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Carbon stocks of trees killed by bark beetles and wildfire in the western United States

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Abstract

Forests are major components of the carbon cycle, and disturbances are important influences of forest carbon. Our objective was to contribute to the understanding of forest carbon cycling by quantifying the amount of carbon in trees killed by two disturbance types, fires and bark beetles, in the western United States in recent decades. We combined existing spatial data sets of forest biomass, burn severity, and beetle-caused tree mortality to estimate the amount of aboveground and belowground carbon in killed trees across the region. We found that during 1984–2010, fires killed trees that contained 5–11 Tg C year−1 and during 1997–2010, beetles killed trees that contained 2–24 Tg C year−1, with more trees killed since 2000 than in earlier periods. Over their periods of record, amounts of carbon in trees killed by fires and by beetle outbreaks were similar, and together these disturbances killed trees representing 9% of the total tree carbon in western forests, a similar amount to harvesting. Fires killed more trees in lower-elevation forest types such as Douglas-fir than higher-elevation forest types, whereas bark beetle outbreaks also killed trees in higher-elevation forest types such as lodgepole pine and Engelmann spruce. Over 15% of the carbon in lodgepole pine and spruce/fir forest types was in trees killed by beetle outbreaks; other forest types had 5–10% of the carbon in killed trees. Our results document the importance of these natural disturbances in the carbon budget of the western United States.

Keywords: bark beetle outbreaks, forest disturbances, forest carbon cycling, western United States

Online supplementary data available from stacks.iop.org/ERL/8/035032/mmedia

1. Introduction

Forests play important roles in the carbon cycle (Denman et al 2007). Globally, tree regrowth following harvest and deforestation contributes substantially to the net carbon fluxes between the land and atmosphere (Goodale et al 2002, Canadell et al 2007, Pan et al 2011). Forest disturbances are significant regulators of carbon cycling (Odum 1969), and tree killing disturbances, including severe wildfire and bark beetle outbreaks, affect forest carbon cycling through multiple processes. Carbon uptake by the forest ecosystem through photosynthesis is immediately reduced following tree mortality. Fires release carbon directly to the atmosphere via combustion of vegetation and soil. Tree mortality moves
carbon from live to dead pools, which begin to release carbon back to the atmosphere via heterotrophic respiration. After disturbance, remaining vegetation (surviving overstory trees and understory seedlings, saplings, shrubs, and herbs) increases growth, altering the net carbon flux. Effects can last decades as killed trees decompose and new vegetation slowly establishes and grows (Hicke et al. 2003, Amiro et al. 2010, Edberg et al. 2011).

Wildfires and insect outbreaks have affected millions of hectares in the western United States in recent decades. Fires are important natural disturbances across North America (Kasischke et al. 2011), and in the western US alone fires burned an estimated mean of 760,000 ha year$^{-1}$ during 1980–2000 (Littell et al. 2009). Bark beetle outbreaks kill trees from Mexico to Alaska (Salinas-Moreno et al. 2004, Raffa et al. 2008). Cumulative mortality area since 1997 from bark beetle-killed trees has exceeded 5 Mha (Meddens et al. 2012). Mountain pine beetles (Dendroctonus ponderosae) in lodgepole pine (Pinus contorta var. latifolia) forests have been particularly damaging, causing 63% of the mortality (Meddens et al. 2012). However, additional bark beetles, including piñon ips (Ips confusus), Douglas-fir beetle (Dendroctonus pseudotsugae), and western balsam bark beetle (Dryocoetes confusus), have caused substantial tree mortality.

Forest disturbances, including wildfire and insect outbreaks, play important roles in the North American carbon budget (CCSP 2007, Kasischke et al. 2013). Substantial carbon is released by direct combustion of forests (Wiedinmyer and Neff 2007, French et al. 2011, Ghimire et al. 2012). Fires also generate dead organic matter that affects postdisturbance carbon fluxes (Harmon et al. 2011, Ghimire et al. 2012, Kashian et al. 2013). Insect outbreaks can also significantly impact carbon cycling (Hicke et al. 2012). The mountain pine beetle outbreak in British Columbia caused forests there to switch from being a slight carbon sink to a significant carbon source for decades (Kurz et al. 2008). However, not all biotic disturbances result in such significant effects. The severity of tree mortality within a given area, type of biotic disturbance agent (particularly growth reducers versus tree killers), and number and size of surviving trees are important influences on net carbon fluxes (Hicke et al. 2012).

