBS dNBR-based classification (e.g., Miller et al., 2009b, 2012; Dillon et al., 2011; Cansler and McKenzie, 2014; Prichard and Kennedy, 2014), but rather worked directly from the continuous RdNBR data, calibrated with on-the-ground data. Our results suggest that this national-scale classification may benefit from further adjustment; possibly with the incorporation of field data where available (Kolden et al., 2015).

4.5. Concluding remarks

In this paper, we have presented the first broad-scale, ground survey-based statistical estimates of fire severity for the full range of severities and fire sizes. In addition, this study provides a broad-scale characterization of the extent of relatively low severity fires and small fires, including prescribed fires, not previously available. This information should be useful as the research and management discussions about the role of managed fires continue. We believe the process we have presented here would be a valuable addition to future fire assessments in the FIA survey.

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Appendix A

See Table A.1.

Table A.1
Estimates and standard errors of area burned (hectares) and percent of burned area by tree-mortality severity class, in Oregon and Washington National Forests System (NFS) lands (1993–2007). Zones as in Table 5. Western Washington (WWA) not included due very low area burned.

	Area	SE	Portion (%)	SE (%)
OR and WA NFS lands				
Very Low	141.5	22.3	12.6	2.0
Underburn	62.0	15.9	5.5	1.4
Low	65.1	16.3	5.8	1.4
Moderate	265.2	29.8	23.6	2.7
Moderately Severe	178.1	26.6	15.9	2.4
Severe	410.2	41.4	36.6	3.7
BLUES				
Very Low	57.5	13.0	19.1	4.3
Underburn	26.8	10.6	8.9	3.5
Low	36.8	13.4	12.2	4.5
Moderate	52.2	10.6	17.3	3.5
Moderately Severe	50.4	13.5	16.7	4.5
Severe	76.9	15.5	25.6	5.2
CEOR				
Very Low	41.6	13.7	24.8	8.2
Underburn	6.2	3.6	3.7	2.2
Low	5.6	2.9	3.4	1.7
Moderate	30.4	10.3	18.1	6.1
Moderately Severe	15.5	5.2	9.2	8.1
Severe	68.3	15.9	40.8	9.5
NEWA				
Very Low	28.4	17.1	8.6	3.3
Underburn	1.5	1.5	0.4	0.4
Low	6.9	3.7	2.1	1.1
Moderate	84.3	19.5	25.4	5.9
Moderately Severe	48.7	16.1	14.7	4.8
Severe	162.4	29.7	48.9	8.9
WOR				
Very Low	14.0	4.0	4.5	1.3
Underburn	27.5	11.2	8.8	3.6
Low	15.8	7.9	5.1	2.5
Moderate	98.4	17.0	31.4	5.4
Moderately Severe	63.5	15.5	20.2	4.9
Severe	94.4	16.8	30.1	5.3
WOR excluding Biscuit Fire				
Very Low	9.8	3.2	13.8	4.6
Underburn	0.9	0.9	1.3	1.3
Low	2.7	1.9	3.8	2.7
Moderate	27.6	6.4	39.0	9.0
Moderately Severe	5.9	2.7	8.3	3.8
Severe	23.9	7	33.7	9.9

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