



Has fire suppression increased the amount of carbon stored in western U.S. forests?

Aaron W. Fellows¹ and Michael L. Goulden¹

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[1] Active 20th century fire suppression in western US forests, and a resulting increase in stem density, is thought to account for a significant fraction of the North American carbon sink. We compared California forest inventories from the 1930s with inventories from the 1990s to quantify changes in aboveground biomass. Stem density in mid-montane conifer forests increased by 34%, while live aboveground carbon stocks decreased by 26%. Increased stem density reflected an increase in the number of small trees and a net loss of large trees. Large trees contain a disproportionate amount of carbon, and the loss of large trees accounts for the decline in biomass between surveys. 20th century fire suppression and increasing stand density may have decreased, rather than increased, the amount of aboveground carbon in western US forests. **Citation:** Fellows, A. W., and M. L. Goulden (2008), Has fire suppression increased the amount of carbon stored in western U.S. forests?, *Geophys. Res. Lett.*, 35, L12404, doi:10.1029/2008GL033965.

1. Introduction

[2] Active fire suppression since the early 20th century has caused a widespread increase in the stem density of Western US forests [Chang, 1996]. The abundance of fire intolerant tree species and smaller individuals has increased under a lengthened fire return interval, leading to more dense forests [McKelvey *et al.*, 1996]. Increased stand thickness has accelerated density dependant and pest-induced mortality [Smith *et al.*, 2005], and resulted in a shift from sparser forests, which are dominated by a few large trees, to denser forests, which are dominated by many small trees [Bouldin, 1999]. This trend is particularly pronounced in California's mid-elevation mixed conifer forest [Minnich *et al.*, 1995].

[3] The process of forest thickening is thought to result in the annual uptake of 2300 kg C/ha/yr, which corresponds to an overall sink of 0.052 Pg Carbon/year for the western US [Houghton *et al.*, 1999], or 8 to 17% of the apparent 0.3 to 0.6 Pg C/yr conterminous US sink [Houghton *et al.*, 1999; Houghton and Hackler, 2000; Houghton *et al.*, 2000; Pacala *et al.*, 2001; Goodale *et al.*, 2002]. However, the magnitude of the thickening-induced sink is highly uncertain, since it is derived from only a few modeling [Keane *et al.*, 1990; Covington and Moore, 1994; Hurtt *et al.*, 2002] and observational [Tilman *et al.*, 2000] studies. A carbon sink associated with thickening is intuitively appealing; increasing stem density must store more carbon in above-

ground biomass if all trees are equivalent. But the systematic loss of large trees, which contain a disproportionate amount of carbon, requires a detailed consideration of the associated demographic shifts.

[4] We compared forest inventory observations from the 1930s that were made in California by the Wieslander Vegetation Type Mapping (VTM) project [Minnich *et al.*, 1995; Wieslander, 1935] with observations from the 1990s made by the Forest Inventory Analysis (FIA) [Waddell and Hiserote, 2005]. Our goals were to characterize the demographic shifts in California forest over the 60-year period and to quantify the change in carbon stored in aboveground live biomass with thickening.

2. Methods

[5] 269 VTM plots were compared with 260 FIA plots from spatially overlapping, legally designated wilderness areas in California to determine how stem density and aboveground biomass changed from the 1930s to 1990s. We obtained VTM data from the Wieslander Vegetation Type Mapping Project at the University of California, Berkeley (vtm.berkeley.edu) and FIA data from the United States Forest Service (<http://fia.fs.fed.us/>).

[6] The plots measured during the two surveys were not collocated, and, in many cases, it has proven difficult to identify the precise location of the original VTM plots [Keeley, 2004]. We therefore compared large samples of plots from the two studies. Designated wilderness is generally inaccessible and not logged, which reduces the likelihood of confounding changes in forest structure caused by active management. The selected plots spanned much of California, and covered large ranges of elevation, mean annual precipitation (MAP), forest type, and fire regime.

[7] The VTM recorded the number of trees by species in four size classes within 0.08 ha plots during 1929 to 1934 (10–30 cm, 30–61cm, 61–91 cm, and >91cm). The FIA recorded tree diameter by species within multiple fixed and variable radius plots during 1990 to 1994. We homogenized the methods by correcting the area of the VTM plots for topography to match the FIA methods, using the recorded slope and simple trigonometric functions. Differences in plot selection criteria between the VTM and FIA required us to omit plots with no trees from the analysis [Bouldin, 1999]. We degraded the FIA DBH information by binning individuals into VTM size classes.