Although large forest fires and bark beetle outbreaks in the western United States have been documented (Littell et al. 2009, Meddens et al. 2012), no studies to date have assessed the impact of these disturbances on the regional carbon cycle. Quantifying effects on carbon stocks for each disturbance type leads to a greater understanding of the role of each in governing carbon cycling in the forests of the western United States.

Here we use the area of trees killed by wildfire and bark beetle outbreaks to estimate the amount of carbon in killed trees. Although changes in carbon stocks do not directly translate into net ecosystem fluxes (e.g., net biome productivity), broad scale, spatially explicit quantification of carbon in killed trees can be estimated with simple approaches, whereas analogous estimates of carbon fluxes require extensive inputs and more complex modeling. Our objective was to combine estimates based on observations of areas disturbed by wildfire and bark beetles and carbon stocks to quantify the spatial and temporal characteristics of carbon in killed trees during the last few decades in the western United States.

2. Methods

Our study area encompassed forested areas of the western United States. Detailed information exists for this area on bark beetle outbreaks, wildfire burn severity, forest cover, and carbon stocks for recent decades on a spatially explicit basis at fairly high spatial resolution.

To compute carbon in trees killed by bark beetles, we used the annual area of mortality produced by Meddens et al. (2012). Mortality area is the summed crown area of killed trees, and is different from ‘area affected’ often reported because mortality area does not include the contribution from live trees. USDA Forest Service Aerial Detection Surveys (ADS) report damage attributes, including beetle and tree species and number of trees killed in the survey year, recorded by observers in planes. Annual records from 1997–2010 were converted from attribute information within polygons to a 1 km grid containing the number of killed trees for different bark beetle species. Meddens et al. (2012) used trees killed per hectare to calculate mortality area using species-specific crown diameters from a USDA Forest Service Forest Health Monitoring data set (Meddens et al. 2012). These crown diameters were from both stand-grown and open-grown trees, thereby increasing the mean crown diameter and accommodating the preference of larger diameter trees by bark beetles (Shore and Safranyik 1992). This process resulted in a ‘lower estimate’ of mortality area. An upper estimate of mortality area was also produced by applying adjustment factors to the lower estimate that were derived by comparing the lower estimate to beetle-caused tree mortality from fine resolution remotely sensed imagery (Meddens et al. 2012). Three adjustment factors were calculated in three different forest types across the western US (in order of increasing value: pinyon pine, whitebark pine, lodgepole pine). The adjustment factor using the pinyon pine imagery was used for tree mortality in pinyon pine only, assuming that aerial surveys were more accurate in more open woodlands. To be conservative, Meddens et al. (2012) used the largest adjustment factor, in lodgepole pine killed by mountain pine beetle, for that tree/beetle combination only, and used the intermediate adjustment factor (in whitebark pine killed by mountain pine beetle) for all other host tree species. More recent analyses of lodgepole pine stands attacked by mountain pine beetle suggest an average adjustment factor in that tree/beetle combination close to that of the whitebark pine adjustment factor. Therefore, in this study, we added a third (‘middle’) estimate using only the pinyon pine adjustment factor for that tree species and the whitebark pine adjustment factor for all other tree species. Because this middle estimate is based on comparisons with highly accurate classifications of tree mortality using fine-scale remotely sensed imagery, we view the middle estimate as the most realistic of the three.
function of aboveground biomass (Cairns adding an estimate of belowground biomass modeled as a aboveground live biomass to total live carbon stocks by (1) 250-m biomass data to 1-km resolution and converted topography, and other ancillary variables. We aggregated (MODIS) imagery acquired in 2001, land cover, climate, and Analysis plots and MODerate Imaging Spectroradiometer modeled biomass from USDA Forest Service Forest Inventory forest biomass map produced by Blackard stocks in trees. For the latter, we used the aboveground live grid cell containing high or moderate + spatial resolution by calculating the percentage of a 1-km burn severity estimates and aggregated the 30-m data to 1-km by EVT. We then combined the forest mask with the two BPS except in locations currently identified as agriculture geospatial union. We added potentially forested areas from NLCD and EVT data sets, and combined the two with a physical Settings (BPS)). We identified forest classes in the pre-EuroAmerican settlement land cover (LANDFIRE Bio-physical Settings (BPS)). We identified forest classes in the NLCD and EVT data sets, and combined the two with a geospatial union. We added potentially forested areas from BPS except in locations currently identified as agriculture by EVT. We then combined the forest mask with the two burn severity estimates and aggregated the 30-m data to 1-km spatial resolution by calculating the percentage of a 1-km grid cell containing high or moderate + high severity 30-m grid cells. The resulting maps of burn severity (high- and moderate + high-severity) in forested areas estimated the percentage area of tree mortality caused by forest fires.

