Modeled and Actual Impacts of Fire Management on Carbon Sequestration and Greenhouse Gas Emissions in Yosemite National Park

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Introduction

Humans dominate, or substantially influence, a growing number of processes that underpin cycling of both carbon and nitrogen at regional to global scales (Vitousek et al. 1997; IPCC 2007). Some effort in recent years has been spent on exploring the potential of forests to "sequester" more carbon, and potentially offset emissions in a carbon trading market. In the National Park Service, quantifying carbon has largely been an academic exercise, because park management was thought to have little need or opportunity to manipulate how much carbon could be stored on park landscapes. In fact, research shows that there is little guarantee that forests not actively cultivated for optimized carbon sequestration will be able to accumulate any more carbon than what they already hold (Mitchell et al. 2009).

On the other hand, recent research has shown that fire management may exert a significant influence over these cycles by changing (or not changing) forest stand structure, composition, and/or forest successional pathways (Hurteau et al. 2008). Yosemite's fire management program has long been on the forefront of managing fire on its landscapes, employing science-based fire prescriptions for over 30 years on some parts of the landscape to "reintroduce" landscapes to more "natural" fire regimes. Yosemite has built some of the most comprehensive and spatially extensive databases documenting vegetation type, fuel bed characteristics, fire behavior, effects, and severity in the country (van Wagtendonk et al. 2002). More recent work has formalized protocols that leverage these datasets as input for fire models that can be used in scenarios quantifying the impact of different fire management actions (or inactions) on forest landscapes (Miller and Davis 2009).

The objective of this analysis was to assess the potential versus actual impact of alternative versus current fire management policies (respectively) on the amount of aboveground biomass and carbon stored on Yosemite's landscape.

Approach and methods

Spatial and temporal extent. This analysis focuses on the south fork of the Merced River watershed (Figure 1) at a spatial resolution of 30 m. Temporally, this analysis accounts for the impacts of fire and successional (e.g., fuel accumulation and stand structure; Davis et al., forthcoming) processes at 1-year time-steps for the period 1994–2004. Each pixel was

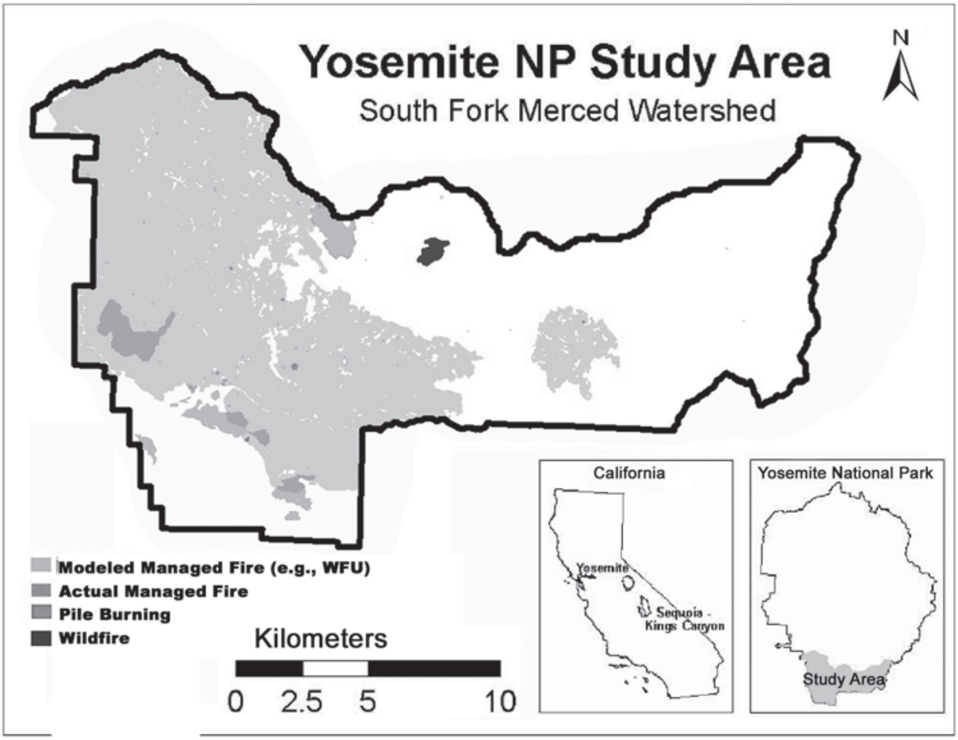


Figure 1. Spatial extent of analysis within the South Fork Merced Study Area. Only biomass from pixels in shaded areas (13,308 ha), where fire actually occurred or where it was modeled to have occurred (1994-2004), were included in this analysis.