[8] The estimation of biomass from stem counts requires information on the average biomass for each species and size bin. The VTM resolution did not allow us to accurately determine the biomass for each bin. We therefore used the average biomass determined from the FIA data and applied it to both the VTM and FIA species and size bins. The

¹Department of Earth System Science, University of California, Irvine, California, USA.

average biomass for each bin was determined by extrapolating the DBH of each reserved tree in the FIA to aboveground biomass using aggregated allometric equations and then averaging over the species and size bin [Jenkins *et al.*, 2003]. Reserved trees are in forests that are closed to harvest, which include plots both inside and outside of our analysis areas. For groupings with <30 trees, average biomass was determined from both reserved and non-reserved forests or, in limited cases, from a congener with similar biomass characteristics. Giant Sequoia, *Sequoiadendron giganteum*, average biomass was determined from reserved areas despite having fewer than 30 trees because this value was within the range of other species. We converted biomass to carbon using 0.45 g C/g biomass.

[9] Historical accounts indicate that early 1900's forests contained larger trees than contemporary forests [Bouldin, 1999]. Our reliance on the FIA dataset to determine the average biomass for each bin provides a conservative estimate of VTM biomass. Aggregated allometric equations often reduce the errors associated with variations in geographic range, species composition, and size distribution, but may lead to errors of as much as 30%, when compared to site-specific allometric equations [Jenkins *et al.*, 2003]. These types of error may have impacted the accuracy of our biomass estimates, but would not be expected to affect the comparison between data sets.

[10] Changes in stem density and carbon content between the surveys were compared as a function of elevation, precipitation, forest type, and geographic location. The forest type for each plot was identified using the GAP LANDCOV spatial dataset [Davis *et al.*, 1998]. Plot elevation and MAP were determined using spatial data sets from the California Spatial Library (<http://old.casil.ucdavis.edu/gis.ca.gov/dem/> and http://casil-mirror1.ceres.ca.gov/casil/etc/catalog/104_286.html).

[11] Data were square root transformed and tested for normality using a Kolmogorov-Smirnov test. Data were normally or near normally distributed after transformation. A two-sample t-test assuming unequal variance was used to determine statistical difference. Reported means are back transformed means of the square root transformed data.

3. Results

[12] The stem density averaged across all plots increased by an insignificant 4% from the 1930s to the 1990s (Table 1). By contrast, the live aboveground carbon stocks declined by a highly significant 34%, which corresponds to an average loss of ~0.7 Mg C/ha/year between surveys (Table 1; $p < 0.001$).

[13] The changes in density and biomass varied with forest type (Table 1). Middle elevation plots (914 to 2438 m) showed the greatest increases in stem density and decreases in aboveground biomass. Higher elevation plots had a constant stem density and a more modest decline in biomass. Lower elevation plots showed declines in both stem density and biomass. Changes in structure also depended on precipitation. Conifer plots receiving a MAP of at least 114 cm thickened ($p = 0.01$), whereas plots receiving a MAP of less than 114 cm showed no change in stem density. Geographical regions exhibited contrasting

trends. Plots pooled from Northern California and the Sierra Nevada Mountains showed a significant increase in stem density and a significant loss of carbon, whereas plots pooled from Southern California, the Ventana wilderness, and Transverse range showed an insignificant thinning and a highly significant loss of carbon.

[14] The trend towards increasing tree density and decreasing biomass was especially pronounced within wet ($> = 114$ cm MAP) conifer (Ponderosa Pine, Jeffrey Pine, Sierra Mixed conifer, White Fir, Mixed Hardwood Conifer forests, Subalpine conifer, and Red Fir) forests (Table 1; Figure 1). The stem density in these forests increased by 38%, while the aboveground biomass decreased by 29%. The size structure of these forests changed markedly over time. The increase in stem density was driven entirely by smaller trees. Increases in 10–30 cm DBH trees ($p < 0.001$) and 30–61 cm DBH trees ($p = 0.02$) led to an increase of 119 stems/ha and a gain of ~17 MgC/ha in aboveground biomass. At the same time, declines in 61–90 cm DBH trees ($p = 0.001$) and >90 cm DBH trees ($p = 0.007$) led to a decrease of 29 stems/ha and a loss of 64 MgC/ha. The loss of carbon from large trees outweighed the gain in small trees, resulting in an overall loss of carbon in aboveground biomass.