We then overlaid tree mortality with spatial data of carbon stocks in trees. For the latter, we used the aboveground live forest biomass map produced by Blackard et al (2008), who modeled biomass from USDA Forest Service Forest Inventory and Analysis plots and MOderate Imaging Spectroradiometer (MODIS) imagery acquired in 2001, land cover, climate, topography, and other ancillary variables. We aggregated 250-m biomass data to 1-km resolution and converted aboveground live biomass to total live carbon stocks by (1) adding an estimate of belowground biomass modeled as a function of aboveground biomass (Cairns et al 1997) (their Equation (1) in table 3) and (2) multiplying by 0.5 to compute carbon (Schlesinger 1997).

Because we noted relatively low biomass in recently disturbed forested areas compared with surrounding undisturbed forests (for example, in the Yellowstone area burned in 1988), we produced a corrected carbon stocks map representing undisturbed conditions. To do so, we identified disturbed areas before 2001 from the bark beetle mortality area and moderate + high-severity burned areas. We calculated the mean carbon stock in undisturbed locations for each major forest type (Ruefenacht et al 2008) within each ecoregion (Olson et al 2001) in the western United States. In disturbed locations, we used the maximum of the carbon stock from this mean and the Blackard et al-based estimate described in the previous paragraph. The corrected biomass map resulted in a 14–16% increase in cumulative carbon in trees killed by beetles and fires for the region and study period. Most significantly, carbon in trees killed by fires increased from 11 to 25 Tg in 1988 associated with the Yellowstone fires. In other years, the increase was minor, usually less than 1–2 Tg C.

To compute carbon in killed trees, we multiplied the percentage mortality area maps (annual for each of bark beetles and forest fires) by the carbon stock map. We summed carbon in killed trees in each forest type using a classification developed from MODIS imagery (250-m spatial resolution) (Ruefenacht et al 2008) that we aggregated to 1 km. We also summed carbon in killed trees by ecoregion defined by the World Wildlife Fund (Olson et al 2001) for better visual presentation in figures. We calculated the percentage of carbon in killed trees within ecoregions and forest types by using the total carbon in all trees for each ecoregion and forest type. When reporting cumulative values across time, we did not account for any decomposition during the time period.

Estimates of the amount of carbon in harvested trees in the western United States were derived from a national USDA Forest Service report on forest resources (Smith et al 2009). Average annual removals in ft³ were reported based on national inventory databases developed for 1976, 1986, 1996, and 2006 (i.e., averages from prior years). We multiplied removals by the ratio of total volume to merchantable volume to account for foliage, bark, branches, and roots. We then used specific gravities for the Pacific Southwest, Pacific Northwest (averaged east and west values), and Rocky Mountains (averaged north and south values) as well as a conversion factor from biomass to carbon (0.5) from Smith et al (2005) to convert volume to carbon.