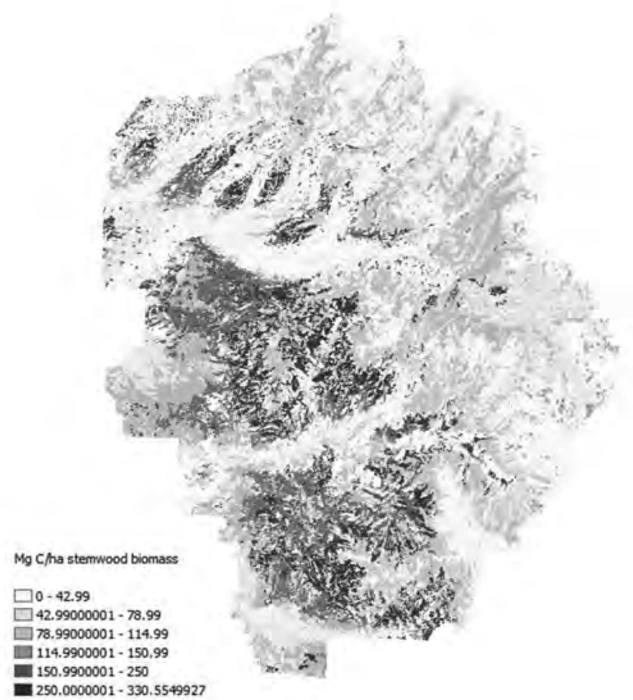
assigned a spatial fuel model (Scott and Burgan 2005), and fire spread for each suppressed lightning ignition was modeled in FARSITE (Finney 1998), using these fuel characteristics, combined with historical meteorological data from the closest available meteorological stations (Miller and Davis 2009). FARSITE is a fire modeling tool that uses spatial information on topography and fuels, along with weather and wind data to simulate wildfire behavior and spread. The specific techniques and inputs for this retrospective FARSITE modeling are detailed by Davis and Miller (in preparation). The resulting perimeters of these modeled fires define the spatial extent of this analysis (Figure 1); pixels outside these perimeters were excluded from the analysis.

Fuels and biomass quantification. In each 30 m x 30 m pixel, and at each annual time step, this analysis quantified the impact of any fire on each of five layers of biomass (duff, coarse woody debris, surface fuels, canopy fuels, and stemwood biomass). Duff and coarse woody debris were estimated in collaboration with Yosemite fire managers and fire ecologists by combining plot-level fuels measurements in the study area, and assuming those values represented the relevant vegetation type. A combination of aerial photography, plot data and expert opinion were used to create the surface and canopy fuel layers (T. Caprio, pers. com.). Succession models were used to estimate fuel consumption and the subsequent re-accumulation of surface fuels (Davis, forthcoming), but duff and coarse wood debris accumulation were not explicitly treated. Fire severity maps were used to adjust the five biomass layers in each of the 11 years.

In a separate exercise, stemwood biomass (Figure 2) was quantified using a set of over 200 1/10 hectare (ha) plots in which diameter at breast height (DBH) was measured for every tree over 3 cm DBH. The biomass in each of the major conifer species was calculated using allometric equations (Means et al. 1994). Where possible, equations represented data collected in the Sierra Nevada (e.g., *Abies* spp., *Pinus* spp.), however some data from other regions (e.g., Pacific Northwest Cascade range and the Rocky Mountains) were used for some species. To avoid overestimating biomass, trees with DBHs under the range given for each equation were not counted, and trees with DBHs that exceeded the upper end of the range were assumed to have the biomass corresponding to that upper end value and no higher. Plot biomass totals were summed and assigned to a vegetation type, both by using the 1997 Yosemite vegetation map, and by checking these values against plot-based vegetation types reported in plot notation. The average of all plots in a given vegetation type was taken as its representative value, and applied via lookup table to the Yosemite vegetation map (AIS 1997).

Variability for these preliminary stemwood biomass carbon estimates was high (relative standard deviations 50% or more), and differences between vegetation types were not necessarily statistically significant. Nonetheless, the calculated stemwood biomass values match

Figure 2. Distribution of biomass C in Yosemite. Only pixels in the 13,308 ha analysis area shown in Figure 1 were used for the purpose of this analysis.



anecdotal observations of the relative amount of biomass in these layers for the different vegetation types (M. Beasley, pers. comm.), and fall within the range and the general spatial pattern exhibited by satellite-based above-ground carbon estimates (Potter 2009; NASA).

