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Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States

ARIAN J. H. MEDDENS,^{1,4} JEFFREY A. HICKE,² AND CHARLES A. FERGUSON³

¹University of Idaho, Environmental Science Program, 810 West 7th Street, McClure Hall 203, Moscow, Idaho 83844-3021 USA

²University of Idaho, Department of Geography, 810 West 7th Street, McClure Hall 203, Moscow, Idaho 83844-3021 USA

³United States Department of Agriculture, Natural Resources Conservation Service, 4407 Bland Road, Suite 117, Raleigh, North Carolina 27609 USA

Abstract. Outbreaks of aggressive bark beetle species cause widespread tree mortality, affecting timber production, wildlife habitat, wildfire, forest composition and structure, biogeochemical cycling, and biogeophysical processes. As a result, agencies responsible for forest management in the United States and British Columbia conduct aerial surveys to map these forest disturbances. Here we combined aerial surveys from British Columbia (2001–2010) and the western conterminous United States (1997–2010), produced 1-km² grids of the area of crown mortality from bark beetle attack, and analyzed spatial and temporal patterns. We converted aerial-survey polygon data for each combination of host type and bark beetle species available in the western United States, and for each bark beetle species available in British Columbia. We converted affected area (which includes live and killed trees) to mortality area (crown area of killed trees) using species-specific crown diameters and the number (U.S.) or percentage (British Columbia) of killed trees. In the United States we also produced an upper estimate of mortality area by forcing the mortality area to match that from high-resolution imagery in Idaho, Colorado, and New Mexico. Resulting adjustment factors of 3.7–20.9 illustrate the underestimate of mortality by the U.S. aerial surveys. The upper estimate, which we suggest is more realistic, better matched the spatial patterns and severity of the British Columbia mortality area. Cumulative mortality area from all bark beetles was 5.46 Mha in British Columbia in 2001–2010 and 0.47–5.37 Mha (lower and upper estimate) in the western conterminous United States during 1997–2010. We note that we report year of detection here; studies that consider year of tree mortality should shift the time series back one year. We conclude by discussing uses and limitations of these data in ecological studies, including uncertainties associated with assumptions in the methods, lack of complete coverage by surveys, and the subjective nature of the survey databases.

Key words: aerial survey; bark beetles; British Columbia; forest disturbance; mortality area; tree mortality; western United States.

INTRODUCTION

Insect outbreaks are major disturbances of forests across North America. Outbreaks of bark beetles cause widespread tree mortality, affecting timber production (Schwab et al. 2009), biogeochemical (e.g., nitrogen, carbon, water; Kurz et al. 2008) and biogeophysical processes (e.g., leaf area, albedo; O'Halloran et al. 2012), wildlife habitat (Klenner and Arsenault 2009), fuels and wildfire characteristics (Jenkins et al. 2008, Simard et al. 2011), and forest composition (Veblen et al. 1991) and structure (Pfeifer et al. 2011). Outbreaks of mountain pine beetle (*Dendroctonus ponderosae*), which attacks several *Pinus* species (see Plate 1), have affected almost 14 million ha in British Columbia from the mid-1990s to 2008 (Safranyik et al. 2010) and affected 3.6 million ha

in the United States in 2009 (USDA Forest Service 2010). Other bark beetles that cause widespread mortality across western North America and their major host tree species include spruce beetle (*Dendroctonus rufipennis*) in Engelmann spruce (*Picea engelmannii*); Douglas-fir beetle (*Dendroctonus pseudotsugae*) in Douglas-fir (*Pseudotsuga menziesii*); western balsam bark beetle (*Dryocoetes confuses*) in subalpine fir (*Abies lasiocarpa*); and piñon ips (*Ips confuses*) in piñon pine (*Pinus edulis*). Thus, tracking spatial and temporal patterns of bark beetle epidemics is critical for assessing their impacts and determining management responses.

There are more than 6000 named bark beetle (Coleoptera: Curculionidae, Scolytinae) species around the world and about 8% of those occur in North America (Wood 1982). Most bark beetles reproduce in the bark (phloem tissue) of their host tree and have very specific host tree species. The most destructive bark beetle species (hereafter referred to as “aggressive bark beetles”) in North American coniferous forests are able to attack apparently healthy trees and need to kill the

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⁴ E-mail: ameddens@uidaho.edu

host to produce a successful brood (Christiansen et al. 1987). Bark beetles employ a “mass attack” strategy in which many beetles attack a single tree at the same time to overwhelm tree defenses. After successful attack, the bark beetle lays eggs in the phloem of the tree and the new generation goes through several life stages before emerging to search for a new host tree. Bark beetle life cycles range from two weeks to three years depending on beetle species and temperature (Wood 1982).

Trees go through several observable stages after successful attack (Hopkins 1909, Amman et al. 1990). Needles on killed trees turn yellowish to reddish, depending on tree species, the summer following attack (sometimes referred to as “red attack”). Three to five years after attack, trees lose all their needles, and typically within one to several decades, snags fall. Variability in the post-attack coloration and timing of needledrop and snagfall occurs across beetle and host species and environmental conditions.

Agencies responsible for forest management in the United States and British Columbia conduct aerial surveys, also known as aerial “sketch mapping,” to map forest disturbances caused by insect outbreaks and other disturbance agents. From airplanes, trained observers record new tree damage (e.g., in the first year the damage becomes visible) together with attributes such as damage agent, tree species, and damage severity as points or polygons on maps. Aerial surveyors use visual signatures of forest insects and diseases to identify damage and distinguish among different damage types (Ciesla 2000), relying on the foliage color change in the year following attack. Aerial surveys are an economical way to collect indicators of tree health over large areas (Johnson and Wittwer 2008) that can augment information on forest health from periodically revisited field plots (Bennett and Tkacz 2008) and provide managers and policy makers with rapid assessments of forest disturbances (Wulder et al. 2009).

In addition to being used by resource managers in making day-to-day management decisions, aerial detection survey (ADS) data in the United States and aerial overview survey (AOS) data in British Columbia have been used by decision-makers as indicators of forest disturbance and in ecological studies for locating tree mortality. The USDA Forest Health Monitoring Program uses ADS data to communicate annual changes in forest disturbance patterns (e.g., Bennett and Tkacz 2008, USDA Forest Service 2010). AOS data in British Columbia have been used to report the impacts of mountain pine beetle and mitigation efforts (Coggins et al. 2008, Westfall and Ebata 2010). ADS data have been used to analyze spatial patterns of infestations of the Douglas-fir beetle in northern Idaho (Dodds et al. 2006) and for evaluating remote-sensing mapping of insect outbreaks (de Beurs and Townsend 2008). Other studies make use of aerial survey data to drive vegetation models to assess impacts in terms of carbon. For instance, Kurz and Apps (1999), Kurz et al. (2008),

and Stinson et al. (2011) used AOS to drive the Carbon Budget Model of the Canadian Forest Sector to assess impacts of beetle outbreaks on carbon cycling in Canada. Multiple studies have used ADS information together with fire data to assess interactions between these disturbances (Lynch et al. 2006, Kulakowski and Veblen 2007, Bond et al. 2009, Preisler et al. 2010).

Several aspects of aerial survey data make analyzing or working with these data challenging. For some applications, aerial survey data have to be converted from polygon format into gridded data to match other data sources. In addition, a significant difference exists between the affected area (reported by the aerial survey and which includes live trees as well as killed trees) and mortality area (which only includes killed trees). Mortality area is more useful for assessing impacts but is generally not reported or used (Wulder et al. 2009). Furthermore, the amount of area surveyed differs from year to year, and although the surveys target areas where insect disturbance is most likely to have occurred, not all forests are surveyed. Aerial surveys are collected in different ways in the United States and British Columbia, leading to different metrics of tree mortality reported in these two areas. Finally, aerial survey databases consist of observations from different observers with a range of skills, experience, and viewing conditions, leading to uncertainty in the actual level of insect-caused mortality severity.

Our objective was to develop a gridded mortality-area product derived from aerial survey data of bark beetle-caused tree mortality for British Columbia and the western conterminous United States. This data set was created by converting percentage killed trees in British Columbia and the number of killed trees in the United States to mortality area (as opposed to affected area). We discuss multiple lines of evidence that show underestimation of the number of killed trees in the U.S. ADS data set, which led to our production of an upper estimate of bark beetle-caused tree mortality area for the United States. Finally, we describe the spatial and temporal patterns of bark beetle-caused tree mortality area in this region during 1997–2010.

METHODS

Bark beetle-caused tree mortality occurs throughout coniferous forest types of western North America. In this study we focused on bark beetle outbreaks in British Columbia and the western conterminous United States because of widespread mortality and the availability of spatial data. We created 1-km² grids for each region, choosing this cell size because it represents a trade-off between finer resolutions that increase uncertainty about the accuracy of polygon locations and damage attributes (e.g., Johnson and Ross 2008) and coarser resolutions that limit the applicability of the data set in ecological studies. Computations and spatial operations were performed with ArcGIS (version 9.3; ESRI 2008) and

TABLE 1. British Columbia (Canada) bark beetle mortality severity classes and factors used to convert to percentage killed trees.

Class	Mortality severity	Percentage of killed trees	
		Overall	Used in this study†
1	trace‡	<1	0.5
2	light	1–10	5
3	moderate	11–30	10
4	severe	31–50	30
5	very severe‡	>50	50

Source: The 2009 Summary of forest health conditions in British Columbia (available online at www.for.gov.bc.ca/hfp/health).

† Taken from Kurz et al. (2008) with the exception of the trace class (we used 0.5% instead of 0%).

‡ “Trace” and “Very severe” classes were added after 2003.

IDL (interactive data language, version 7.1.1; ITT Visual Information Solutions 2009) software.

We note an important characteristic of our database, which follows the reporting of the aerial surveys. We report mortality area in the same year as was reported by the surveys. However, survey years lag attack years by one year because of the time between attack and foliage color change, as described above. Therefore, studies interested in using our database to document attack (or mortality) should shift mortality area values back by one year.