3. Results

Between 1997 and 2010, fires and beetles together killed trees that contained >100 Tg C (table 1). The most realistic middle estimate for bark beetles and the higher estimate for fires resulted in 486 Tg C in killed trees during this time period. The middle estimate for bark beetles was 47% greater than the higher estimate for fires. The amount of carbon in killed trees by fires (higher estimate) and beetles (middle estimate) consisted of 3% and 6%, respectively, of the
Figure 1. Carbon in trees killed by major bark beetle species (1997–2010; red lines representing upper, middle, and lower estimates; gray shading indicates range between lower and upper estimates) and forest fires (1984–2010; blue lines; hatching indicates range between moderate- and moderate + high-severity burned areas).

Table 1. Carbon in trees killed by forest fires, bark beetles, and harvest.

<table>
<thead>
<tr>
<th>Disturbance type</th>
<th>Time period</th>
<th>Cumulative carbon in killed trees (Tg C)</th>
<th>% of total tree C</th>
<th>Annual mean C in killed trees (Tg C year(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest fires</td>
<td>1984–2010</td>
<td>146–285</td>
<td>2.4–4.6%</td>
<td>5.4–10.5</td>
</tr>
<tr>
<td></td>
<td>1997–2010</td>
<td>100–197</td>
<td>1.6–3.2%</td>
<td>7.2–14.1</td>
</tr>
<tr>
<td>Bark beetles</td>
<td>1997–2010</td>
<td>25–342 (289(^a))</td>
<td>0.4–5.5% (4.7(^a))</td>
<td>1.8–24.4 (20.6(^a))</td>
</tr>
<tr>
<td>Harvest</td>
<td>1976</td>
<td></td>
<td></td>
<td>49.4(^b)</td>
</tr>
<tr>
<td></td>
<td>1986</td>
<td></td>
<td></td>
<td>49.4</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td></td>
<td></td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td></td>
<td></td>
<td>29.9</td>
</tr>
</tbody>
</table>

\(^a\) Most realistic middle estimate for bark beetles.

\(^b\) Annual average from inventory database developed for listed year.

total tree carbon in the western United States. An additional 46–88 Tg C was associated with trees killed by forest fires during 1984–1996, a time of reduced burned area compared with the later period. The sum of carbon in trees killed by these two natural disturbances slightly exceeded the estimate from harvest in recent decades, and was less than that from harvest in the 1970s and 1980s (table 1).

Table series of the amount of carbon in killed trees reveals several years of substantial tree mortality caused by fires (figure 1). Notable high forest fire years included 1987–1988, 2000, 2002–2003, and 2006–2008. In other years, the amount of carbon associated with fire-killed trees was typically fairly low, less than 5–6 Tg C year\(^{-1}\). Bark beetles killed increasing numbers of trees during 1997–2010. Although there were a few years of declines, the amount of carbon in trees killed by beetles rose from <5 Tg C in 1997 to a peak of 45 Tg C in 2009, exceeding that from wildfire, 35 Tg C in 2002.

Spatial patterns illustrate large variability in the amount of carbon killed by beetles and fire (figure 2 and supplementary information, available at stacks.iop.org/ERL/8/035032/mmedia). Patterns do not change significantly among lower, middle, and higher estimates, so here we present results associated with the most realistic middle estimate for bark beetles and the moderate + high-severity estimate for forest fires. For fires, higher amounts of C in killed trees occurred in the middle Rocky Mountains and the Siskiyou Mountains of California and Oregon, where ecoregion totals exceeded 35 Tg C for the 1984–2010 period. In terms of percentage carbon in killed trees (compared with total tree (Meddens et al 2012). At the same time, populations of mountain pine beetle were increasing and continued to remain high through 2010, resulting in the peak of carbon in killed trees during the latter part of the study period. In addition to causing a greater cumulative amount of carbon in killed trees, beetles also were associated with more carbon in killed trees during any individual year than forest fires (i.e., the maximum annual carbon in killed trees from beetles, 45 Tg C in 2009, exceeded that from wildfire, 35 Tg C in 2002).
C) within ecoregions, the highest percentage occurred in the forests of coastal southern California (>18%), and values of 4–11% occurred in the Rocky Mountains, northern Cascades, and northern California.