Fire severity scenarios and biomass reduction assumptions: Fire severity estimates were the key to estimating the impact of fire on biomass. Three severity classes were used, corresponding to the effects detectible from satellite relativized normalized burn ratio (rdNBR) measurements (Miller and Thode 2007). Under this remote sensing scheme, (1) low severity corresponded to no detectable canopy reductions, (2) medium severity corresponded to some isolated torching and canopy scorch, and (3) high severity corresponded to a completely blackened canopy, indicative of nearly complete tree mortality. For the purposes of this exercise, any stemwood from a tree that was killed was assumed to be an immediate emission to the atmosphere, even though some fraction of those emissions would be the result of a more long term decay process rather than immediate combustion by fire.

Severity was calculated as a raster map in each of the 11 years of analysis, for each of three scenarios: (1) actual fire, (2) modeled fire, and (3) maximum severity fire. The same analysis that underpinned the FARSITE fire spread modeling also gave rise to these annual scenario-based severity maps. The "actual fire" scenario included all fires that actually occurred, including natural wildland fires and prescribed fires (Figure 1). The "modeled" scenario included all the above fires, plus those fires started by historically documented, suppressed lightning ignitions and modeled out to the end of the fire season. The maximum severity scenario was a one-year event that was applied in 1994. For this scenario, the maximum severity possible for each pixels fuel model was applied as a way to estimate the maximum amount of biomass reduction that could possibly be attributed to fire. Assumptions for specific consumption percentages under each of these severity classes for coarse woody debris, canopy fuels, and duff layers were based on composite burn index (CBI) values (Key and Benson 2004). In stepwise fashion, each year's fire and its associated severity were applied to each pixel, one year at a time. When the final 2004 value was reached, the five biomass layers were summed and total losses could be estimated by comparing to the 1994 totals.

Results and discussion

The resulting spatial patterns of relative carbon losses at the pixel scale (Figure 3) represent the total losses from all five biomass layers over the period 1994-2004. To show the overall effect of fire at the landscape scale, sums of the amount of biomass in each pixel over the 13,308 ha analysis area before and after each of the three scenarios are given in Figure 4.

Overall, these results showed that business as usual, as represented by the "actual fires" scenario, had little to no effect on the total amount of biomass on the landscape: they burned only 809 ha out of the 14,480 ha analysis area, releasing only .04 million metric tons carbon (MMTC) and allowing 99% of biomass of carbon to remain after the 11-year study period. Much more burned under the "modeled" fire scenario, releasing an order of magnitude more biomass of carbon (0.32 vs. 0.02 MMTC). Even though the entire 13,308 ha area of analysis burned, only 14% of the total amount of biomass on the landscape (0.32 out of 2.67 MMTC) was released to the atmosphere. Most of that 14% appears to have come from the

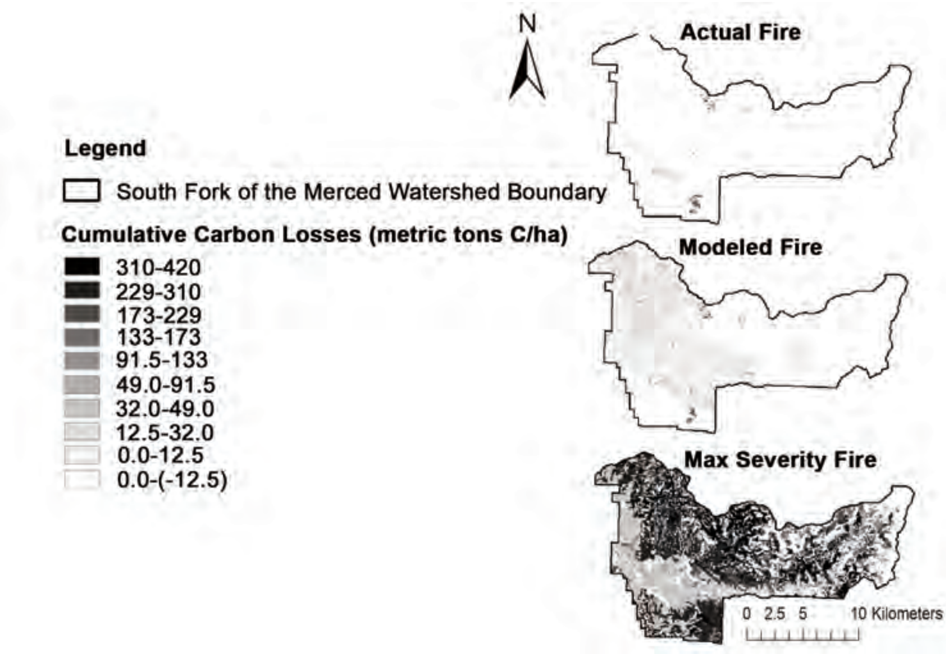


Figure 3. Actual, modeled, and maximum severity carbon losses or gains (metric tons C per ha, gains are displayed as negative values) due to fire in the South Fork of the Merced River (1994–2005).

