Characterizing recent bark beetle-caused tree mortality in the western United States from aerial surveys

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Highlights

- Estimated bark beetle-caused tree mortality in the western US from aerial surveys
- A range of results from different methods indicates some uncertainty
- Annual Westwide tree mortality continued to be high in recent years
- Multiple severe outbreaks in different locations contributed to mortality

Author contributions:

Jeffrey Hicke: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing.

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Abstract

Bark beetle (Curculionidae, Scolytinae) outbreaks have been extensive and severe across the western United States in recent decades, and assessments of tree mortality are critical for documenting patterns and increasing understanding of drivers and impacts. Aerial surveys have produced a rich data set that includes damage severity, year and location of damage, and beetle and tree species. Here we update a data set of bark beetle-caused tree mortality for the western United States to include five additional years (now 1997-2018) and use these data to characterize recent outbreaks and compare with earlier tree mortality. We estimated “mortality area” (MA), the canopy area of beetle-killed trees and a more accurate representation of outbreak impacts than “affected area”, as well as the number of killed trees. Recently, the US Forest Service changed survey approaches, creating challenges for linking observations from the old and new approaches. We compared four methods to harmonize these approaches to produce consistent time series of tree mortality. General similarity of MA occurred in several methods; however, the range of results indicated some uncertainty. Based on limited analyses and a desire to be conservative in damage estimates, we suggest that the FHP\textsubscript{R1-R4} method, which produced intermediate mortality among the methods, is most realistic for representing tree mortality from bark beetles. Using this recommended method, we found that bark beetles caused 4.3 Mha of MA and 3.8\times10^9 killed trees when summed across space, time, and bark beetle/host combination (range among methods: 1.5-7.4 Mha and 1.2-6.3\times10^9 killed trees). This total mortality area was 4.7\% of forest area in the western United States; 28\% of this mortality occurred in 2013-2018. Annual tree mortality remained high recently, with values comparable to earlier years, and was a result of combinations of outbreaks of different beetle species in different regions with different
Bark beetles continue to be agents of significant forest disturbance in the western United States. Given a range of mortality area results from the different methods, we encourage further evaluation of estimates using independent observations.

1. Introduction

Bark beetles (Curculionidae, Scolytinae) have caused substantial tree mortality in the western United States in recent decades as determined from aerial surveys (Hicke et al., 2016). These biotic disturbance agents have killed similar numbers of trees as wildfire in the region (Hicke et al., 2016). This mortality has important ramifications for timber production, species composition, carbon sequestration, water cycling, recreation, and other forest processes and ecosystem services. Quantifying the extent and timing and continued monitoring of this mortality are therefore important for understanding the state of forests and impacts in the western United States.

Currently the only annual, spatially explicit data set documenting outbreaks and beetle and host characteristics in the US is produced by USDA Forest Service (USFS) aerial surveyors using airplanes. Aerial survey information about tree mortality caused by bark beetles is regularly reported by the USDA Forest Service (e.g., Potter and Conkling, 2018) and other forest agencies and has been used in numerous studies of bark beetle ecology and impacts (e.g., Berg et al., 2013; Hicke et al., 2013; Biederman et al., 2015; Ghimire et al., 2015; Buotte et al., 2017; Young et al., 2017). Aerial surveyors record location, tree species, bark beetle species, affected area
(area of a damage polygon), and a measure of tree mortality, which can include the number of killed trees (NKT), the number of killed trees per acre (TPA) (which can be combined with affected area to calculate the number of killed trees), or a percent mortality class (McConnell et al., 2000) (see Table 1 for terms, abbreviations, and definitions used in this study). Aerial survey information has been available electronically for the western United States since 1997.

**Table 1. Terms, abbreviations, and definitions used in this study.**

<table>
<thead>
<tr>
<th>Term</th>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Digital Aerial Sketch Mapping</td>
<td>DASM</td>
<td>aerial survey approach used in earlier years; surveyors record %AA class within aerial survey polygons</td>
</tr>
<tr>
<td>Digital Mobile Sketch Mapping</td>
<td>DMSM</td>
<td>aerial survey approach used in later years; surveyors record TPA or NKT within aerial survey polygons</td>
</tr>
<tr>
<td>trees killed per acre</td>
<td>TPA</td>
<td>recorded by aerial surveyors using DASM approach</td>
</tr>
<tr>
<td>affected area</td>
<td>--</td>
<td>area of aerial survey polygon; includes live and killed trees</td>
</tr>
<tr>
<td>mortality area</td>
<td>MA</td>
<td>canopy area of killed trees</td>
</tr>
<tr>
<td>percent affected area</td>
<td>%AA</td>
<td>percent of aerial survey polygon containing killed trees; equivalent to percent mortality area</td>
</tr>
<tr>
<td>percent affected area class</td>
<td>%AA class</td>
<td>classes of %AA; one of five recorded by aerial surveyors using DMSM approach; FHP&lt;sub&gt;1-4&lt;/sub&gt; method uses three classes</td>
</tr>
<tr>
<td>number of killed trees</td>
<td>NKT</td>
<td>number of killed trees within an aerial survey polygon, within a grid cell, or summed across regions</td>
</tr>
</tbody>
</table>
Aerial survey information is subjective in nature, with variability and uncertainty introduced by different surveyors, viewing conditions, and flying conditions (Coleman et al., 2018). A study of USFS aerial survey damage location for a range of bark beetles reported 79% accuracy for a spatial tolerance of 500 m (i.e., allowing for a spatial error of 500 m) and 68% accuracy for 50 m (Johnson and Ross, 2008). An extensive accuracy assessment of USFS aerial surveys across the US and for different damage agents using ground measurements and remote sensing reported high accuracies of distinguishing general damage type (e.g., tree mortality) and tree genera, lower accuracies for tree species (87%) and feeding guild or injury category (84%), and damage agent species (70%), and found some difference in location and extent of damage polygons among surveyors (Coleman et al., 2018). In a mixed conifer forest in northern Idaho that experienced mortality from different bark beetles, Bright et al. (2020) found accuracies of 35-56% for severity class reported by aerial surveys compared with satellite remote sensing, with higher accuracies (71-78%) achieved when correctness criteria were somewhat relaxed.