Ecoregional totals of C (summed over time) in trees killed by bark beetles were typically greater than those from fires. The Rocky Mountains and Sierra Nevada experienced especially large effects on carbon, on the order of 30–50 Tg C. Carbon in killed trees exceeded 10% of the total tree C in the southern and middle Rocky Mountains and northern Cascades. In terms of total C, fires were more significant than beetle outbreaks in coastal northern California and Oregon, northeastern Oregon, and parts of the Southwest.

Fire and beetle impacts to C stocks varied substantially by forest type (figure 3). The large areas of lower-elevation pinyon pine killed by pinyon ips beetle translated into relatively low amounts of carbon (figure 3). Forests at somewhat higher elevations (ponderosa pine and especially Douglas-fir) were more affected, with 60–80 Tg C in trees killed by beetles and fires. We note that impacts within a given forest type may be associated with other tree species; substantial lodgepole pine mortality was included in the Douglas-fir forest type, for instance. Lodgepole pine forests were subjected to widespread mortality from beetles and to a lesser degree from fires: 20% and 7% of the total tree carbon in this forest type were in trees killed by beetles and fires, respectively. Higher-elevation spruce/fir forests were also heavily impacted. Beetles were more significant disturbances than fires in lodgepole and spruce/fir forest types, and fires and beetles were similar in magnitude in the other coniferous forest types.

4. Discussion

Our analysis estimated the effects of beetle outbreaks and forest fires in terms of carbon in killed trees. We accounted for several processes to more realistically represent carbon impacts than simply using affected area reported by the Aerial Detection Surveys (beetles) and burned area (fires). For beetles, we used a data set of mortality area that represents the area of killed trees, not the affected area (which includes live trees) (Meddens et al 2012). For fires, we limited burned areas to forests only and considered only more severely burned areas that represent tree mortality. For both disturbance types, we accounted for variability in forest cover and tree size by utilizing spatial biomass data. Our data sets were derived from observations, increasing the confidence of our results.

We found that the most realistic middle estimate for bark beetles was associated with more C in killed trees.
Figure 3. Cumulative carbon by forest type and over time in trees killed by bark beetles (1997–2010) and forest fires (1984–2010) in (a) Tg C and (b) per cent carbon in killed trees within forest type. Forest types (except ‘other conifer’ and ‘other’) sorted by elevation (Daubenmire 1966, Allen et al 1991).

Significant mountain pine beetle outbreaks happened in the early to mid-1980s, affecting 0.4–2 Mha year$^{-1}$ (comparable to the affected area in the late 2000s) (USDA Forest Service 2012). Including these outbreaks would substantially increase our estimated cumulative impacts on carbon stocks. However, because spatial information about these outbreaks is lacking, these older outbreaks were not included in this analysis.

Our upper estimate of carbon in trees killed by bark beetles (285 Tg C) is less than that from a recent outbreak of mountain pine beetle in British Columbia (471 Tg C; Kurz et al 2008) despite similar areas of mortality (Meddens et al 2012). Several factors may contribute to this. First, some of the outbreak in British Columbia occurred after the end of the Meddens et al study (2012), corresponding to an additional 30 Tg C. Second, 63% of the beetle-caused mortality in the western United States was in lodgepole pine, whereas 94% of the British Columbia mortality was in lodgepole pine. The remainder of the mortality in the United States occurred in lower-biomass forest types (23% lower biomass than US lodgepole pine stands). Third, lodgepole pine stands in British Columbia have higher biomass than those from the US; the mean aboveground biomass in lodgepole pine stands in the western United States (100 Mg ha$^{-1}$) (Blackard et al 2008) is about 66% of that of forests in the montane cordillera (interior) region of British Columbia (all forest types; 152 Mg ha$^{-1}$) (Penner et al 1997). Finally, some of the difference may be attributable to differences in methodology.