Data conversion: British Columbia

British Columbia aerial overview survey (AOS) data were obtained from the British Columbia Ministry of Forests (available online).⁵ Only bark beetle species that contributed more than 0.1% of the entire mortality area during 2001 to 2010 were considered (see *Results: Bark beetle-caused mortality area*, and Table 2). Attributes include a severity code that indicates the level of damage for each polygon, ranging from “trace” in which <1% of the trees in the polygon exhibit red attack to “very severe” in which >50% of the trees exhibit red attack. Spot infestations (single or small clusters of trees [point data]) were omitted from the analysis. We converted the severity classes (each class is a range of percentages) to a representative percentage of killed trees following Kurz et al. (2008), with the exception of the “trace” class for which we used 0.5% instead of 0% (Table 1). Because cumulative mortality cannot exceed 100% cumulative mortality, Kurz et al. (2008) calibrated the ranges of percentages of killed trees so that the calculated cumulative mortality matched the mortality levels observed in the forest. By taking the lower estimates of the “severe” and “very severe” classes, our mortality calculations likely result in a conservative calculation of mortality area across British Columbia.

Several processing steps were taken to convert the polygonal AOS data to a gridded mortality area (Fig. 1).

We created a regular grid of polylines (“fishnet”) covering British Columbia to delineate 1-km grid cell boundaries. The fishnet was then intersected with the AOS polygons, and the area of the intersected polygon(s) was calculated for each grid cell. We defined mortality area within a forested area MA_{forest} (in ha) as the area of an AOS polygon (a) multiplied by the fraction of mortality area within that polygon, defined here as the ratio of the crown area of killed trees ($NKT \times \bar{c}_{\text{killed}}$) to the crown area of all trees ($NT \times \bar{c}_{\text{all}}$):

$$MA_{\text{forest}} = a \times \frac{NKT \times \bar{c}_{\text{killed}}}{NT \times \bar{c}_{\text{all}}} \quad (1)$$

where NKT is the number of killed trees, NT is the number of all trees, \bar{c}_{killed} is the average crown area of killed trees, and \bar{c}_{all} is the average crown area of all trees. AOS reports the percentage of killed trees within forested areas (%KT), defined as NKT/NT divided by 100. We summed MA_{forest} over all polygons within a grid cell i, j :

$$MA_{i,j}^{\text{forest}} = \sum_n^{k=1} a_{i,j,k} \times \frac{\%KT_{i,j,k}}{100} \times \frac{\bar{c}_{\text{killed}}}{\bar{c}_{\text{all}}} \quad (2)$$

where $a_{i,j,k}$ is the area of the k th polygon in the i,j th grid cell (in ha). We computed $(\bar{c}_{\text{killed}})/(\bar{c}_{\text{all}})$ ($=1.35$) from the average crown area of bark beetle-killed trees (\bar{c}_{killed}) and the average crown area of all trees (\bar{c}_{all}). We used \bar{c}_{killed} (9.28 m^2) and \bar{c}_{all} (6.87 m^2) from a field study of lodgepole pine (*Pinus contorta*)-dominated stands (Meddens et al. 2011) because we were unable to find these values for stands in British Columbia. Although this ratio was taken from a field study in Colorado (and not in British Columbia), we felt that using this ratio was reasonable because lodgepole pine occurrence in British Columbia was greater than 93% and the preference of bark beetles for larger diameter trees exists regardless of location (e.g., Amman and Baker 1972, Safranyik et al. 1975).

We then used the moderate resolution imaging spectroradiometer (MODIS) vegetation continuous fields (VCF) product, which represents tree cover within a grid cell, to convert from mortality area within the forested area of a 1-km² grid cell to mortality area (ha) within that grid cell ($MA_{i,j}$). The MODIS VCF (MOD44B, Collection 4) data product was downloaded for British Columbia for 2005 from the Global Land Cover Facility (GLCF) web site.⁶ The VCF data were aggregated from the original 500-m spatial resolution to 1 km, reprojected, and resampled (using nearest neighbor resampling) to match the aerial survey grid, and used to convert to $MA_{i,j}$:

$$MA_{i,j} = MA_{i,j}^{\text{forest}} \times \text{MODIS}_{i,j}^{\text{VCF}} \quad (3)$$

where $\text{MODIS}_{i,j}^{\text{VCF}}$ is the fraction of forest area derived

⁵ www.for.gov.bc.ca

⁶ glcf.uniacs.umd.edu

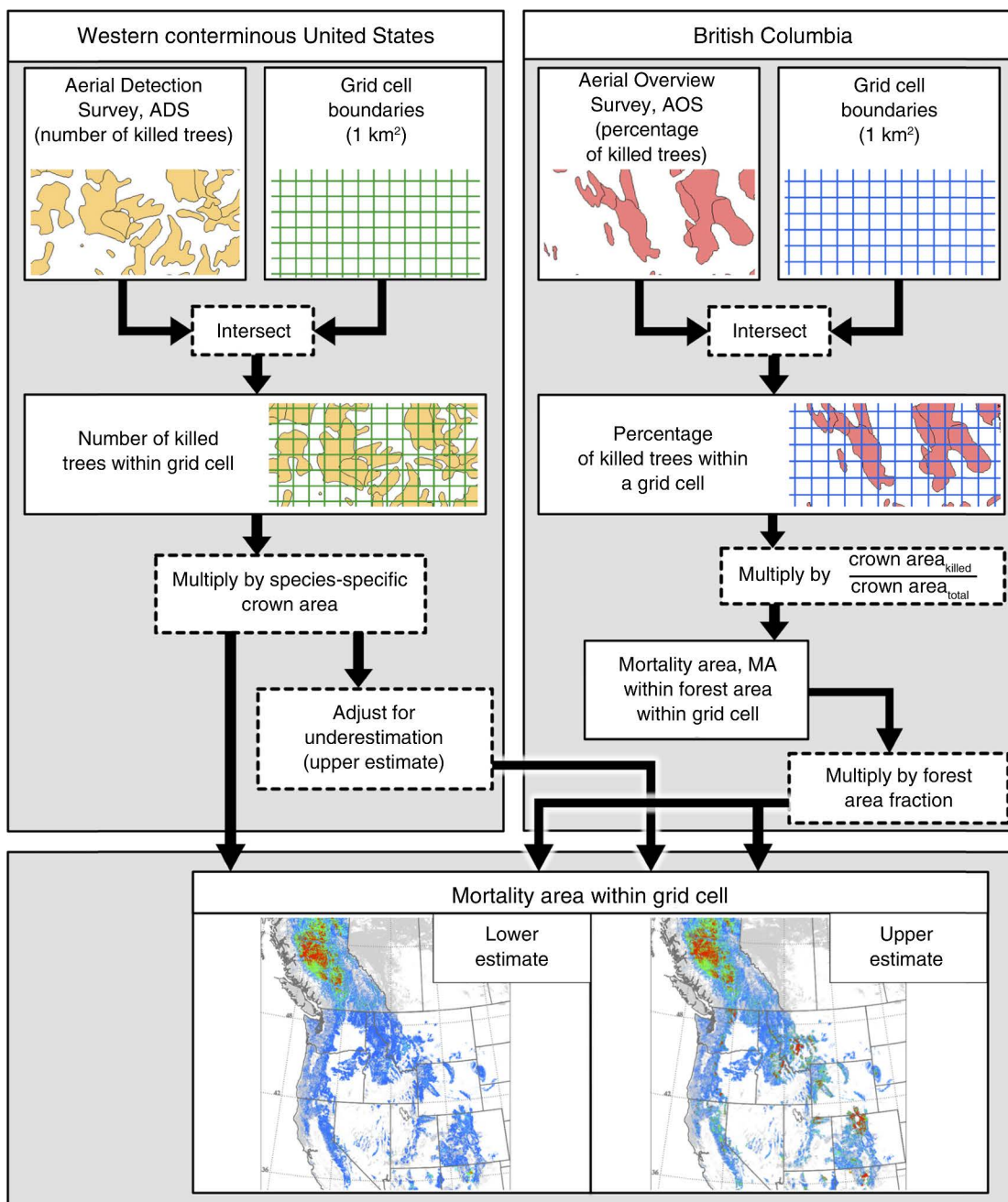


FIG. 1. Workflow showing operations (boxes with dashed outlines) and intermediate and final products (boxes with solid outlines) for the conversion of polygonal aerial survey data to a gridded tree-mortality area product. Percentage of killed trees was based on the total number of trees rather than on area.

from MODIS vegetation continuous fields data. The MODIS VCF may have been low because of tree mortality caused by bark beetles. We tested this possibility by calculating MODIS VCF values for attacked grid cells (>10 ha mortality) in and before 2005 and compared that to grid cells attacked after 2005. We found that differences of unattacked and attacked grid cells averages $<2\%$, implying minimal effects of beetle disturbance on MODIS VCF.

Roughly 0.4% of grid cells had combined (all bark beetles) and cumulative (summed for 2001–2010) mortality area that exceeded 100 ha (100% of a grid cell), possibly due to slight overestimation of the percentage number of killed trees in some locations. To correct this, we proportionally reduced the mortality area of each year and bark beetle species in these grid cells so that the combined and cumulative mortality area never exceeded 100 ha.

Data conversion: western conterminous United States

Aerial detection survey (ADS) data for the western conterminous United States were obtained from the USDA Forest Service Forest Health Technology Enterprise Team (FHTET) in Fort Collins, Colorado. FHTET consolidated and regularized the ADS data from the different Forest Service regions for 1997 to 2010. The data were in polygon format and included associated database tables detailing information about insect species (and other disturbance agents), host tree species, damage type (e.g., defoliation, mortality), forest type, and trees killed per acre. Mortality from up to three different bark beetle species could be associated with a single polygon. We included all bark beetle species that killed >100 000 trees for the period 1997–2010 (see *Results: Bark beetle-caused mortality area*, below; Table 3; Appendix F).

The mortality area for the western conterminous U.S. data set was calculated slightly differently than the British Columbia aerial overview data because the U.S. polygon information included number of killed trees per acre, whereas the British Columbia data included percentage severity classes (Fig. 1). A similar fishnet delineating cell boundaries was created to cover the western conterminous United States with a grid with a spatial resolution of 1 km². The fishnet was then intersected with the polygon database and the areas of intersected polygons were calculated for each grid cell. We used the number of killed trees per hectare (tph) for a given damage causal agent (e.g., mountain pine beetle) and host type (e.g., lodgepole pine) combination reported in the ADS for each polygon. We multiplied this number of killed trees per hectare by the intersected area of that polygon within a grid cell (thereby assuming a uniform spatial density of killed trees across the polygon), repeating this step for each intersected polygon within the grid cell. We summed tph for all intersected polygons of a given damage causal agent and host type combination within a given grid cell to generate the number of killed trees (KT_{*i,j*}) for each unique bark beetle species and host combination:

$$KT_{i,j} = \sum_n^{k=0} (a_{i,j,k} \times tph_k) \quad (4)$$

where $a_{i,j,k}$ is the area (ha) of the k th intersected ADS polygon within a given i,j grid cell and tph_k is the number of killed trees per hectare (transformed from trees per acre reported in the ADS database) of this intersected polygon.