In a previously published study (Meddens et al., 2012), we used the aerial survey database to produce an estimate of bark beetle-caused tree mortality for 1997-2010. The affected area of damage polygons recorded by USFS aerial surveys includes live trees and thus overestimates the impact; for the western US, affected area was larger than mortality area (the crown area of killed trees; MA) by a factor of four (Hicke et al., 2016). In addition, the polygon-based data structure of the aerial survey database makes using these data in conjunction with other data sets challenging. Meddens et al. (2012) used aerial survey information to estimate the number of killed trees (NKT) within 1-km grid cells for the western US, and converted NKT to mortality area by multiplying by tree species-specific crown areas. Comparisons of gridded mortality area
with maps of mortality derived from remote sensing studies suggested that aerial survey-based
results were underestimated. Thus, Meddens et al. (2012) also provided a “higher” estimate that
applied adjustment factors derived from comparisons with remote sensing studies, and Hicke et
al. (2013) produced a middle estimate using updated adjustment factors. Two additional years
(2011-2012) and a middle estimate with updated adjustment factors was added in a study of
forest carbon (Hicke et al., 2013), and this data set was used in a comparison with mortality area
from wildfires (Hicke et al., 2016). Given significant bark beetle outbreaks in a number of
different areas since 2012 (reported as affected area in, e.g., USDA Forest Service, 2019a), we
sought to update the prior record of mortality area and characterize the mortality by space, time,
and beetle species.

Prior to 2012, surveyors collected information using the Digital Aerial Sketch Mapping (DASM)
approach, in which tree mortality was documented by TPA or NKT (McConnell et al., 2000).
(Here we use “approach” when discussing the way aerial surveyors recorded information and
“method” for the different techniques this study used to link time series of observations from the
two approaches.) These data were the basis for the mortality area estimates from our previous
studies (Meddens et al., 2012; Hicke et al., 2013; Hicke et al., 2016). Beginning in 2012 or later,
depending on location (Figure 1), surveyors began using the Digital Mobile Sketch Mapping
(DMSM) approach. The recommended protocols for the DMSM approach are for surveyors to
estimate tree mortality within one of five different percent treed area affected classes (USDA
Forest Service, 2019b) (Table S1). However, it is our understanding that aerial surveyors
typically record the percentage of an entire polygon instead of the percent treed area and that
surveyors post-process the data to remove unforested areas from polygons. Training and
certification classes encourage surveyors to utilize the smallest polygon extent practical and avoid such nonforest areas and when mapping damage. Thus, for this study we interpret these classes as percent area affected of the damage polygon (%AA). We report the sensitivity of testing this assumption below.

Figure 1. Annual maps of locations where surveyors recorded bark beetle-caused tree mortality using DASM (TPA) approach (red) or DMSM (%AA class) approach (blue). USFS Region boundaries indicated by thick lines and numbers in map. In 2011, all locations used the DASM
approach; in 2017, only Region 6 used the DASM approach; in 2018, all locations used the
DMSM approach.

The discontinuity in time from the DASM (TPA- or NKT-based) approach to the DMSM (%AA-
based) approach poses challenges for developing consistent time series of bark beetle-caused tree
mortality. It is not possible to directly compare mortality from DASM records to mortality from
DMSM records. In addition, the DMSM (%AA) approach may mean that applying adjustment
factors to account for underestimation, as was developed by Meddens et al. (2012), is not
needed. Yet a consistent time series of mortality is critical to continue to monitor these forest
disturbances, better understand drivers, and document aggregate, multi-year effects.

Our study objectives were to update the time series of bark beetle-caused tree mortality to 2018,
characterize recent outbreaks, and compare the damage from these later outbreaks to earlier
outbreaks. To do this, we explored four methods of linking the DASM and DMSM approaches
to permit continuity in time of estimates of bark beetle-caused tree mortality. We gridded these
data to 1-km spatial resolution and applied a capping correction to grid cells whose MA
exceeded 100% of a grid cell. We then compared results from different methods. Finally, we
quantified the spatiotemporal patterns of mortality area and assessed the contributions of
outbreaks of different bark beetle species.
2. Materials and Methods

2.1 Aerial survey data

We downloaded all available aerial survey data from 1997-2018 for each USFS region in the western US in Insect and Disease Survey (IDS) databases (https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/detection-surveys.shtml, accessed 19 October 2019). Data were projected to Albers equal-area conic projection, and records of tree mortality caused by bark beetles were extracted for each year. For each polygon, surveyors recorded multiple attributes about damage, trees, and disturbance agents. We used the damage causal agent (DCA; all three possible attribute columns in database) and damage type (=2, mortality) attributes to identify trees killed by bark beetles in a particular year. When DCA was not recorded but host tree species or forest type was, we assigned a damage agent if the bark beetle and host tree species (or forest type) combination was unambiguous and limited to one choice (similar for the reverse situation in which DCA was known but host/forest type was not) (Meddens et al., 2012). Because some DASM records had only one of either TPA or NKT, we ensured that both were present for each record using

\[ NKT = TPA \times A, \]

where A is the area of the polygon (acres). We did not include Alaska in our analysis because of limited data availability.
2.2 Mortality area for DASM records

We describe below the four methods of converting TPA observations in DASM records to mortality area for DASM polygons (Figure 2, Table S2).

Figure 2. Workflow diagrams for different methods to convert DASM records of killed trees per acre (TPA) to mortality area (MA) for damage polygons. (MA from DMSM records was computed by multiplying percent affected area (%AA) by the area of the damage polygon.) Bold text in boxes indicate the results from the four methods.

2.2.1 Histogram matching (HM) method
Histogram matching is a method to transform one distribution to match a second distribution, and is commonly used in remote sensing image analyses (e.g., Wegener, 1990). Here histogram matching is used to match the distribution of TPA records from the older survey approach (DASM) with the distribution of %AA class records from the newer approach (DMSM) (Zweifler, 2019). The objective was to provide a consistent time series of tree mortality from observations of both approaches. The assumptions were that surveyors have been consistent in their estimates of tree mortality across time (and therefore also across approaches), that surveyors observed the same frequency of severities during the time periods of the DASM approach and the DMSM approach, and that the DMSM approach allowed surveyors to more accurately estimate the actual mortality.

To estimate the histogram matching transformation, we formed cumulative histograms of the areas of polygons with %AA class and TPA (Figure 3). Percentiles of each %AA class (y1-y4 in Figure 3) were determined; the y1-y4 values were the upper limit percentiles of each %AA class (y5 is set to 100%). We identified TPA values (t1-t4) for these percentiles in the TPA cumulative histogram; these values formed the upper limits of TPA ranges associated with each %AA class (together with the maximum TPA as the upper limit of %AA Class 5). Thus, the TPA range for %AA Class 1 was 0-t1, for %AA Class 2 was t1-t2, and so on.

After the histogram matching transformation was determined, we converted TPA values first to %AA class, then to %AA using the midpoint of the percent mortality range (Table S1). Mortality area was then computed for each record by multiplying the %AA by the polygon area.
Figure 3. Illustration of histogram matching method. Histograms of area of polygons with each % area affected (%AA) class (a) and with trees per acre killed (TPA) (c) were used to compute cumulative distributions of these variables ((b) and (d), respectively). Percentiles of the upper limit of each %AA class were determined (y1-y4; y5=100%) (#1 in figure). These upper limits were applied to the cumulative histogram of TPA (d, #2), and corresponding values of TPA were determined (t1-t4) to define upper limits of TPA for each %AA class (#3). A TPA value then corresponds to the %AA class that contains the TPA value within its range (0-t1, t1-t2, etc.).
We developed histogram matching transformations for each USFS region individually to account for possible differences in surveying protocols among the regions. We also explored the sensitivity of the HM method to the shape of the DASM record distribution (because of the greater number of DASM records compared with the number of DMSM records). Different transformations were computed with subsets of DASM records from each year (22 years in total resulting in 22 different transformations) as well as one additional transformation with records from all years, for a total of 23 different estimates. We only include subsets (years) for which the number of DASM records exceeded 5000 to minimize undersampling influences.