4. Discussion

4.1. Patterns of Forest Density and Biomass

[15] The increases in stand density we observed are consistent with the patterns of forest thickening that have been reported in previous studies. We observed the greatest increases in stem density in mid-elevation conifer forests, where fire suppression is believed to have altered historic fire regimes the most. Previous studies have also reported that thickening has been greatest at mid elevation [c.f., Bouldin, 1999; Minnich *et al.*, 1995]. Higher elevation forests showed a negligible amount of thickening (Table 1), a pattern that is generally attributed to a longer natural fire return interval and a reduced impact of fire suppression [Chang, 1996]. Previous studies have shown that the increase in stem density is driven almost entirely by an increase in the smaller classes, and that the abundance of larger trees has decreased [c.f., Bouldin, 1999; Minnich *et al.*, 1995]. Bouldin [1999] and Minnich *et al.* [1995] reported somewhat greater rates of stand density increases than we found. This discrepancy may arise from our focus on wilderness. Some of the plots analyzed by Bouldin [1999] may have been logged, which would be expected to result in a greater increased density of small trees.

[16] We observed thinning in low elevation forests ($p = 0.05$). This thinning was driven by a reduction in smaller (<61 cm) trees ($p = 0.07$) and the retention of larger trees. These patterns may indicate a lack of recruitment in low elevation forests. Several reports indicate that regeneration of California oaks is currently poor, especially at low elevations, on sites with a southern aspect or thin soil, and in areas that have a low MAP [Standiford *et al.*, 1996].

[17] Fire suppression leads to an accumulation of carbon in Coarse Woody Debris (CWD) and the forest floor [McKelvey *et al.*, 1996]. Using expansion factors embedded in the FIA database indicates that California's reserved forests contained 17 ± 1 Mg C/ha (standard error) of

Table 1. Stand Density and Carbon Stored in Aboveground Live Biomass for Various Categories^a

| Category | Stand Density (Stems ha ⁻¹) | | | | Carbon in Biomass (Mg ha ⁻¹) | | | | Count | |
|-------------------------------|---|-----|-----|-------|--|-----|-----|--------|--------|---------|
| | VTM | FIA | % | p | VTM | FIA | % | p | n(VTM) | n (FIA) |
| Elevation (m) | | | | | | | | | | |
| 0–914 | 281 | 181 | –36 | 0.05 | 97 | 73 | –25 | 0.26 | 39 | 26 |
| 914–2438 | 204 | 242 | 19 | 0.10 | 126 | 77 | –39 | <0.001 | 151 | 180 |
| >2438 | 231 | 233 | 1 | 0.96 | 123 | 89 | –28 | 0.04 | 79 | 54 |
| All | 223 | 233 | 4 | 0.54 | 120 | 79 | –34 | <0.001 | 269 | 260 |
| Forest type | | | | | | | | | | |
| mid-montane conifer | 195 | 261 | 34 | 0.07 | 118 | 87 | –26 | 0.10 | 53 | 77 |
| upper-montane conifer | 240 | 254 | 6 | 0.72 | 172 | 122 | –29 | 0.03 | 76 | 44 |
| Precipitation in conifer (cm) | | | | | | | | | | |
| 1–114 | 226 | 194 | –14 | 0.45 | 97 | 68 | –30 | 0.14 | 35 | 46 |
| ≥114 | 219 | 302 | 38 | 0.013 | 171 | 121 | –29 | 0.01 | 94 | 75 |
| Geographic region | | | | | | | | | | |
| NorCa/Sierra | 206 | 269 | 31 | 0.008 | 138 | 100 | –28 | 0.004 | 154 | 140 |
| SoCa/Tr/Vent | 245 | 195 | –20 | 0.06 | 99 | 53 | –46 | <0.001 | 115 | 120 |

^aVTM gives mean values for 1929–1934 forests for the region studied. FIA gives mean values for the 1990–1994 forests for the region studied. p gives p-value for significance of change between VTM and FIA surveys. Mid-montane conifer forests include Sierra mixed conifer, ponderosa pine, Jeffrey pine, white fir, and mixed conifer-hardwood forests in the GAP dataset. Upper-montane forests include subalpine conifer and red fir forests in the GAP dataset. Precipitation in conifer (cm) includes plots from both upper and mid-montane conifer forest that receive mean annual precipitation amounts <114 cm and ≥114 cm. NorCa/Sierra are plots from northern California and the Sierra Nevada Range. SoCa/Tr/Vent are plots from Southern California, Transverse Range, and the Ventana wilderness.

CWD and standing dead trees. This is less than the 41 Mg C/ha lost from aboveground biomass implying that much of the carbon lost from aboveground biomass has already decayed.

[18] Previous analyses indicate that California's forests sequestered carbon during 1990 to 2002 and that this uptake was greatest where past management caused forest regrowth [Bemis and Allen, 2005]. Our findings neither confirm nor contradict these results. We focused on wilderness areas, where active management did not occur. Moreover, Bemis and Allen [2005] examined forest changes over 12 years during the 1990s, whereas we integrated changes in Californian forest from the 1930s to 1990s.