Finally, we converted the number of killed trees to mortality area using average crown areas for each host tree species. We calculated the average tree crown diameter from the 1992–1999 USDA Forest Service Forest Health Monitoring program (FHM)⁷ data set in each of the available western states (i.e., California,

Colorado, Idaho, Nevada, Oregon, Utah, Washington, and Wyoming) (Appendix A). For calculating the average crown diameter, we followed tree selection criteria of Bechtold (2004). The criteria included selection of only the most recent tree measurement of a tree in a plot (some plots were remeasured) to avoid double counting of trees, and a cut-off value of diameter breast height >12.7 cm (5 inches). However, we also included open-grown trees in addition to stand-grown trees. Because this selection resulted in inclusion of larger (canopy) trees we did not use a conversion factor to account for the preference of bark beetles that attack larger diameter trees, in contrast to the British Columbia data-conversion process. The mortality area was calculated using KT_{*i,j*} (Eq. 4) and the mean crown area of each host species ($\bar{c}a_{\text{host}}$; Appendix A):

$$MA_{i,j} = KT_{i,j} \times \bar{c}a_{\text{host}} \quad (5)$$

where MA_{*i,j*} is the mortality area (in ha) within the i,j th grid cell for a given damage agent–host combination.

In some cases, we updated the damage causal agent and host type information. We added a missing host type when only one host type was possible given the preference of the recorded bark beetle species [e.g., Jeffrey pine beetle (*D. jeffreyi*) attacks only Jeffrey pine (*P. jeffreyi*)] (Appendix B). Using similar logic, we updated missing beetle species. We also added missing host species information by using the forest type when that was recorded. Note that we coded all piñon pine mortality (both common piñon (*P. edulis*) and singleleaf piñon (*P. monophylla*) pine) as caused by piñon ips. Piñon ips, however, might not be the sole mortality agent, and in most cases piñon pine mortality has been attributed to the combination of drought and beetle-kill (Shaw et al. 2005). Because the attribution of the piñon pine mortality is very difficult to determine from aerial surveys, the mortality agents were combined into a single piñon ips mortality agent class. Finally, we found a small number of overlapping polygons with the same damage causal agent and host type for certain years in the ADS data, but because these polygons accounted for less than 0.03% of the total area, we performed no action to correct for this.

Upper estimates of U.S. mortality area

Several lines of evidence suggested that the number of trees killed from the U.S. ADS data sets were underestimated. We compared published rates of background mortality and field-derived mortality rates to the estimates of mountain pine beetle-caused tree mortality reported by ADS to investigate this possibility. We converted background mortality percentages (0.5–1.5%) recently reported for old-growth stands in the western United States (van Mantgem et al. 2009) to the number of dead trees per hectare using the average tree density (1065 trees/ha for lodgepole pine-dominated stands) derived from two field studies, in Idaho (Pfeifer et al. 2011) and Colorado (Meddens et al. 2011). For the

⁷ <http://www.fia.fs.fed.us/>

field-derived estimates of bark beetle-caused tree mortality we calculated the average number of mountain pine beetle-killed trees per hectare from the top 25% of the most severely attacked plots from the abovementioned field studies in Idaho and Colorado. Both the background mortality values of dead trees per hectare and the field-derived values of killed trees per hectare were compared to the highest 25% of mountain pine beetle-killed trees per hectare derived from ADS polygons with mortality caused by mountain pine beetle in lodgepole pine for “outbreak” years (defined as years with >0.5 million trees/ha mortality area; 2004–2010).

Based on our findings (described below in *Results: Upper estimate of U.S. mortality area*), we developed adjustment factors to generate an upper estimate for mortality area in the United States. To accomplish this, the number of killed trees from the ADS data was compared to classified remotely sensed imagery in three bark beetle outbreak locations in different forest types. The first location was Railroad Ridge, Idaho, which is dominated by whitebark pine (*Pinus albicaulis*), with lower elevations also containing lodgepole pine and other conifers. A mountain pine beetle outbreak started in 2003, killing whitebark and lodgepole pines. A 2005 QuickBird satellite image (2.4-m spatial resolution) over a 64 km² area was classified to map tree mortality (Hicke and Logan 2009). The second location was a 94-km² area in northcentral Colorado (Meddens et al. 2011). The area is comprised of lodgepole pine-dominated forests and experienced high levels of mountain pine beetle mortality beginning in 2003. The 30-cm aerial image acquired in 2008 was aggregated to 2.4-m spatial resolution, which resulted in the highest classification accuracy across a range of resolutions. The third forest type was piñon pine woodlands in northern New Mexico that were affected by drought and a piñon ips outbreak (Breshears et al. 2005, Shaw et al. 2005). A 2004 QuickBird satellite image was acquired over a 422-km² study area and used to map piñon pine mortality (Ferguson 2006). All three images classified land-cover types to separate killed trees from other classes, including live trees. See Appendix C for more information about the three study locations and classifications.

To calculate adjustment factors, we first estimated the number of killed trees in the classified imagery as the total area of killed trees from the three study locations divided by the average crown area of the dominant tree species. The adjustment factor (AF) in each location was then calculated as follows:

$$AF = \frac{\text{bb mortality area} / \bar{c}a_{\text{spp}}}{\text{ADS killed trees}} \quad (6)$$

where “bb mortality area” is the total bark beetle-caused tree mortality area (in m²) classified from the available remotely sensed imagery; $\bar{c}a_{\text{spp}}$ is the average crown area (in m²; Appendix A) of the dominant tree species in these locations (whitebark pine in Idaho, lodgepole pine in Colorado, and common piñon in New Mexico); and

“ADS killed trees” is the total number of killed trees reported in ADS by (a) mountain pine beetle in Idaho, 2003–2005, (b) mountain pine beetle in Colorado, 2003–2008, and (c) drought/piñon ips in New Mexico, 2003–2004, which were the years in which tree mortality occurred. We used killed trees directly from the ADS database, not our grids, and only included areas that overlapped with the study locations (we clipped polygons that extended outside these locations). In addition to the calculation of the adjustment factor for each location, we used the upper and lower 95% confidence boundaries of the tree crown area and recalculated the adjustment factor to obtain an uncertainty range associated with the variability of tree crown area.

We used the adjustment factors to modify the number of killed trees for each damage agent and host type (only in the United States). The adjustment factor derived from the lodgepole pine-dominated Colorado location was used for mountain pine beetle disturbance in lodgepole pine forest, the adjustment factor derived from the New Mexico data was used for piñon ips in piñon pine (both common and singleleaf piñon pine), and the adjustment factor derived from whitebark pine-dominated forests in Idaho was used for all other bark beetle and host type combinations. Because of the lack of spatially explicit studies in other forest types, we used the adjustment factor from the Idaho location for other host tree species and damage types. This factor was the lowest of the two closed-canopy forest types (i.e., excluding the piñon pine forest type), thereby resulting in a more conservative estimate of mortality area. We then used this upper estimate of the number of killed trees to produce an upper estimate of the mortality area using the procedures described above.

Similar to the British Columbia data set, some grid cells (<2%) of the combined (all bark beetles) and cumulative (1997–2010) mortality area exceeded 100-ha mortality area within the grid cell (100% of a grid cell). This error likely occurred because of uncertainties in: (1) the variability of underestimation of observers across the western United States, (2) differences in tree crown area across the study domain, and (3) possible double-counting (year to year) by ADS of killed trees. To account for this overestimate, we proportionally reduced each annual value so that the combined and cumulative value was 100% of the grid cell.

The lower and upper estimates of U.S. mortality area were compared to the British Columbia values. We expected there would be some grid cells with higher (>40%) mortality area in the United States, as occurred in British Columbia. For instance, Amman and Baker (1972) reported a range of 5.4–66.8% basal area killed by mountain pine beetle in Wyoming, USA, whereas Shore et al. (2000) reported a similar range of 11–63% of basal area killed by mountain pine beetle in the Southern Interior Forest Region of British Columbia, Canada; both were for lodgepole pine-dominated

stands. Therefore, maps and a relative-frequency histogram were plotted for U.S. (both upper and lower estimates) and British Columbia mortality area for comparing these data sets.

RESULTS

Upper estimate of U.S. mortality area

Our comparisons of the number of trees killed by bark beetles in the western United States reported by the aerial detection survey (ADS) with other sources suggested that the ADS numbers were underestimated. The average number of killed trees in major outbreak years (2004–2010) of ADS polygons with the highest 25% of mortality severity was 31 dead trees/ha for our lower estimate (i.e., reported by ADS). The mean background mortality rate reported by van Mantgem (2009) (1%; range, 0.5–1.5%) converted to 10.6 (5–16) dead trees per ha, about one-third of the value (range, 16–52%) of the most severely attacked locations reported by ADS. The average number of mountain pine beetle-killed trees in the most severely attacked lodgepole pine plots from field observations was 768.8 dead trees/ha (range, 675–1000) and 631.3 dead trees/ha (range, 375–925) for Colorado (Meddens et al. 2011) and Idaho (Pfeifer et al. 2011), respectively, 20–25 times the value reported by ADS (31 dead trees/ha). Our upper estimate of the most severely attacked locations based on ADS data was 648 dead trees/ha, much greater than background mortality (as expected) and much closer to field observations.

The comparison with estimates from remotely sensed imagery yielded similar results regarding underestimation. The total number of killed trees calculated from the aerial surveys at the Idaho location was 44 681 dead trees, whereas the number estimated from the classified QuickBird image was 609 415 dead trees, resulting in an adjustment factor of 13.6 (10.5–19.5 when propagating the 95% confidence interval of the whitebark pine crown area). The total number of killed trees estimated from ADS in Colorado was 198 621, whereas the number estimated from the classified aerial image was 4 154 206. The underestimation of ADS (or adjustment factor) for this location and forest type was 20.9 (19.6–22.4 for the 95% confidence interval). The total number of killed trees calculated from ADS at the New Mexico location was 938 125, whereas the number estimated from the classified QuickBird image was 3 506 477, leading to a factor of 3.7 (3.5–4.0 for the 95% confidence interval).