We applied the histogram matching transformations to convert TPA values to %AA class. We multiplied the %AA midpoint for each %AA class (Table S1) by the area of the damage polygon to calculate MA of the polygon.

2.2.2 Meddens method

The Meddens method (Meddens et al., 2012; Hicke et al., 2013) converted TPA to NKT by multiplying TPA by the damage polygon area in acres. For each record, we then multiplied NKT by the mean species-specific crown area (CA, Table S3; from plot measurements) to produce a lower estimate of mortality area ($MA_{\text{low}}$):

$$MA_{\text{low}} = NKT \times CA.$$
We then computed a second, middle estimate of mortality area following Meddens et al. (2012) and Hicke et al. (2013) by multiplying piñon pine records by 3.7 and other species by 13.6. These adjustment factors were determined by direct comparisons of aerial survey-based mortality area with remote-sensing-based estimates (e.g., Hicke and Logan, 2009; Meddens et al., 2011) that indicated significant underestimation of $MA_{low}$.

### 2.2.3 FHP$_{R1-R4}$ method

The FHP$_{R1-R4}$ method used factors developed from field measurements for converting TPA in the DASM records to %AA class developed from field measurements (Table S1) (Egan et al., 2019). Observations of 30,386 trees exposed to *Dendroctonus* spp. of bark beetles in 329 fixed-area plots (0.04-0.81 ha) were collected from published and unpublished records that focused on yellow pine-dominated forest types across the western US and from 1961-2016. TPA and percent mortality (%M) were calculated for each plot (percent mortality in this study was tree-based; here we assume that it is equal to canopy (area) percent mortality). Boundaries of 10% and 30% for three bins of percent mortality were determined based on increasing variability in TPA values for a given percent mortality, which suggested a relatively low upper boundary (30%) compared with the DMSM %AA bins, as well as input from surveyors and foresters. To determine the TPA values corresponding to these boundaries, three linear regression models were developed from the plot-level percent mortality and TPA values: one for the entire data set (natural log-transformed) and two models that used observations near the boundaries (untransformed). Predicted TPA values at the lower 95% confidence interval from the all-data model and the local model were estimated at the boundaries (two values each for 10% and 30%...
mortality), then averaged to determine the TPA bin boundaries listed in Table S1. A classification of the data using these boundaries resulted in an overall accuracy of 84%. See Egan et al. (2019) for details. We converted the recorded TPA from the DASM approach to percent mortality using Table S1 and multiplied by the polygon area of the record to compute MA.

2.3 Mortality area from DMSM records and point data

For the HM and Meddens methods, %AA class for each DMSM record was converted to %AA (Table S1), then multiplied by the area of the damage polygon to calculate mortality area. For the FHP R1-R4 method, we collapsed the five %AA classes into the three used in the FHP R1-R4 method: low (very low+low %AA classes), moderate (moderate %AA class), and high (high+very high %AA classes). We used the percentages in Table S1 for converting these three classes into percent mortality area and therefore mortality area of the polygon.

The aerial survey databases contained buffered point (DASM approach) and true point data (DMSM approach) as well as polygon data (which are described above). We converted NKT reported in these point records to MA using crown areas as discussed above.

2.4 Gridded mortality area and number of killed trees

Following Meddens et al. (2012), we summed MA from DASM and DMSM polygons within 1-km grid cells across the western United States. First, a fishnet of the grid boundaries was used to
intersect polygons for each bark beetle/host combination and year. Mortality area for intersected
polygon fragments was then computed as the fraction of MA (assumed constant across the
polygon) represented by the polygon fragment area relative to the area of the entire polygon.
Mortality areas from all polygon fragments within one grid cell were summed, thus producing
MA for one grid cell per year and per bark beetle/host combination. Only the estimates from the
histogram matching transformation using all DASM records, not the 22 transformations that used
annual subsets of DASM records, were converted to grids.

For some grid cells and methods, cumulative (over time and bark beetle/host combinations)
mortality area exceeded 100 ha, or 100% of a 1-km grid cell. These unrealistic values likely
resulted from variability in surveyor approaches and accuracy and crown area of killed trees and
overestimation by different methods. We used the frequency of these grid cells as guidance for
which of the four methods produced the most accurate results. To eliminate these values, for
each grid cell with cumulative mortality area exceeding 100%, we scaled the mortality area
estimates over time and for all bark beetle/host combinations such that the cumulative mortality
area equaled 100%. This process had the advantage that cumulative MA was realistic but the
disadvantages that this method was applied on a per-grid cell basis and for affected grid cells,
does not allow future mortality (beyond years considered here) to occur unless MA is rescaled
again (thereby changing 1997-2018 values).

We tested the sensitivity of our mortality area results to the assumption that surveyors reported
percent area affected, not percent treed area affected, by multiplying MA in 1-km grid cells by an
estimate of percent tree canopy. We aggregated the two USDA Forest Service Tree Canopy
Cover datasets (from 2012 and 2016; “cartographic” product, [https://data.fs.usda.gov/geodata/rastergateway/treecanopycover/](https://data.fs.usda.gov/geodata/rastergateway/treecanopycover/), accessed 7 March 2020) from 30-m to 1-km spatial resolution, then took the maximum cover of the two years by grid cell to minimize disturbance effects. We then multiplied the two methods that converted TPA to %AA, FHP<sub>R1-R4</sub> and HM, by the percent tree canopy cover.

The number of trees killed by bark beetles (NKT) is an additional metric of tree mortality that is useful in some situations. Multiple ways of estimating NKT exist for both DASM and DMSM records. Here we estimated NKT by dividing MA estimates from Section 2.2 by mean species-specific crown areas (Table S3). This method allowed us to incorporate the capping constraint that mortality area cannot exceed 100%. For DASM records, the Meddens lower method of computing NKT is equivalent to summing NKT calculated from the recorded TPA in each grid cell.

3. Results

3.1 Comparison among methods

Mortality area estimates using the histogram matching method exhibited sensitivity to the subsets of DASM records that were used to develop the histogram transformations. Estimates for t1-t4 varied within a region and across regions as a result of the different subsets of DASM records that were used to develop the histogram transformations (Table S1, Figure 4). For some cases, high variability in t1-t4 and mean TPA resulted from extensive tree mortality concentrated in one
year (Figure S1). The variability from subsets of DASM records yielded a range of “preliminary” mortality area time series (note that these areas were from summing damage polygons, not gridded results, to assess sensitivity) (Figure 5). In many years and regions, preliminary mortality area varied by a factor of two. For the remainder of the analysis presented here, we used the HM results from the set of DASM records from all years.