Previous studies have reported the amount of carbon associated with fires in the United States. Our results agree with those of Ghimire et al (2012), who used a combination of carbon cycle modeling and forest inventories for carbon and burned severities from MTBS. Their estimate of 10.5 Tg C year$^{-1}$ for carbon in killed trees is the same as our upper estimate, and good agreement occurs in the two
time series. The amount of tree carbon released by combustion during fires should be less than the total amount of carbon in trees killed by fires (reported in this study). Two studies report combustion emissions in the United States, although the reported estimates include carbon from combustion of components of forest ecosystems (e.g., litter) in addition to trees, making comparisons difficult. van der Werf et al. (2010) reported a mean combustion emission of 9 Tg C year⁻¹ during 1997–2009 for the conterminous United States, slightly less than our upper estimate of carbon in trees killed by fires, but for a larger region. Wiedinmyer and Neff (2007) reported that 29 Tg C year⁻¹ resulted from combustion emissions in the western United States in 2002–2006. This amount is higher than the total carbon in killed trees in our study, although the time period of the Wiedinmyer and Neff study (2007) was a period when large fires occurred and, as noted above, includes contributions from dead organic matter.

We produced a large range of estimated carbon impacts, and although we provide guidance about the most realistic beetle effect, each of the disturbance data sets has notable uncertainties. Bark beetle-caused tree mortality was recorded by trained observers in planes, suggesting uncertainty associated with this subjectivity. Although we reduced uncertainty by using colocated fine spatial resolution imagery to compute adjustment factors and produce a more realistic middle estimate, the large number of observers, their range in skills and experience, and variability in flying conditions imply that uncertainty in the number of killed trees remains. Field evaluations and consistent classification thresholds are also needed to translate spectral burn severity indices more accurately into fire-caused tree mortality.

Our study is a key first step toward quantifying impacts of these disturbances on the carbon cycle, and a more complete assessment should include additional components. We estimated the carbon in killed trees; this carbon is then shifted to dead carbon pools, which slowly decompose over decades, except for the combustion losses during fires (Kashian et al. 2006, Edburg et al. 2011). Additional studies are needed to estimate these carbon fluxes as well as regrowth. Killed trees no longer take up carbon from the atmosphere through photosynthesis, and decompose over several decades (Hicke et al. 2012). Based on observations and modeling, we expect that areas with substantial tree mortality will be carbon sources in the first decade or so following beetle attack or fire and become weaker carbon sinks for a long period (Amiro et al. 2010, Edburg et al. 2011). Effects on carbon fluxes are more challenging to estimate than effects on C stocks, in part because of the difficulty of observing or modeling fluxes over large regions. However, flux studies such as those by Ghimire et al. (2012), who investigated wildfires, are needed to better understand the full effect of disturbances on the carbon cycle. Furthermore, low-severity fires also modify forest carbon cycling and need to be included when considering a full accounting of the effects of fire.

5. Conclusions

We used spatially explicit maps of biomass, wildfires, and bark beetle-caused tree mortality to quantify how fire and beetle disturbances affect carbon in killed trees in the western United States in the past several decades. We found that during this time period, bark beetles resulted in more carbon in killed trees than wildfires, and that together, fires and beetles were associated with a similar amount of carbon in killed trees as harvesting. The period since 2000 has been subject to a particularly large area of tree mortality from fires and beetle outbreaks. Fires affected lower-elevation forest types more than higher-elevation forest types, whereas beetle outbreaks also affected upper montane and subalpine forest types.

Forest disturbances are also important in areas outside the western United States. The ready availability of spatially explicit databases facilitated our study of the western United States, yet such information is lacking or limited in other locations. Furthermore, a full assessment of the impacts of these disturbances on regional carbon cycling requires investigation of fluxes in addition to stocks. One means of doing so uses ecosystem models. Our results provide a comparison for these modeling studies.

Given expected continued warming, we anticipate that fires and beetle outbreaks will become more extensive and/or severe (Karl et al. 2009, Bentz et al. 2010). Because forest carbon cycling will continue to be substantively affected by these disturbance agents, fires and bark beetle outbreaks will continue to play major roles in the North American carbon budget (CCSP 2007).

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