We also compared mortality area from British Columbia with that from the United States. When using the original ADS data (lower estimate), the values of mortality area in the United States are low compared to those in British Columbia (Fig. 2A). Note in particular the discontinuity across the U.S.–Canada border. However, the values between the United States and British Columbia show much better agreement when using the upper estimate of the U.S. data set (Fig. 2B), although for some areas such as north-central Wash-

ington the agreement may not have been improved, indicating that the adjustment factors might not be completely constant across the entire study region.

Histograms of the cumulative mortality area (2001–2010) revealed that the relative frequency of mortality-area values of the original data (lower estimate) were lower than those from the British Columbia data set (Appendix D). The relative frequency of mortality area distributed across the range of mortality in the U.S. upper estimate better matches the range of the British Columbia values. In particular, there are many more grid cells with higher mortality severity (more mortality area) in the upper estimate, more similar to that from British Columbia. Note that we do not assume that the British Columbia data set is correct. Instead, our point is that differences with British Columbia values decrease when using the upper estimate of the United States, lending additional support for evidence that the upper estimate is more realistic.

Bark beetle-caused mortality area

Bark beetle-caused tree mortality extended from the northern parts of British Columbia to almost the U.S.–Mexican border (Fig. 2). In most of the locations that experienced bark beetle outbreaks, mortality area was low in recent years (1–5 ha per grid cell). However, major bark beetle outbreaks with high mortality severity occurred in central British Columbia and parts of the U.S. Rocky Mountains. Severe mortality also occurred in the Sierra Nevada and southwestern United States. Coastal regions of the United States and British Columbia experienced relatively fewer attacks by bark beetles in recent years.

Our estimates of mortality area showed patterns that differ from affected area: an order-of-magnitude difference existed between the affected area and the mortality area (Fig. 3A and C). In addition, temporal patterns in affected (Fig. 3A) and mortality (Fig. 3C) area were different, particularly in British Columbia, because mortality area takes into account the severity of mortality in the areas, whereas the affected area only considers the combined area of polygons (which also include live trees). Affected area in British Columbia in 2009 showed an increase from 2008, whereas mortality area remained relatively constant as a result of the lower bark beetle severity (a high proportion of polygons in the “trace” class) in 2009 (Appendix E). The amount of area surveyed varied from year to year and the variation was higher in the United States than in British Columbia (Fig. 3B); the surveyed area fluctuated from the mean by ~20% in the United States and 15% in British Columbia over the study period.

From 2001 through 2010, bark beetles killed 5.46 Mha in British Columbia (Table 2) out of a total of 55 Mha of forest (British Columbia Ministry of Forests, Mines and Lands 2010), or ~9.9%. Mountain pine beetles accounted for >90% of the damage, and only three other bark beetle species in British Columbia, namely western

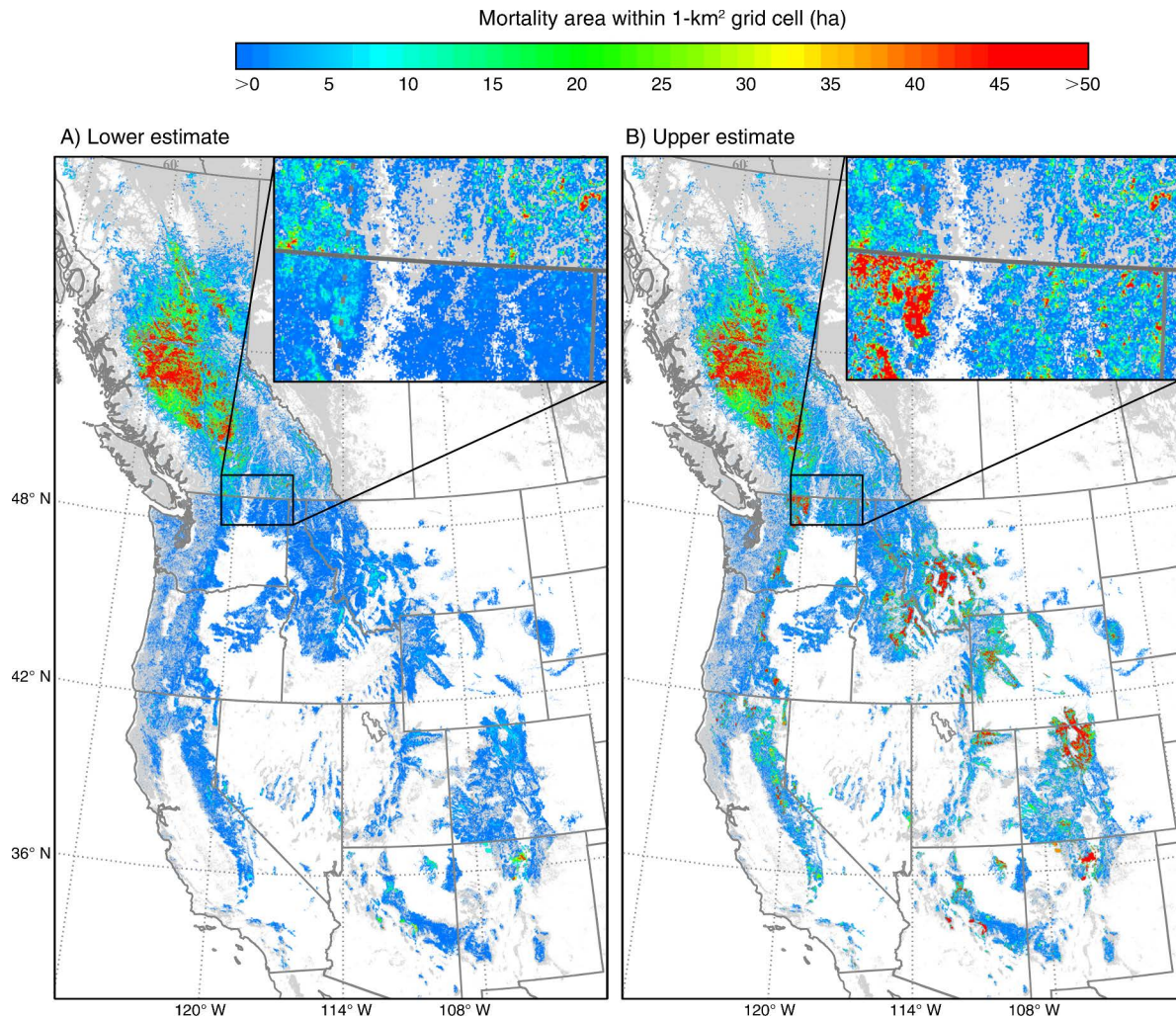


FIG. 2. Cumulative mortality area (ha) from 1997 to 2010 for western conterminous United States and British Columbia for trees killed by bark beetles. (A) U.S. data without adjustment (original data; lower estimate) and (B) U.S. data adjusted for underestimation (calculated by comparison with classified imagery; upper estimate). Light-gray shading represents forested areas (Loveland et al. 2000).

balsam bark beetle, spruce beetle, and Douglas-fir beetle, reached more than the cut-off value of 0.1% of total mortality area.

Of the 13 bark beetle categories we included in the United States from 1997 through 2010, mountain pine beetle accounted for the highest number of killed trees (63%; upper estimate). Mountain pine beetle in lodgepole pine (only) accounted for 53%, and piñon ips in common piñon accounted for 8%. Douglas-fir beetle and unspecified bark beetles each individually accounted for >5% of the total mortality, whereas other bark beetle categories (such as spruce beetle and western balsam bark beetle) contributed <5% of the total tree mortality in the western conterminous United States.

The U.S. upper estimate exceeded British Columbia mortality area in 2003 and from 2008 through 2010 (Fig. 3C). In addition, the cumulative mortality area caused by bark beetles in the western conterminous United

States (for 1997–2010) is almost identical to British Columbia (2001–2010) mortality area (Fig. 3D). From 1997 through 2010 bark beetles killed 404–5872 million trees (lower and upper estimates) or 0.47–5.37 Mha in the western conterminous United States (Appendix F; Table 3), ~0.5–5.7% of the total forest area (as reported in Smith et al. 2001).

Differences in temporal patterns of mortality exist among bark beetle species (Fig. 4). For instance, piñon ips, fir engraver (*Scolytus ventralis*), and ips engraver beetles had a rapid build-up of mortality and a fast decline, whereas the mountain pine beetle showed more gradual increases and slower decreases across western North America, partially as a result of the contribution of different mountain pine beetle outbreaks at different locations with slightly different timing. Douglas-fir beetle, western balsam bark beetle, and spruce beetle

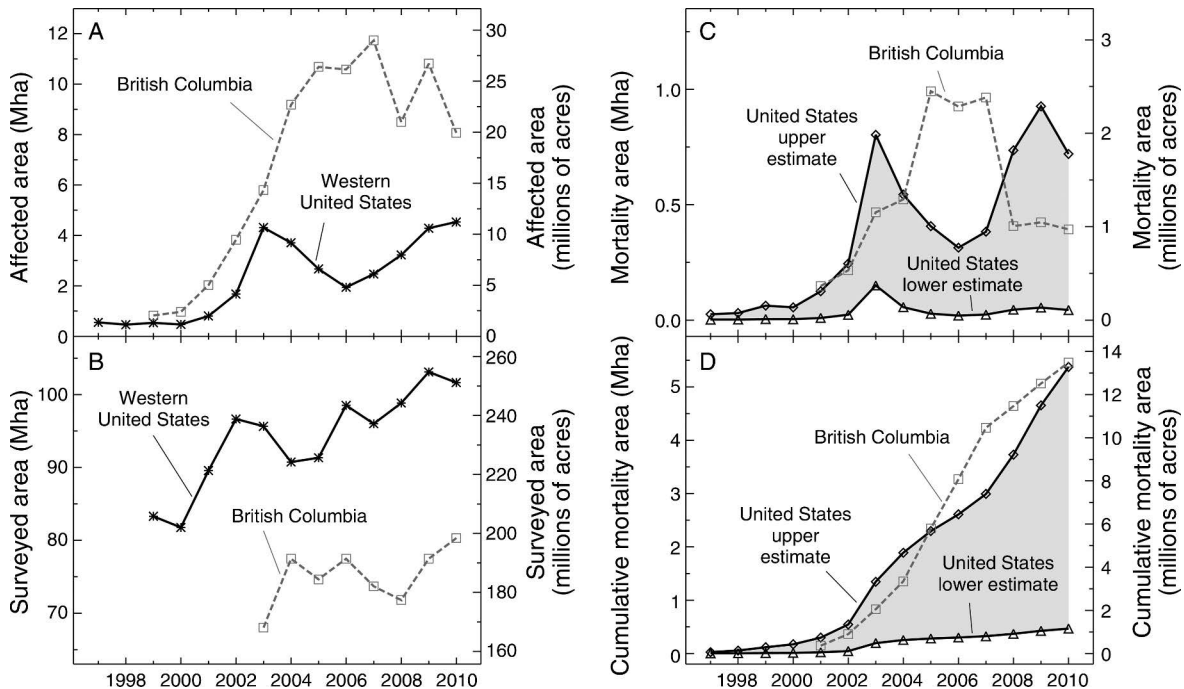


FIG. 3. (A) Affected area, (B) surveyed area, (C) mortality area, and (D) cumulative mortality area for British Columbia (2001–2010) and the western conterminous United States (1997–2010). Left-hand panels (A, B) include all available data (sources: Westfall 2007, Westfall and Ebata 2008, 2009, 2010, 2011; USDA Forest Service 2005, 2007, 2009a, b, 2010; T. Ebata, *personal communication*). Right-hand panels (C, D) show mortality area from U.S. original data (lower estimate) and after adjusting for underestimation (upper estimate). Note that the year of detection is reported, not the year of mortality.

showed constant mortality amounts across the surveyed years.