The different methods varied in their conversion of TPA to %AA. For a given TPA, the Meddens lower method calculated the lowest %AA for California conifers or lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.) (Figure 6). The Meddens middle method produced the highest %AA for TPA > 10, and the HM and FHP\textsubscript{R1-R4} methods were intermediate in their estimates of %AA. The HM method produced similar or higher %AA than the FHP\textsubscript{R1-R4} method for TPA < 30. This range of TPA is significant because the vast majority of DASM polygons had TPA values in this range (TPA exhibited a negative exponential distribution; Figure 6).
Figure 4. Distributions of means of TPA weighted by polygon area for all histogram subsets across regions within each %FAA class. Small dots are results from individual subsets; rectangles define 25th and 75th percentiles; horizontal lines are median values; whiskers indicate range of results excluding outliers. Large dots are results from histogram that used all years. Only subsets (years) with >5000 DASM records are plotted. See Figure 1 for map of regions.
Figure 5. Variability in histogram matching transformations illustrated by estimates of “preliminary” mortality area (from summed polygons, not grids) for each of the USDA Forest Service regions in the western US (see Figure 1 for map of regions). Black line: estimates from histogram matching transformation using all DASM years. Shaded gray band: range of estimates from histogram matching transformations developed from subsets of DASM records (one year of records per subset).
Figure 6. Trees killed per acres (TPA) versus percent area affected for the four methods used in this study: histogram matching (values averaged across all regions): thick black lines; FHP\textsubscript{R1-R2}: gray line; Meddens middle and lower methods for tree species killed in California that have large crown area (California red fir, white fir, ponderosa pine; “CA”) and for lodgepole pine, which has a small crown area (“LP”). Thin gray line and right $y$-axis: histogram of TPA for DASM polygons.

Cumulative (over bark beetle/host combination and year) mortality estimates before applying the capping correction allowed us to estimate which methods may have overestimated mortality.
Methods that resulted in high tree mortality had cumulative mortality area that exceeded 100% of a grid cell more frequently and by greater amounts. The Meddens lower method had the fewest grid cells exceeding 100% (199, with a maximum of 274%) and the Meddens middle method had the greatest (18,594, maximum exceeding 1000%) (Figure S2). Exceedances occurred in locations of severe outbreaks and were distributed across the associated beetle and host species (i.e., were not concentrated in one beetle/host system).

After capping corrections were applied, mortality area and corresponding number of killed trees summed for each region exhibited variability among methods (Figure 7). NKT from the Meddens lower method produced much lower values than the other methods during years when surveyors used the DASM approach. The Meddens middle method produced the highest estimates for in most regions and years, although the HM method was similar in Region 1 across years and for some years in other years. Estimates from the Meddens middle method were substantially higher than from other methods in Region 5 in 2015-2016 and in peak years in other regions (e.g., Region 3 in 2003, Region 4 in 2010-2011). NKT from the FHPR1-R4 method was generally lower than the estimates from the HM and Meddens middle methods, although similar in some years.
Figure 7. Number of trees killed (NKT) by region calculated from capped mortality area grids.

Thin black lines with asterisks: histogram matching (HM) method using all DASM records. Thick gray lines with plusses: FHP\(_{R1-R4}\) method. Thin gray lines: Meddens lower method (squares) and Meddens middle method (plusses). For DASM records (i.e., until late in the study period), the Meddens lower method is equivalent to summing the number of trees killed reported by the aerial survey database. See Figure 1 for map of regions.

We summed mortality area across regions to produce the time series for the western US (Figure 8). The HM and Meddens middle methods produced similar results except in 2003-2004 and 2015-2016. MA from the FHP\(_{R1-R4}\) method was somewhat lower, and the results from the Meddens lower method were substantial lower than the other methods. Notable was the higher
estimate of the Meddens middle method in 2016 (discussed above), which exceeded other
estimates by a factor of 2-3. Mortality area from the Meddens lower method was substantially
dlower than other estimates during periods when surveyors used the DASM approach (TPA).
Estimates become more similar in 2017 and 2018 as regions transitioned to DMSM approach
(because all methods used same calculation of MA for DMSM records). Temporal patterns were
typically similar among methods, indicating that the main effect of the different methods was to
amplify or dampen the outbreak severity (number of killed trees). Some differences in temporal
patterns did occur, however, such as different relative amounts of MA in 2003 and in 2016
among the methods. The sensitivity test of applying percent tree canopy cover to the %AA
records reduced annual Westwide mortality area by 20-50% depending on year (related to the
dominant killed conifer species within different outbreaks).

Given the wide range in estimates, we cautiously suggest a recommended method based on
several lines of evidence. The Meddens middle method was developed because the MA from the
Meddens lower method was substantially lower than collocated maps from remotely sensed
imagery. Thus, we suggest that for the period when surveyors were using the DASM approach,
TPA was underestimated. The rough agreement among the HM, FHP_{R1-R4}, and Meddens middle
methods, which use different methodologies to convert TPA to MA, gives some confidence that
those methods are more realistic. However, the much higher grid cell values of MA and NKT
from the Meddens middle method in 2015-2016 and perhaps 2003 suggest that the method may
be overestimating killed trees. The lower number of grid cells with cumulative MA exceeding
100% is an indication that the FHP_{R1-R4} method may not have been overestimating tree mortality.
Based on our analysis, we recommend that the FHP\textsubscript{R1-R4} method may be most realistic, and our analyses below are based on this method unless stated otherwise.

Figure 8. Mortality area from different methods for the western US. Black line with asterisks: histogram transformation computed from all DASM years. Dark thick gray line with plusses: FHP\textsubscript{R1-R4} method. Light gray lines: Meddens lower method (squares) and middle method (plusses).

3.2 Regional and Westwide mortality area and number of killed trees

Total Westwide MA for 1997-2018 ranged among methods from 1.5-7.4 Mha (Table 2) or 1.7-8% of the total forest area in the western United States and cumulative NKT was 1.2x10^9-6.3x10^9 trees. Using the FHP\textsubscript{R1-R4} method, cumulative MA was 4.3 Mha (4.7% of forest area)
and $3.8 \times 10^9$ killed trees. Twenty-eight percent of the total MA (summed for 1997-2018) occurred in 2013-2018.