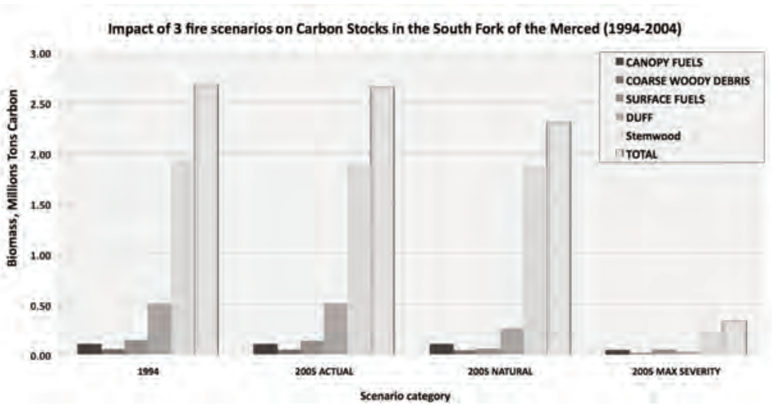


Figure 4. Sums for total C in all five biomass categories over the analysis area (13,308 ha) compared to 1994 values for three fire management scenarios. Total C drops only 14% after the natural fire, illustrating how resistant stemwood biomass, which is the bulk of this carbon sink, can be to natural fire regimes.

duff, coarse woody debris, and surface fuels layers, while canopy fuels and stemwood biomass stocks remained relatively intact (Figure 4). Some areas of high severity were seen in the modeled scenario and these could potentially have consumed that stemwood, but they did not represent enough of the landscape to reduce overall biomass substantially. Only the maximum severity fire scenario, which also burned every pixel of the 13,308 ha analysis area, but at the highest possible severity, substantially impacted the stemwood biomass, leaving only 12% (0.33 MMTC) of the landscape carbon stock intact, and releasing over 2.4 MMTC.

While these fluxes are relatively small as a percentage of the total carbon stock on the entire (~300,000 ha) park landscape (60 MMTC, just counting the stemwood), they are still very large relative to other fluxes in the Yosemite emission inventory. Net ecosystem productivity alone, at a relatively slow rate of 1 metric ton per ha per yr and taken over the entire park (approximately 300,000 ha), produces over 0.3 MMTC of losses, largely due to warming soils respiring more carbon than the photosynthesizing biomass fixes (Potter 2009; NASA). While some of these landscape and biomass based "leaks" might be recovered in subsequent, cooler years, or in less active fire years, projected net warming trends increase the probability that a substantial fraction of carbon losses from these landscapes will be "permanent" on the decadal, centennial, even millennial scales (Solomon et al. 2008).

These stocks are also much larger than even the largest fires that California has experienced. For example, a large 235,267 ha fire event in 2003 in southern California resulted approximately 2 MMTC (Potter et al. 2003). At the other end of the scale, the rest of Yosemite's greenhouse gas emission inventory (e.g., non-fire sources like mobile source emissions, heating, waste treatment) totals at most 0.02 MMTCE (Tarnay, unpublished data). The large size of this stock notwithstanding, it is not invulnerable to fire: if the above large, high severity fires become more frequent on the Yosemite landscape as the Western United States warms (Westerling et al. 2006), they have the potential to substantially reduce Yosemite carbon stocks, and dramatically increase greenhouse gas emissions. If the forests cannot regenerate fully enough to replace those big trees, these emissions and stock reductions have the potential to be permanent.

Conclusion

The sheer magnitude of Yosemite's forest carbon stocks, and the fire-driven emissions from it, have the potential to dwarf other sectors of the Yosemite greenhouse gas emissions inventory. Protecting Yosemite forests and the carbon they contain from uncharacteristically high severity fire is thus not only an ecological priority; it is a priority for minimizing greenhouse gas emissions. Our scenario-based analysis suggests that suppressing most fires (i.e., our "actual" scenario) does not necessarily protect the carbon stored in Yosemite forests. Rather, the key to protecting that carbon sink lies in preventing large tracts of high severity fire effects over the landscape. Modeled, naturally ignited fire, even though it burned 100% of the analyzed area, only released 14% of its biomass to the atmosphere, primarily because stemwood in fire adapted ecosystems is resistant to all but the most extreme fire conditions. To the extent that it can prevent uncharacteristic fire behavior by using these natural ignitions to remove understory vegetation and ladder fuels (but not the stemwood), fire management may be one of the few landscape-level tools for minimizing the potentially huge greenhouse gas emissions from our warming, fire-dependant forest ecosystems.

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