Mapping individual bark beetle activity revealed different mortality patterns for different bark beetle species (Fig. 5). Some bark beetle categories were confined to a particular region (e.g., piñon ips and ips engraver beetles), whereas other beetle species were less restricted to a particular region (e.g., mountain pine beetle and western balsam bark beetle), inherently related to the distribution of host tree species.

Major bark beetle epidemics (defined here as bark beetles with >40 000 ha of mortality area per year [upper estimate]) occurred across the entire region (Fig. 6), with some grid cell locations having more than one bark beetle species present (Fig. 6, inset). Major outbreaks of mountain pine beetle occurred throughout interior mountains (i.e., Rocky Mountains) during the last decade (2001–2010). Piñon ips-caused tree mortality was predominant in the southwestern United States (2003–2004) and ips engraver beetles outbreaks were extensive in Arizona in 2003. Western balsam bark beetle-caused tree mortality (2001–2003) occurred in the most northern parts of British Columbia, with substantial mortality also occurring in Colorado. Unspecified bark beetle-caused mortality (2002–2004) was only present in California, where aerial detection survey (ADS) sketchmappers did not distinguish among bark

beetle species. Fir engraver outbreaks in 2004 occurred across the entire western conterminous United States, with most mortality occurring in the northwestern United States. Douglas-fir beetle epidemics (2004–2005) occurred mainly in the Rocky Mountains from central British Columbia to New Mexico, with reduced mortality along the northwestern Pacific coast of the United States.

DISCUSSION

We developed methods to produce maps of bark beetle-caused mortality area that combined aerial survey observations from the western United States and British Columbia. This mortality area is an estimate of the actual area of mortality rather than the affected area reported by government agencies that includes live as well as killed trees within polygons (Wulder et al. 2009).

TABLE 2. Bark beetle-caused mortality area in British Columbia, summed for 2001 through 2010.

Bark beetle species	Mortality area (ha)	Total mortality area
Mountain pine beetle	5 102 378	93.5%
Western balsam bark beetle	276 565	5.1%
Spruce beetle	64 238	1.2%
Douglas-fir beetle	14 987	0.3%
Total	5 458 168	100%

TABLE 3. Summary of bark beetle-caused mortality area in the western conterminous United States, summed from 1997 to 2010 (see Appendix F for the complete table).

Bark beetle	Mortality area (ha)		Total mortality area, upper estimate
	Lower estimate†	Upper estimate	
Mountain pine beetle	201 582	3 384 471	62.97%
Piñon ips	136 818	476 877	8.87%
Douglas-fir beetle	22 721	303 604	5.65%
Unspecified bark beetle	22 739	291 667	5.43%
Western balsam bark beetle	18 712	251 303	4.68%
Other beetle species	65 640	666 843	13.40%
Total	468 211	5 374 765	100%

† The “Lower estimate” entries are the actual numbers reported by the aerial detection survey (ADS).

In the United States we found that the estimates of mortality severity were lower than those reported in past publications using field observations and remotely sensed imagery, and were also lower than those estimated from British Columbia observations. As a result, we developed an upper estimate of the U.S. data that, based on several lines of evidence, we suggest is more realistic than the lower estimate.

Bark beetle-caused tree mortality occurred in the last 14 years in most forests of British Columbia and the western conterminous United States. The cumulative total mortality area across years and bark beetle species in the western conterminous United States was very similar to that in British Columbia (for the upper estimate, which we feel is more realistic), with both exceeding 5 Mha. Mountain pine beetle accounted for most of this mortality, in multiple outbreaks across the study region. Different beetle species had different temporal patterns of mortality area. The spatial extent of the beetle-caused tree mortality differed among beetle species, with epidemics of some beetle species occurring across the entire study region (e.g., mountain pine beetle) and epidemics of other beetle species confined to specific areas (e.g., piñon ips). We note that our results are not necessarily representative of outbreak regimes (i.e., long-term characteristics of outbreaks), but rather only quantify mortality during 1997–2010. For example, the current mountain pine beetle outbreak is the most extensive since 1928 (Safranyik et al. 2010), whereas past extensive outbreaks of mountain pine beetle in the 1980s that affected millions of hectares (USDA Forest Service 2009a) do not appear in our data set.

We encourage more accuracy assessments in the amounts of killed trees in different forest types with different damage agents. For instance, piñon pine generally grows in a more open forest type than in closed forest types such as lodgepole pine and thus mortality may be more accurately observed and recorded in the aerial detection survey (ADS) data set. Our calculation of a separate adjustment factor generated a substantially lower value than the ones calculated for mountain pine beetle-affected forests. However, we note challenges in accuracy assessment of aerial surveys

related to their subjective methods and therefore potentially variable results among observers and years.

We produced estimates of actual bark beetle-caused tree mortality (and not affected area), similar to Kurz and Apps (1999). Kurz and Apps (1999) used multipliers derived in consultation with entomologists to convert polygons from Canadian aerial-survey data to mortality area from 1980 to 1989. For instance, they used a multiplier with a value of 0.13 to convert mountain pine beetle-affected areas to mortality area. The average yearly adjustment factor from affected area to mortality area derived in our study for all bark beetles in British Columbia was 0.07, and in the United States the multipliers were 0.01 and 0.15 for lower and upper estimates, respectively. Our multiplier for the U.S. upper estimate was similar to that used by Kurz and Apps (1999), whereas our multiplier for British Columbia was slightly lower, possibly due to the addition and the relatively high proportion of the “trace” class in the recent British Columbia survey data (Appendix E). Similar to Kurz et al. (2008) and Wulder et al. (2009), we combined spatial data with bark beetle severity to improve estimates of forest mortality in British Columbia and applied similar techniques to derive compatible mortality area maps for the western conterminous United States.

Several assumptions and caveats should be taken into consideration when using our mortality area for the western conterminous United States. First, ADS estimates of killed trees per polygon were intended to be a relative indicator of mortality severity rather than accurate values of killed trees, implying uncertainties and variability in estimates across space and time. Second, the transformation of the number of killed trees to mortality area in the U.S. data set was based on mean crown area values. However, tree growth (and thus crown dimensions) changes for different locations depending upon local environmental conditions such as forest structure/age, soil type, and climate (e.g., Littell et al. 2008), leading to different mortality values. Third, the adjustment factors were highly dependent upon the area detected by remotely sensed imagery and average crown area. Tree crown areas in remotely sensed

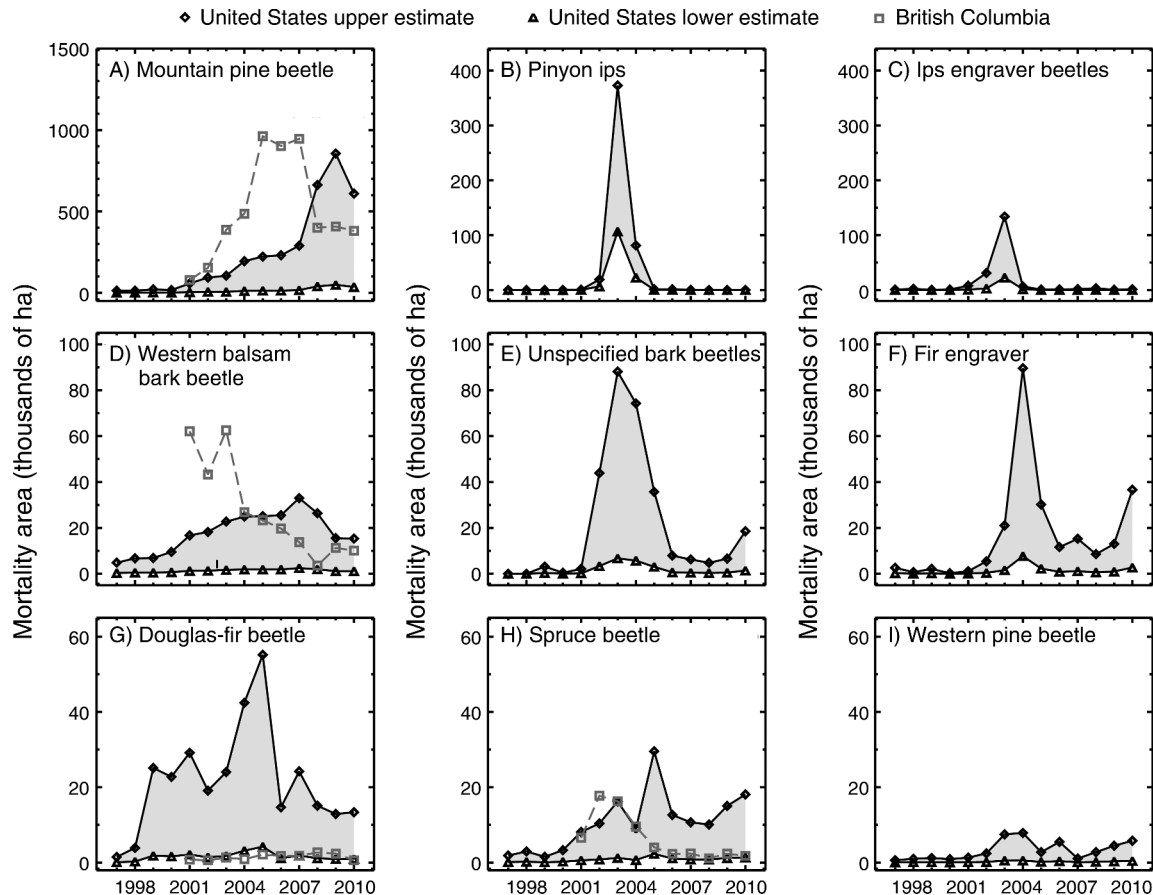


FIG. 4. Mortality area for major damaging bark beetles for western conterminous United States (lower and upper estimates; 1997 through 2010) and British Columbia (2001 through 2010). Note that the year of detection is reported, not the year of mortality, and note different scales on the y-axes.