Annual Westwide mortality area was initially nearly 0 (i.e., before 2001). Peaks in MA occurred in 2003 from outbreaks of pinyon ips ($Ips$ confuses (LeConte)), Ips engraver beetles ($Ips$ spp.), and unknown bark beetles (see next section for details about bark beetle species); in 2008-2011, associated with the extensive outbreaks of mountain pine beetles ($Dendroctonus$ ponderosae Hopkins); and in 2016 in California, associated with widespread tree mortality from fir engraver ($Scolytus$ ventralis LeConte) and western pine beetle ($Dendroctonus$ brevicomis LeConte).

Westwide mortality remained elevated since 2010 as a result of the expansion and contraction of populations of different beetle species occurring at different times.

Cumulative (over time and bark beetle species) tree mortality was widespread throughout the western United States, though most locations with outbreak experienced low severity (less than 15%) (Figure 9). Notable locations of high mortality occurred in Colorado, northern New Mexico, California, the northern Rocky Mountains, and the northern Cascade Mountains. These areas had mortality severity exceeding 50% (50 ha per 1-km grid cell) in many locations. Severe outbreaks since 2010 occurred in southern Colorado and California.
Table 2. Mortality area and number of killed trees summed across space, time, and beetle species, by method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Mortality area</th>
<th>Number of killed trees</th>
</tr>
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<tbody>
<tr>
<td>histogram matching</td>
<td>5.9 Mha</td>
<td>5.5x10^9</td>
</tr>
<tr>
<td>FHP_{R1-R4}</td>
<td>4.3 Mha</td>
<td>3.8x10^9</td>
</tr>
<tr>
<td>Meddens lower</td>
<td>1.5 Mha</td>
<td>1.2x10^9</td>
</tr>
<tr>
<td>Meddens middle</td>
<td>7.4 Mha</td>
<td>6.3x10^9</td>
</tr>
</tbody>
</table>

Figure 9. Mortality area summed for 1997-2018 and for all bark beetle species for the western United States from the FHP_{R1-R4} method. Units are in ha or equivalently % (because grid cells are 1 km by 1 km spatial resolution). Gray areas indicate forests not affected by bark beetles.
We assessed tree mortality caused by various outbreaks of different bark beetle species, with an emphasis on those that occurred since 2010 (as an update to Meddens et al. (2012)). Mountain pine beetle has been the most damaging bark beetle species in the western US, accounting for 1.9 Mha or 44% of the total mortality area and $2 \times 10^9$ killed trees (Table 3). Westwide mortality caused by this beetle declined since peaking in 2009 (Figure 10). However, a number of locations in the northern Rocky Mountains experienced severe mortality from this beetle since 2010. The widespread locations of outbreaks of mountain pine beetle (Figure 11) together with the different timing in peak mortality in these regions suggest different outbreaking populations.

During 2015-2018 in California, substantial tree mortality occurred from fir engraver, which killed white firs (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), and from western pine beetle, which killed ponderosa pines (*Pinus ponderosa* Lawson & C. Lawson) (Fettig et al., 2019). Also at this time and location, Jeffrey pine beetles (*Dendroctonus jeffreyi* Hopkins) killed Jeffrey pines (*Pinus jeffreyi* Grev. & Balf.) throughout much of their range. Total mortality area in this period and location was almost 800,000 ha. Additional significant fir mortality from fir engraver occurred in the northern Rocky Mountains and northern Cascade Mountains in 2002-2005.

A major outbreak of spruce beetles (*Dendroctonus rufipennis* (Kirby)) occurred in Colorado during 2009-2018 (MA was >400,000 ha), killing Engelmann spruce (*Picea engelmannii* Parry).
The region experienced significant mortality over ten years, with the peak occurring in 2014 and a slight decline afterward.

Pinyon ips beetles killed two-needle pinyon pines (*Pinus edulis* Engelm.) and singleleaf pinyon pines (*Pinus monophyla* Torr. & Frem.) in 2003 and 2004 throughout the US Southwest (Arizona and New Mexico). A small amount of additional mortality by this beetle occurred in 2013-2015. *Ips* species of engraver beetles were active at similar times and locations, killing mainly ponderosa pines.

Unlike most other beetle species discussed here, two bark beetle species were killing trees throughout the study period. Western balsam bark beetle (*Dryocoetes confuses* Swaine) killed mainly subalpine firs (*Abies lasiocarpa* (Gord. & Glend.) Lindl. ex Hildebr.) in the northern and central Rocky Mountains and northern Cascade Mountains throughout the study period (1997-2018). Mortality area was in decline since reaching a maximum in 2007 and was almost zero in 2018. Outbreaks of Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopk.) killing Douglas-firs (*Pseudotsuga menziesii* (Mirbel) Franco) were recorded in the Rocky Mountains, Cascade Mountains, and southwestern US. Douglas-fir beetle-caused mortality was typically low severity (<10% in most grid cells).
Table 3. Mortality area summed for 1997-2018 and across the western United States for the ten most damaging bark beetle species (results from the FHP\textsubscript{R1-R4} method). “Unknown bark beetles” primarily consisted of unspecified bark beetle species in pine and/or true fir host types.

<table>
<thead>
<tr>
<th>bark beetle</th>
<th>mortality area (Mha)</th>
<th>% of total mortality area</th>
<th>number of killed trees (x10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mountain pine beetle</td>
<td>1.894</td>
<td>44</td>
<td>2,003,000</td>
</tr>
<tr>
<td>fir engraver</td>
<td>0.562</td>
<td>13</td>
<td>348,194</td>
</tr>
<tr>
<td>piñon ips</td>
<td>0.546</td>
<td>14</td>
<td>404,196</td>
</tr>
<tr>
<td>spruce beetle</td>
<td>0.417</td>
<td>10</td>
<td>420,339</td>
</tr>
<tr>
<td>western pine beetle</td>
<td>0.233</td>
<td>5</td>
<td>139,534</td>
</tr>
<tr>
<td>western balsam bark beetle</td>
<td>0.227</td>
<td>5</td>
<td>268,289</td>
</tr>
<tr>
<td>Douglas-fir beetle</td>
<td>0.14</td>
<td>3</td>
<td>58,481</td>
</tr>
<tr>
<td>unknown bark beetles</td>
<td>0.133</td>
<td>3</td>
<td>82,796</td>
</tr>
<tr>
<td>Ips engraver beetles</td>
<td>0.094</td>
<td>2</td>
<td>55,839</td>
</tr>
<tr>
<td>Jeffrey pine beetle</td>
<td>0.049</td>
<td>1</td>
<td>16,961</td>
</tr>
<tr>
<td>all bark beetles</td>
<td>4.319</td>
<td>100</td>
<td>3,814,491</td>
</tr>
</tbody>
</table>