4.2. Mechanism Accounting for Biomass Loss With Thickening

[19] The forest thickening we observed did not result in a large increase in aboveground biomass, as has been assumed [Houghton et al., 1999]. The relationship between DBH and biomass is markedly non-linear [Jenkins et al., 2003]. A single large tree (>90 cm) contains the same amount of carbon as 60 small (10–30 cm) trees. Trees <61 cm DBH accounted for nearly 85% of the total stems across all surveys, but just 33% of the biomass. We found that thickening was largely driven by an increase in small trees, which stored a small amount of carbon. Thickened forests also showed a reduction in the number of large trees, which stored a large amount of carbon. The loss of carbon from the reduction in large trees outweighed the gain in carbon from the increase in small trees and resulted in an overall loss of aboveground biomass.

[20] Trees in denser forests face greater competition for water and other resources. Ponderosa pines in high-density stands have lower xylem water potentials and rates of photosynthesis, indicating greater drought stress [Kolb et al., 1998]. These trees also have decreased resin production and foliar toughness, suggesting an increased susceptibility to insect and pathogen attack [Kolb et al., 1998]. Western conifer forests undergo periodic drought associated with climatic cycles such as the Pacific Decadal Oscillation [Swetnam and Betancourt, 1998]. Trees that are growing

in denser stands are thought to be especially vulnerable to attack or mortality during dry periods [Kolb et al., 1998; Smith et al., 2005].

[21] Large trees may be particularly prone to mortality under these conditions [Smith et al., 2005]. Some bark beetles prefer large trees, which have a thicker phloem (Cole and Amman, 1969; but see Kolb et al., 2006). Large

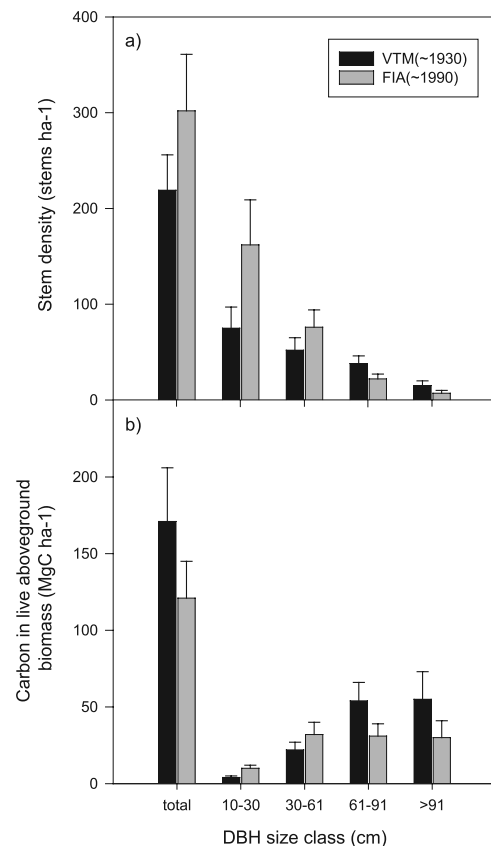


Figure 1. Mean and 95% confidence intervals for (a) tree density and (b) carbon stored in live aboveground biomass for conifer forests receiving ≥ 114 cm mean annual precipitation.

trees may have increased vulnerability to cavitation during drought, either because their leaves are higher off the ground or because restrictions in the xylem cause more negative xylem water potential compared with small trees [Hubbard *et al.*, 1999]. Large trees may be more exposed to wind and radiation than small trees, further increasing drought stress. Large trees may have higher respiration costs associated with greater biomass (Makela and Valentine, 2001; but see Ryan and Waring, 1992). Finally, large trees are often approaching the end of their natural lifespan [Day *et al.*, 2001].

[22] The effect of thickening on stand structure in California's conifer forests appears simple, direct, and strong. Fire suppression increases the density, and, probably, the leaf area, of forest. The trees in denser forests are exposed to greater stress during periodic extreme drought. Large trees are more likely to suffer mortality than small trees. Fire suppression leads over time to a forest with more small trees and fewer large trees. Large trees contain a disproportionate amount of biomass. Fire suppression in California's conifer forests therefore leads to an increase in stand density and a decrease in aboveground biomass due to a loss of large trees. This loss of carbon from aboveground biomass in thickened stands conflicts with the assumption that forest thickening in western forests has led to a significant carbon sink in North America, and underscores the importance of demography as a controller of forest carbon balance.

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A. W. Fellows and M. L. Goulden, Department of Earth System Science, University of California, Irvine, CA 92697-3100, USA. (afellows@uci.edu)