imagery might be larger than projected tree crown area due to sensor angles that differ from nadir (Sayn-Wittgenstein 1961). Fourth, individuals of some tree species such as whitebark pine exist as tightly packed clumps, increasing the difficulty of identifying the number of killed trees in the ADS data set. Thus, we likely underestimated the number of killed trees in such forest types, although this effect is reduced in our estimate of mortality area because that is calibrated against remote-sensing classifications of mortality area. Finally, we assumed that every observer had the same degree of underestimation of the number of killed trees as occurred at the three sites with remotely sensed imagery. Although we feel that the upper estimate is more realistic than the lower estimate, we provide both lower and upper estimates in acknowledgement of these assumptions.

Scientists, managers, and policy makers should take the following considerations into account when using our gridded-data product. First, data collection is limited to the areas flown in a particular year, which do not encompass all forest areas (e.g., some wilderness

areas and national parks have not been regularly surveyed in the western United States) (see Fig. 3B for the year-to-year variability in the area surveyed). These possible omissions can lead to skewed estimates of whitebark pine mortality, for example, because whitebark pine is more predominant in wilderness areas and national parks (Logan et al. 2009). Another example of year-to-year variability of data collection is the piñon pine mortality in southwestern United States in the early 2000s. Because of its vast extent and a recent history of low levels of insect activity, aerial surveys were not routinely conducted over much of the piñon pine range. The beginning of the beetle mortality event in 2002 was incompletely surveyed, whereas in 2003 the amount of data collected in piñon pine-dominated woodlands significantly increased. Second, we provide no information about which part of a grid cell is affected, and so analyses requiring precise overlays (such as a study of burned areas within outbreak locations) are subject to uncertainty. We recommend that fine-scale analyses include field or remote-sensing studies to provide more confidence about the location and nature of the

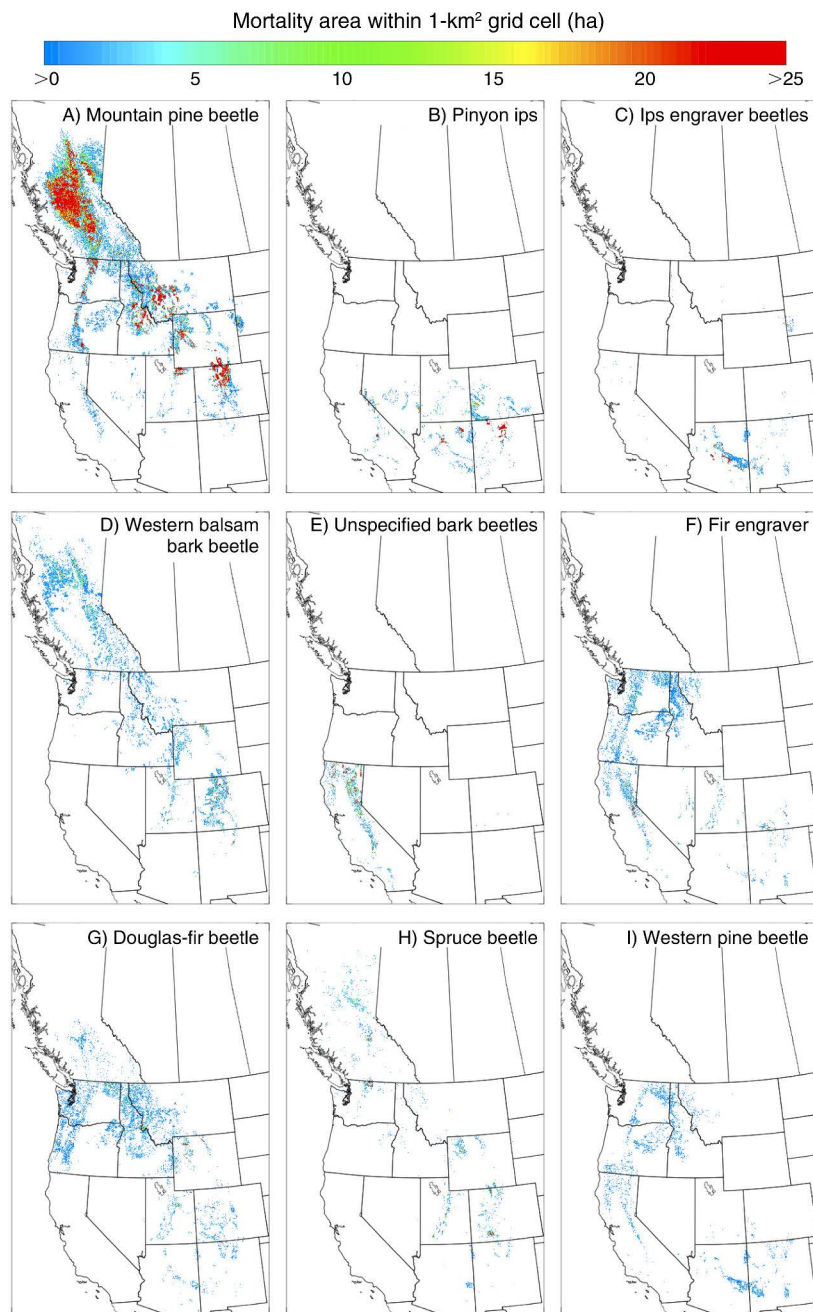


FIG. 5. Cumulative mortality for the nine major damaging bark beetles (U.S. upper estimate, 1997 through 2010; British Columbia, 2001 through 2010).

disturbance. Third, aerial surveys are conducted by different individuals under conditions that vary day to day and year to year and thus are subject to uncertainty. Scientists or policy makers making use of these data should therefore consider both lower and upper estimates to convey the uncertainties associated with the data set. Finally, studies needing the year of attack instead of detection year should shift mortality areas back one year.

CONCLUSIONS

Our newly established mortality-area data set builds upon aerial survey databases in several ways. We combined information from British Columbia and the western conterminous United States, processing each data set to develop a consistent measure of tree mortality. We produced maps of mortality area instead of affected area to more accurately account for the number of bark beetle-killed trees, which is important

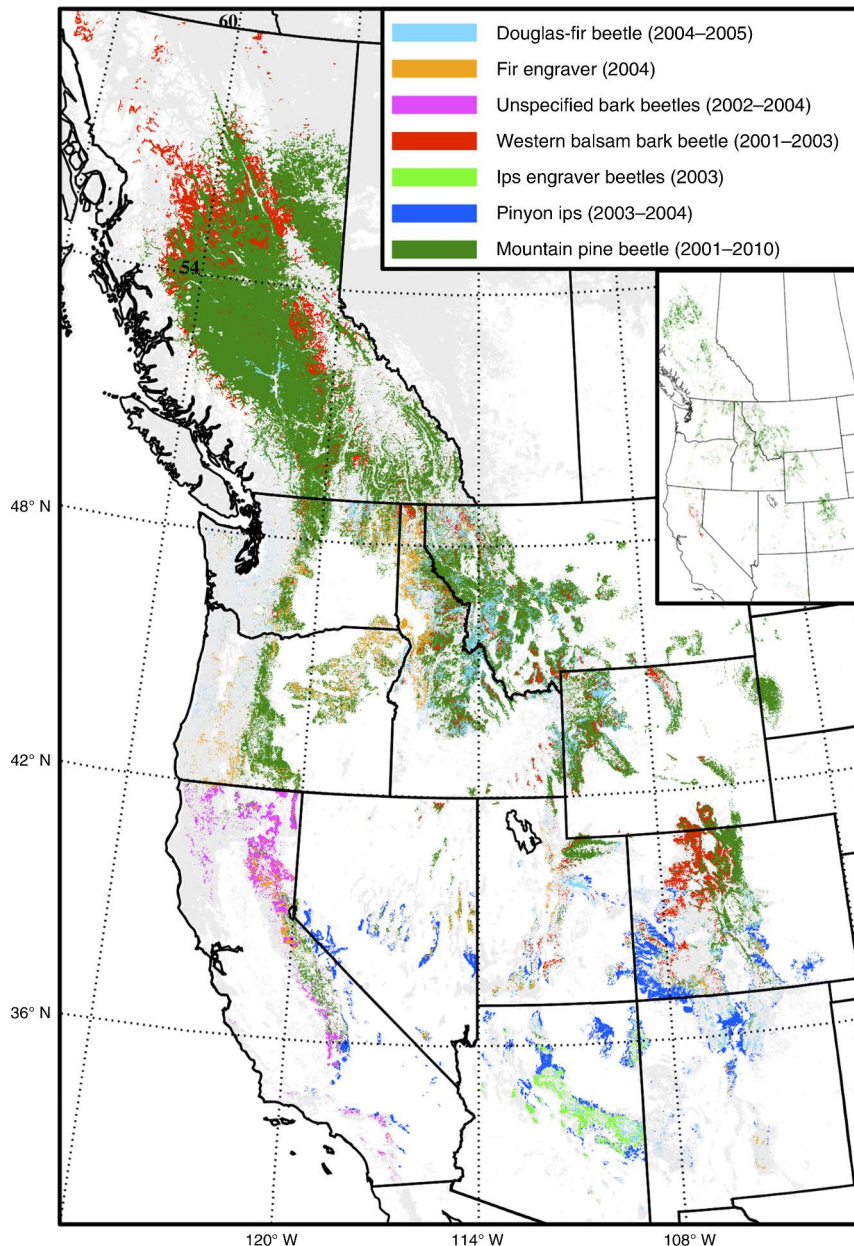


FIG. 6. Major bark beetle disturbances (>40 000-ha mortality area per year) in the western United States (upper estimate) and British Columbia. Note that if there were more than one beetle present in a grid cell, the colors were drawn on the map in the bottom-to-top order of the key (i.e., mountain pine beetle drawn first, Douglas-fir beetle last). Light-gray shading represents all forest areas (Loveland et al. 2000). The inset map shows the next-to-last bark beetle disturbance drawn in locations where there was overlap. For example, if the grid cell had both unspecified bark beetles and western balsam bark beetles, the big map shows pink, and the inset map shows red.

for assessing some impacts of these disturbances. Finally, we generated an upper estimate for mortality area in the United States that likely resulted in a more realistic representation of bark beetle epidemics. Our findings of underestimates of mortality from U.S. ADS by a factor of 3–20 will inform resource managers who consult aerial survey information when planning.