Significant tree mortality from other unknown (not recorded by aerial surveyors) beetle species occurred in California in 2002-2005 and in Arizona and New Mexico in 2015-2018. Based on inspection of surveyor notes, much of this mortality was pine or fir species or combinations of these genera, and may have been influenced by other biotic agents such as root disease.
Figure 10. Mortality area for the western United States for the ten most damaging bark beetle species (from the FHP\textsubscript{R1-R4} method) (separated into two panels for clarity). Note different y-axis ranges in panels. “Unknown bark beetles” primarily consisted of unspecified bark beetle species in pine and/or true fir host types.
Figure 11. Mortality area summed for 1997-2018 for the nine most damaging bark beetle species for the western United States from the FHP$_{R1-R4}$ method. Units are in ha or equivalently % (because grid cells are 1 km by 1 km spatial resolution). Gray areas indicate forests not affected by bark beetle species. “Unknown bark beetles” primarily consisted of unspecified bark beetle species in pine and/or true fir host types.
4. Discussion

4.1 Comparison among methods

Our study found substantial variability in the estimates of mortality area and number of trees killed among the harmonization methods assessed. The histogram matching method used existing observations from the DASM and DMSM approaches to convert TPA to MA. The histogram transformation, and therefore the conversion to MA, was dependent on the set of DASM observations. Variability occurred among subsets because of differences in polygon area at different TPA levels (i.e., in the shape of the histogram). We suggest using the estimates from the full set of DASM records (all years) may be best to capture as many outbreak conditions and severities as possible. However, results are also dependent on the outbreak conditions and severities captured by the DMSM records. Because aerial surveyors were likely more accurate in representing the actual damage when recording %AA than when recording TPA, converting TPA to %AA using the HM method produced values more similar to the Meddens middle method (which applied an adjustment factor explicitly to account for underestimation) than to the Meddens lower method (which computed MA directly from recorded TPA). Thus, the HM method implicitly accounted for TPA underestimation by surveyors.

The FHP\textsubscript{R1-R4} method did not explicitly correct for underestimation of TPA recorded by surveyors as reported by Meddens et al. (2012). However, the reported relationship between TPA and %M (Egan et al., 2019) and our assumption that %M = %AA yielded an average crown diameter of killed trees that was much higher than reported by field measurements for species
that were killed in significant numbers during recent outbreaks (see Appendix B for details).

Thus, the FHP method produced greater values of MA and NKT than reported by aerial surveyors (represented by the Meddens lower method), thereby implicitly accounting for underestimation.

Across years and regions, the Meddens lower method produced much lower NKT and MA than other methods. Estimates from the HM method and the Meddens middle method were similar in many years, although MA and NKT from the Meddens middle method was substantially higher than results from the other methods (including the HM method) in some years and regions, particularly during years of peak mortality. The FHP method was more similar to, although somewhat smaller than, the Meddens middle and HM methods than to the Meddens lower method.

The FHP method included corrections for apparent underestimation by aerial surveyors, required relatively few corrections for overestimating mortality within grid cells, and was conservative compared with the histogram matching and Meddens middle methods. A key aspect of the FHP method may be the use of fewer %AA classes than other methods. Fewer classes may be more representative of the methodologies applied by the aerial surveyors. We recommend the use of the FHP method as the most realistic method, but also recommend that users discuss the variability among methods reported here.
4.2 Spatial and temporal patterns of tree mortality

Annual tree mortality continued to be high during 2013-2018. Outbreaks of multiple bark beetle species contributed to the high rates of mortality, but at different times and in different locations. Even for one bark beetle species (such as mountain pine beetle), different timing and locations of tree mortality indicate that multiple outbreaks (different populations) occurred in the western US. Thus, the time series of annual mortality (Figure 8) and a map of cumulative mortality (Figure 9) obscure a shifting mosaic of different beetle species attacking different host tree species at different times, all adding up to substantial tree mortality. Our estimates of bark beetle-caused tree mortality from aerial surveys are supported by estimates from other sources of large-scale mortality. Studies that used satellite remote sensing or extensive plot networks confirmed the large outbreak areas of mountain pine beetle (Meigs et al., 2011; Meddens and Hicke, 2014; Thompson, 2017; Fettig et al., 2019), spruce beetle (Hart et al., 2017), pinyon ips beetle (Breshears et al., 2005), *Ips* species (Negron et al., 2009), Douglas-fir beetle (Negron et al., 1999), and western pine beetle and fir engraver (Fettig et al., 2019; Stephenson et al., 2019).

Since 2010, notable outbreaks of mountain pine beetle, spruce beetle, western pine beetle, and fir engraver contributed to substantial mortality. For mountain pine beetle, outbreaks continued after 2010 and declined in severity in most locations, whereas in a few other locations new outbreaks emerged. Populations of another species, spruce beetle, erupted after 2010 associated with drought in Colorado (Hart et al., 2013) and declined after 2014. The drought in California during 2015-2018 facilitated outbreaks of western pine beetle, mountain pine beetle, Jeffrey pine beetle, and fir engraver (Fettig et al., 2019).
Despite the subjective nature of the data, it is probable that outbreaks are reasonably well characterized by aerial surveys. At finer scales, aerial surveys identify the presence and location of bark beetle-caused tree mortality (Johnson and Ross, 2008; Coleman et al., 2018). At coarser scales, such as the 1-km spatial resolution used in this study, uncertainty in presence and location is reduced, and severity may be reasonably well captured, though with reduced accuracy (Meddens et al., 2012). As a result, aerial survey data are valuable for comparison with other estimates that report forest disturbances from insects over large extents, such as done by Masek et al. (2013) and Meigs et al. (2011). Multiple efforts using satellite remote sensing have produced forest disturbance maps, especially from 30-m Landsat imagery (Healey et al., 2018; Zhao et al., 2018) but also with coarser-resolution MODIS imagery (Hargrove et al., 2009). We suggest that mortality area data in particular (as opposed to affected area) can be a valuable reference data set for evaluating these satellite-based products. Timing, location, and amount of tree mortality should be comparable among products.

4.3 Assumptions, caveats, and need for future studies to reduce uncertainty

We made several significant assumptions in this study. The aerial survey observations may be subject to multiple biases associated with surveyor, locations, flying conditions, and amount of tree mortality that may change over space and time. We partly accounted for these changes by calculating histogram transformations for individual regions, and by assessing adjustment factors in the Meddens middle method for different forest types. However, we were unable to account for year-to-year variability. Surveyors were likely inconsistent in whether they recorded percent
area affected or percent treed area affected, with variability associated with surveyor and forest conditions. The FHP\textsubscript{R1-R4} method collected information among several bark beetle species to develop conversion factors, but we applied these factors to all forest types and bark beetle species.

Another assumption was that the DMSM observations of \%AA class were accurate. This assumption may be reasonable in many years and locations for most methods. However, noticeable increases for the Meddens lower method occurred for several years between the DASM and DMSM years, suggesting either that method underestimated the MA and NKT for the DASM records (as suggested by comparisons with remotely sensed imagery) and/or the \%AA classes were overestimated for DMSM records.