Bark beetle outbreaks that kill trees leave a long legacy in forests. Our study of mortality area provides an improved assessment of tree mortality (i.e., mortality area rather than affected area), leading to better understanding of the spatial and temporal patterns of outbreaks and to increased knowledge of the extent and severity of these disturbances. In addition, the data set



PLATE 1. (Left) Pitch tubes (resin) on a tree attacked by bark beetles, (top right) mountain pine beetle on pitch tube, and (lower right) j-shaped gallery in the phloem tissue of a killed pine tree. Photo credits: left and top right, J. A. Hicke; lower right, A. J. H. Meddens.

provides expanded opportunities for studying tree mortality caused by bark beetles, including (a) understanding the interaction with other forest disturbances such as climate change, wildland fire, and harvest; (b) quantifying impacts to timber, wildlife, recreation, and water sources; (c) driving ecosystem models that evaluate effects on biogeochemical and biophysical processes; and (d) comparison with remote-sensing methods for mapping mortality.

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SUPPLEMENTAL MATERIAL

Appendix A

A table presenting mean diameter at breast height (dbh), crown radius, and crown area of tree species present in the ADS (aerial detection survey) gridding (*Ecological Archives* A022-102-A1).

Appendix B

A table showing damage causal agents and host type conversions for bark beetle–host species combinations missing some data for the western conterminous U.S. grids (*Ecological Archives* A022-102-A2).

Appendix C

A table summarizing additional information about the image classifications performed in the three study locations (*Ecological Archives* A022-102-A3).

Appendix D

A figure depicting the relative frequency distribution of cumulative mortality area (all bark beetle species, all years) for the western conterminous U.S. and British Columbia data sets (cells with mortality area greater than 0) (*Ecological Archives* A022-102-A4).

Appendix E

A figure depicting the affected area for each mortality severity class (Table 1) in British Columbia (*Ecological Archives* A022-102-A5).

Appendix F

A table listing the number of killed trees, mortality area, and percentage of total killed trees by bark beetle species and host type and summed from 1997 through 2010 (United States only) (*Ecological Archives* A022-102-A6).

Appendix A. Mean diameter breast height (DBH) (cm), crown radius (m), and crown area (m²) of tree species present in the ADS gridding. Standard deviation in parentheses where available. Source: all canopy trees greater than 12.7 cm DBH (5 inches) of the 1992-1999 USDA Forest Service Forest Health Monitoring program plots in western US states (www.fia.fs.fed.us; accessed 14 April 2011).

Tree species		Mean DBH ^a (stdev) (cm)	Crown radius (stdev) (m)	Crown area (stdev) (m ²)	<i>n</i>
<u>Pine</u>					
1	bristlecone pine	27.4 (10.4)	2.57 (0.86)	22.88 (15.68)	9
2	common piñon	24.9 (9.4)	1.99 (0.64)	13.73 (9.13)	482
3	Jeffrey pine	54.4 (33.5)	3.27 (1.72)	42.61 (49.31)	42
4	limber pine	24.5 (9.2)	1.95 (0.69)	13.46 (9.67)	85
5	lodgepole pine	22.7 (8.8)	1.53 (0.65)	8.68 (8.50)	1847
6	ponderosa pine	29.95 (14.8)	2.13 (0.91)	16.78 (15.09)	932
7	western white pine	38.6 (21.5)	2.21 (1.02)	18.61 (18.73)	46
8	whitebark pine	27.14 (13.7)	1.69 (0.91)	11.49 (15.16)	76
9	singleleaf piñon	25.5 (9.3)	1.81 (0.68)	11.74 (9.09)	669
<u>Fir</u>					
1	California red fir	59.3 (29.1)	2.50 (0.99)	22.72 (17.28)	57
2	corkbark fir	19.9 (6.4)	1.52 (0.97)	10.08 (24.65)	40
3	subalpine fir	24.9 (9.2)	1.55 (0.54)	8.42 (6.44)	732
4	white fir	36.3 (20.4)	2.15 (11.03)	15.97 (11.03)	399
<u>Spruce</u>					
1	Engelmann spruce	28.7 (12.3)	1.67 (0.61)	9.88 (7.87)	858
<u>Other</u>					
1	Douglas-fir	33.7 (18.2)	2.61 (0.97))	24.28 (19.89)	2677
2	fir species ^b	30.0	1.60	11.59	
3	no data ^c	28.9	2.03	15.50	
4	softwoods ^c	28.9	2.03	15.50	
5	spruce species ^d	28.7 (12.3)	1.67 (0.61)	9.88 (7.87)	858

^aDiameter at breast height except for piñon pine species that were measured at root collar.

^bWeighted average (by number of trees) of all fir species.

^cWeighted average (by number of trees) of all species.

^dEngelmann spruce values.

Appendix B. Damage causal agents and host type conversions for bark beetle/host species combinations missing some data for the western conterminous US grids.

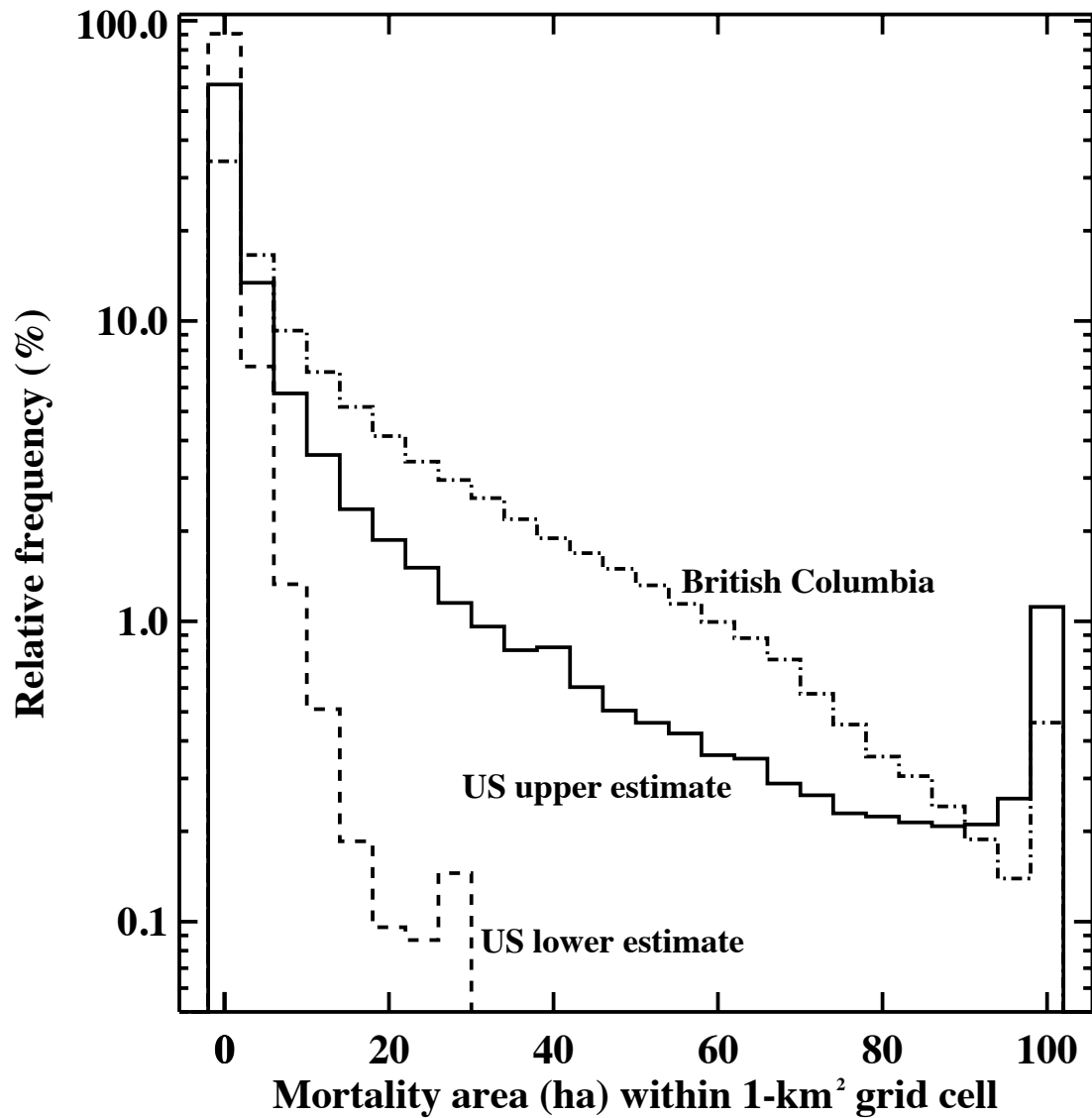
Old				New	
	Damage causal agent	Host	Forest type	Damage causal agent	Host
1	11000 bark beetles	-9999 no data	3015 white fir	11000 bark beetles	15 white fir
2	11000 bark beetles	-9999 no data	3021 shasta red fir	11000 bark beetles	21 shasta red fir
3	11000 bark beetles	-9999 no data	2117 sugar pine	11000 bark beetles	117 sugar pine
4	11000 bark beetles	-9999 no data	2122 ponderosa pine	11000 bark beetles	122 ponderosa pine
5	11000 bark beetles	108 lodgepole		11006 mountain pine beetle	108 lodgepole pine
6	11000 bark beetles	-9999 no data	2108 lodgepole pine	11006 mountain pine beetle	108 lodgepole pine
7	11000 bark beetles	-9999 no data	2116 Jeffrey pine	11000 bark beetles	116 Jeffrey pine
8	11000 bark beetles	-9999 No data	3020 Cal. red fir	11000 bark beetles	20 Cal. red fir
9	11002 western pine beetle	-9999 no data	2122 ponderosa pine	11002 western pine beetle	122 ponderosa pine
10	11004 Jeffrey pine beetle	-9999 no data		11004 Jeffrey pine beetle	116 Jeffrey pine
11	11006 mountain pine beetle	-9999 no data	2108 lodgepole pine	11006 mountain pine beetle	108 lodgepole pine
12	11006 mountain pine beetle	-9999 no data	7101 whitebark pine	11006 mountain pine beetle	101 whitebark pine
13	11006 mountain pine beetle	-9999 no data	2117 sugar pine	11006 mountain pine beetle	117 sugar pine
14	11006 mountain pine beetle	-9999 no data	2119 western white pine	11006 mountain pine beetle	119 western white pine
15	11006 mountain pine beetle	-9999 no data	2122 ponderosa pine	11006 mountain pine beetle	122 ponderosa pine
16	11009 spruce beetle	-9999 no data	3090 spruce	11009 spruce beetle	93 Engelmann Spruce
17	11015 western balsam bark beetle	-9999 no data		11015 western balsam bark beetle	19 subalpine fir
18	11019 piñon ips	-9999 no data	7133 singleleaf piñon	11019 piñon ips	133 singleleaf piñon
19	11019 piñon ips	-9999 no data		11019 piñon ips	106 common piñon
20	11048 true fir bark beetle	-9999 no data	3015 white fir	11048 true fir bark beetle	15 white fir
21	11048 true fir bark beetle	-9999 No data	3020 Cal. red fir	11048 true fir bark beetle	20 Cal. red fir
22	11050 fir engraver	-9999 no data	3015 white fir	11050 fir engraver	15 white fir
23	11050 fir engraver	-9999 no data	3020 Cal. red fir	11050 fir engraver	20 Cal. red fir
24	80002 subalpine fir mortality	19 Subalpine fir		11015 western balsam bark beetle	19 subalpine fir
25	80002 subalpine fir mortality	-9999 no data		11015 western balsam bark beetle	19 subalpine fir
26	80003 five-needle pine decline	101 whitebark pine		11006 mountain pine beetle	101 whitebark pine
27	80003 five-needle pine decline	102 bristlecone pine		11006 mountain pine beetle	10 bristlecone pine
28	80003 five-needle pine decline	113 limber pine		11006 mountain pine beetle	113 limber pine
29	80004 piñon pine mortality	106 common piñon		11019 piñon ips	106 common piñon
30	80004 piñon pine mortality	133 singleleaf piñon		11019 piñon ips	133 singleleaf piñon

Appendix C. Additional information of the image classifications performed in the three study locations.

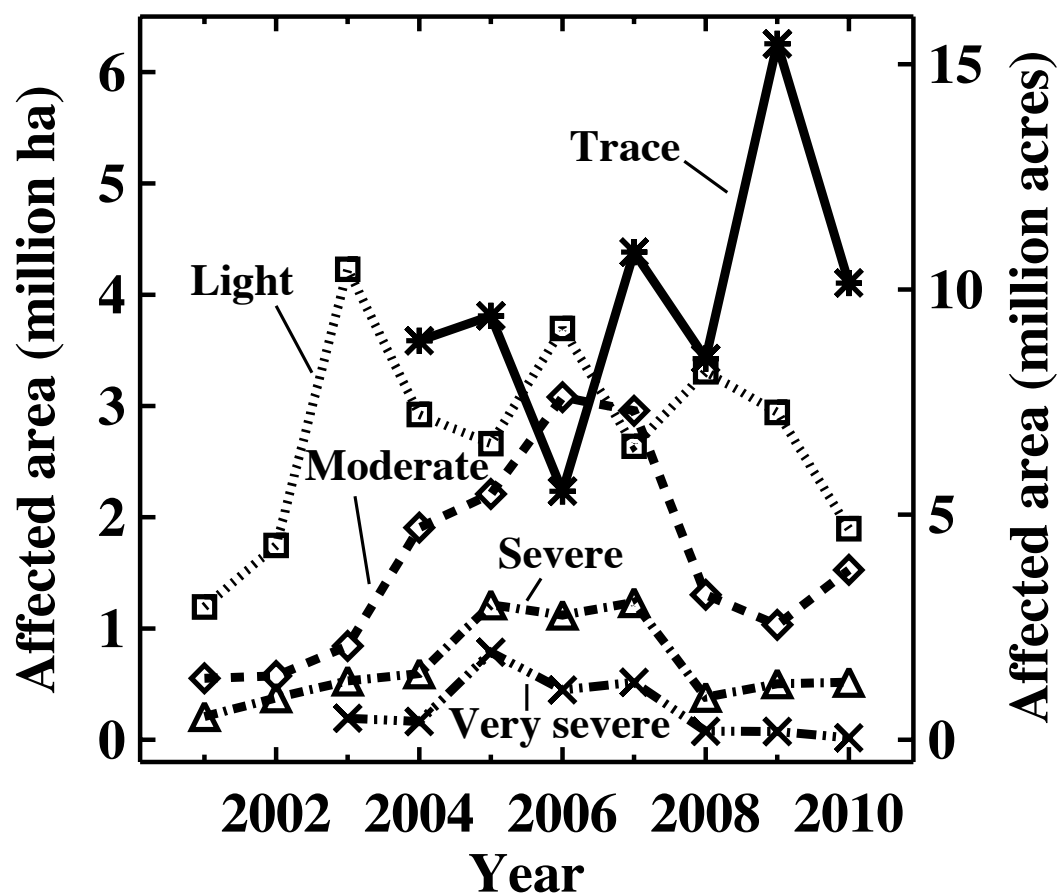
Location	Area	Disturbance / dominant host	Image type	Classes of interest	Accuracy
Idaho ^a	64 km ²	mountain pine beetle in whitebark pine	QuickBird	green (live) tree, red- attack tree, green herbaceous, and brown herbaceous cover	86%-91% kappa=0.82
Colorado ^b	94 km ²	mountain pine beetle in lodgepole pine	aerial imagery	green trees, red-attack, gray-attack, and non- forest	90% kappa=0.88
New Mexico ^c	422 km ²	piñon ips/drought in piñon pine	QuickBird	piñon pine mortality, no mortality	89% kappa=0.73

^aHicke and Logan (2009), ^bMeddens et al. (2011), and ^cFerguson (2006)

Appendix D. Relative frequency distribution of cumulative mortality area (all bark beetle species, all years) for the western conterminous US (dashed: lower estimate; solid: upper estimate) and British Columbia (dashed-dotted) data sets (cells with mortality area greater than 0).



Appendix E. Affected area for each mortality severity class (Table 1) in British Columbia.



Appendix F. Number of killed trees, mortality area, and percentage of total killed trees by bark beetle species and host type and summed from 1997 to 2010 (US only).

Bark beetle	Host type	Number of killed trees		Mortality area (ha)		% of total mortality area
		(lower)	(upper)	(lower)	(upper)	(upper)
mountain pine beetle	lodgepole pine	184,956,145	3,869,282,562	160,541	2,858,860	53.19
	ponderosa pine	9,915,720	135,250,424	16,638	213,299	3.97
	whitebark pine	10,582,398	144,343,908	12,159	158,714	2.95
	no data	4,585,220	62,542,407	7,272	88,827	1.65
	limber pine	2,734,503	37,298,627	3,681	49,091	0.91
	bristlecone pine	289,590	3,950,011	663	8,048	0.15
	western white pine	337,830	4,607,996	629	7,634	0.14
Total		213,401,407	4,257,275,934	201,582	3,384,471	62.97
piñon ips	common piñon	94,126,730	352,033,969	129,240	448,544	8.35
	singleleaf piñon	6,455,108	24,142,102	7,578	28,333	0.53
Total		100,581,837	376,176,071	136,818	476,877	8.87
Douglas-fir beetle	Douglas-fir	9,205,130	125,557,972	22,350	298,572	5.56
	no data	233,581	3,186,050	370	5,032	0.09
Total		9,438,711	128,744,022	22,721	303,604	5.65
unspecified bark beetle	no data	9,378,543	127,923,324	14,874	191,191	3.56
	ponderosa pine	940,872	12,833,494	2,138	27,920	0.52
	white fir	1,229,813	16,774,646	2,064	26,035	0.48
	California red fir	1,215,466	16,578,957	1,884	25,282	0.47
	softwoods	1,114,024	15,195,286	1,779	21,239	0.40
Total		13,878,717	189,305,707	22,739	291,667	5.43
western balsam bark beetle	subalpine fir	21,510,103	293,397,805	18,111	243,114	4.52
	no data	595,603	8,124,018	600	8,189	0.15
Total		22,105,706	301,521,823	18,712	251,303	4.68
fir engraver	fir species	6,739,476	91,926,452	7,811	105,098	1.96
	white fir	4,886,316	66,649,348	7,803	93,895	1.75
	no data	770,066	10,503,706	1,750	21,261	0.40
	California red fir	868,391	11,844,847	1,377	17,814	0.33
Total		13,264,249	180,924,353	18,741	238,068	4.43
ips engraver beetles	ponderosa pine	16,702,290	227,819,233	28,026	187,041	3.48
	no data	226,700	3,092,193	360	3,815	0.07
Total		16,928,990	230,911,425	28,386	190,856	3.55
spruce beetle	Engelmann spruce	6,259,134	85,374,585	6,184	82,992	1.54
	spruce species	5,170,162	70,521,012	5,108	60,902	1.13
	no data	266,468	3,634,617	423	5,760	0.11
Total		11,695,763	159,530,214	11,715	149,654	3.78
western pine beetle	ponderosa pine	1,828,634	24,942,564	3,068	41,314	0.77
	no data	188,068	2,565,242	298	4,052	0.08
Total		2,016,701	27,507,805	3,367	45,367	0.84
pine engraver	ponderosa pine	810,031	11,048,823	1,359	18,427	0.34
Jeffrey pine beetle	Jeffrey pine	366,335	4,996,812	1,561	17,557	0.33
true fir bark beetle	white fir	213,518	2,912,381	341	4,600	0.09
roundheaded pine beetle	ponderosa pine	101,090	1,378,863	170	2,314	0.04
Total		404,803,056	5,872,234,233	468,211	5,374,765	100.00