We also assumed that the mortality was evenly distributed in each polygon, which allowed us to simplify the gridding process by assigning one MA value to each polygon. This might be problematic for larger damage polygons that occupied multiple grid cells and were more likely to have uneven mortality patterns.

Future studies that include our bark beetle-caused tree mortality estimates from aerial surveyors should, at a minimum, note the variability among estimates that we report here, and if only one method is used, we recommend using the results from the FHP\textsubscript{R1-R4} method. We caution that the FHP\textsubscript{R1-R4} method warrants additional evaluation and may not be correct for some damage agents (beetle species).
There is a need for credible estimates of MA and NKT for documenting actual effects, comparison with other forest disturbances, estimating impacts to forest ecosystem processes, and increasing scientific knowledge. However, it is not clear from our analysis which method is most accurate in an absolute sense, or what the accuracies are. In addition to methodological uncertainties linking DASM and DMSM data that we describe here, the subjective and incomplete nature of surveys suggest that variability in accuracy occurs among years, regions, and surveyors. Medium- (e.g., Landsat and Sentinel) and high-resolution (e.g., WorldView and QuickBird) satellite imagery have the potential to objectively and accurately quantify tree mortality across larger spatial scales. In addition, remotely sensed imagery can be used to evaluate aerial survey information, as demonstrated by Coleman et al. (2018) and Bright et al. (2020). Future investigations in which mortality from both DASM and DMSM approaches (i.e., across time) are evaluated by medium-resolution (e.g., Landsat imagery; Meddens and Hicke, 2014) and/or high-resolution imagery (e.g., QuickBird imagery; Hicke and Logan, 2009) have great potential and are needed to reduce the uncertainties of the aerial survey data. We also note the potential for large-scale plot networks such as the USDA Forest Service Forest Inventory and Analysis data that may facilitate comparisons and evaluation.

5. Conclusions

The USFS aerial survey data set continues to be a valuable database for evaluating biotic disturbances in the United States. The widespread extent and long time record, coupled with the rich set of forest insect and host tree attributes, are very useful for assessing forest disturbances such as bark beetle outbreaks. However, new challenges have arisen with the migration of aerial
surveyors to the new DMSM approach. Linking this approach with the old DASM approach is valuable for assessing trends in time and space. Yet as we have shown, different estimation methods produce different results. The relatively similar results among estimation methods for earlier DASM records suggest that surveyors were underestimating actual mortality, as was corrected for by the Meddens middle method. However, the amount of underestimation appears to have decreased over time, as indicated by mortality area frequently exceeding the area of the grid cell and by the substantially larger results of the Meddens middle method in Region 5 in 2015 and 2016, the last years before that region switched to the DMSM approach. Furthermore, although the similar agreement among several methods provides increased confidence of outbreak damage, our analysis used several lines of evidence to suggest that the FHP_{R1-R4} method appeared most accurate for harmonizing the two aerial survey approaches. Our analysis did not directly investigate which method is most accurate or identify error bounds associated with estimates from each method because there is not a comprehensive reference data set suitable for evaluating beetle-caused mortality area across the western US. Thus, additional studies to refine and augment the aerial survey data are needed to quantify accuracies and improve confidence in our estimates.

Extensive tree mortality occurred recently (since 2010), continuing these forest disturbances that have occurred since the early 2000s. Outbreaks of different bark beetle species caused tree mortality in different host tree species in different locations and at varied times. Warming and drought have played major roles in facilitating outbreaks (e.g., Weed et al., 2013), and projections of continued climate change from anthropogenic activities (USGCRP, 2017) suggest that substantial tree mortality will continue into the future. Therefore, continuing to monitor
forests for biotic disturbance agents to document trends and patterns in space and time is needed to better understand and quantify impacts and assess management options.

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Table S1. Percent area affected (%AA) and trees per acre killed (TPA) information by %AA class:

1) %AA range and midpoint for DMSM records; 2) TPA boundaries for and mean TPA (weighted by damage polygon area) in parentheses from histogram matching transformation that used DASM records from all years, by region; and 3) %AA classes, values, and TPA from FHP\textsubscript{R1-R4} method.

<table>
<thead>
<tr>
<th>%AA class</th>
<th>1: very light</th>
<th>2: light</th>
<th>3: moderate</th>
<th>4: heavy</th>
<th>5 very heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>%AA range</td>
<td>1-3%</td>
<td>4-10%</td>
<td>11-29%</td>
<td>30-50%</td>
<td>50-100%</td>
</tr>
<tr>
<td>%AA midpoint</td>
<td>2%</td>
<td>7%</td>
<td>20%</td>
<td>40%</td>
<td>75%</td>
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</tbody>
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<table>
<thead>
<tr>
<th>HM method</th>
<th>TPA range (weighted mean TPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>region</td>
<td>0-t1 (mean)</td>
</tr>
<tr>
<td>1</td>
<td>0-1 (0.45)</td>
</tr>
<tr>
<td>2</td>
<td>0-1 (0.41)</td>
</tr>
<tr>
<td>3</td>
<td>0-1 (0.43)</td>
</tr>
<tr>
<td>4</td>
<td>0-3 (1.32)</td>
</tr>
<tr>
<td>5</td>
<td>0-1 (0.59)</td>
</tr>
<tr>
<td>6</td>
<td>0-1 (0.41)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FHP\textsubscript{R1-R4} method</th>
<th>1: low</th>
<th>2: moderate</th>
<th>3: high</th>
</tr>
</thead>
<tbody>
<tr>
<td>%AA</td>
<td>5%</td>
<td>20%</td>
<td>65%</td>
</tr>
<tr>
<td>TPA</td>
<td>&lt;10</td>
<td>10-30</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>
Table S2. Summary of different methods used to compute mortality area for DASM and DMSM records. Underlined text indicates the four methods to convert DASM records to %AA.

<table>
<thead>
<tr>
<th>Method</th>
<th>Survey type</th>
<th>Brief description and alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>histogram matching DASM</td>
<td>convert TPA to %AA class using histogram matching transformation, multiply by polygon area; 23 different histogram transformations from subsets of DASM records using different years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DMSM</td>
<td>multiply %AA class by polygon area</td>
</tr>
<tr>
<td>Meddens</td>
<td>DASM</td>
<td>multiply TPA by species-specific crown area for lower method; apply adjustment factors for middle method</td>
</tr>
<tr>
<td></td>
<td>DMSM</td>
<td>multiply %AA class by polygon area</td>
</tr>
<tr>
<td>FHP R1-R4</td>
<td>DASM</td>
<td>convert TPA to %AA class for three (not five) classes, multiply by polygon area</td>
</tr>
<tr>
<td></td>
<td>DMSM</td>
<td>aggregate the five %AA classes to three classes, multiply by polygon area</td>
</tr>
</tbody>
</table>
Table S3. Tree species crown area (m²) averaged using 1999 values (to avoid double counting trees); data from USDA Forest Service Forest Inventory and Analysis National Program, Forest Health Monitoring (https://www.fia.fs.fed.us/tools-data/other_data/index.php, accessed 22 October 2019).

<table>
<thead>
<tr>
<th>Species name</th>
<th>Crown area (m²)</th>
<th>Species name</th>
<th>Crown area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no data</td>
<td>15.86</td>
<td>lodgepole pine</td>
<td>8.68</td>
</tr>
<tr>
<td>softwood</td>
<td>15.50</td>
<td>Coulter pine</td>
<td>12.49</td>
</tr>
<tr>
<td>fir spp.</td>
<td>11.59</td>
<td>Apache pine</td>
<td>12.49</td>
</tr>
<tr>
<td>Pacific silver fir</td>
<td>21.84</td>
<td>limber pine</td>
<td>13.46</td>
</tr>
<tr>
<td>balsam fir</td>
<td>11.59</td>
<td>southwestern white pine</td>
<td>18.61</td>
</tr>
<tr>
<td>Santa Lucia or bristlecone fir</td>
<td>11.59</td>
<td>Jeffrey pine</td>
<td>29.10</td>
</tr>
<tr>
<td>white fir</td>
<td>15.97</td>
<td>sugar pine</td>
<td>33.50</td>
</tr>
<tr>
<td>grand fir</td>
<td>22.26</td>
<td>Chihuahuan pine</td>
<td>12.49</td>
</tr>
<tr>
<td>corkbark fir</td>
<td>10.08</td>
<td>western white pine</td>
<td>18.61</td>
</tr>
<tr>
<td>subalpine fir</td>
<td>8.42</td>
<td>bishop pine</td>
<td>12.49</td>
</tr>
<tr>
<td>California red fir</td>
<td>22.72</td>
<td>ponderosa pine</td>
<td>16.78</td>
</tr>
<tr>
<td>Shasta red fir</td>
<td>19.39</td>
<td>Monterey pine</td>
<td>12.49</td>
</tr>
<tr>
<td>Arizona cypress</td>
<td>15.50</td>
<td>gray or California foothill pine</td>
<td>53.65</td>
</tr>
<tr>
<td>redcedar/juniper spp.</td>
<td>20.16</td>
<td>singleleaf pinyon</td>
<td>11.74</td>
</tr>
<tr>
<td>alligator juniper</td>
<td>20.16</td>
<td>border pinyon</td>
<td>11.74</td>
</tr>
<tr>
<td>western juniper</td>
<td>27.05</td>
<td>Austrian pine</td>
<td>12.49</td>
</tr>
<tr>
<td>Utah juniper</td>
<td>9.14</td>
<td>Washoe pine</td>
<td>12.49</td>
</tr>
<tr>
<td>oneseed juniper</td>
<td>14.36</td>
<td>four-leaf or Parry pinyon pine</td>
<td>13.73</td>
</tr>
<tr>
<td>incense-cedar</td>
<td>13.73</td>
<td>Great Basin bristlecone pine</td>
<td>22.88</td>
</tr>
<tr>
<td>spruce spp.</td>
<td>9.88</td>
<td>bigcone Douglas-fir</td>
<td>24.28</td>
</tr>
<tr>
<td>Engelmann spruce</td>
<td>9.88</td>
<td>Douglas-fir</td>
<td>24.28</td>
</tr>
<tr>
<td>white spruce</td>
<td>9.88</td>
<td>mountain hemlock</td>
<td>10.72</td>
</tr>
<tr>
<td>blue spruce</td>
<td>15.29</td>
<td>whitebark &amp; limber pine</td>
<td>12.48</td>
</tr>
<tr>
<td>red spruce</td>
<td>9.88</td>
<td>lodgepole pine, ponderosa pine</td>
<td>12.73</td>
</tr>
<tr>
<td>pine spp.</td>
<td>12.49</td>
<td>whitebark, limber &amp; Rocky Mtn.</td>
<td>15.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bristlecone pine</td>
<td></td>
</tr>
<tr>
<td>whitebark pine</td>
<td>11.49</td>
<td>Apache, ponderosa, Arizona, and</td>
<td>12.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chihuahuan pine</td>
<td></td>
</tr>
<tr>
<td>Rocky Mountain bristlecone pine</td>
<td>22.88</td>
<td>Arizona cypress; Utah, one-seed,</td>
<td>12.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rocky Mountain, and alligator juniper</td>
<td></td>
</tr>
<tr>
<td>knobcone pine</td>
<td>9.43</td>
<td>single-leaf and four-leaf or Parry</td>
<td>12.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pinyon pine</td>
<td></td>
</tr>
<tr>
<td>foxtail pine</td>
<td>12.49</td>
<td>Pacific silver, grand, California red,</td>
<td>19.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>noble, and white fir</td>
<td></td>
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<tr>
<td>Species</td>
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</tr>
<tr>
<td>jack pine</td>
<td>12.49</td>
<td>Pacific silver, noble, and grand fir</td>
<td>22.66</td>
</tr>
<tr>
<td>common or two-needle pinyon</td>
<td>13.73</td>
<td></td>
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Figure S1. Illustration of how differences in histogram subsets based on years influences calculation of t1-t4. (a) Histogram for Region 3 for two years with similar number of records but different distributions: 2003 (thin black line) and 2005 (thick gray line). (b) Corresponding cumulative histograms that were used to compute t1-t4. Total area of polygons was 1.0 Mha in 2003 and 0.089 Mha in 2005.
Figure S2. Histograms of grid cells with cumulative mortality area greater than 100% (or 100 ha) and therefore subject to capping, by method: (a) histogram matching; (b) FHP$_{R1-R4}$; (c) Meddens lower; (d) Meddens middle. Numbers in lower right are number of grid cells with cumulative mortality area greater than 100%. Inset maps show locations in black where cumulative mortality area exceeded 100%.
Appendix B.

To understand differences in the Meddens and FHP_{R1-R4} methods, we calculated the mean crown area of killed trees reported by the FHP_{R1-R4} method using information from Egan et al. (2019).

The equation for %AA is:

%AA = \frac{MA}{A} \times 100

Defining mortality area in terms of TPA and crown area yields

%AA = \frac{TPA \times A \times CA}{A} \times 100 = TPA \times CA \times 100

If we assume that %AA is equivalent to %M (percent mortality area is equivalent to the percent number of killed trees) and use Egan et al.’s (2019) finding of TPA \approx %M, we calculate the crown area of the average tree killed using the FHP_{R1-R4} method:

CA = \frac{1}{100} \text{ acre} = 40.6 \text{ m}^2

This value is greater than crown areas of all the species we considered here (Supplemental Table 1) except one (gray pine, 54 m²). Thus, the FHP_{R1-R4} method produces greater mortality area from a given TPA than the Meddens lower method (i.e., with no adjustment added) and lower mortality area than the Meddens middle method (see also Figure 6).