Mara St. Amant - R-2: Methods Revision
Wildfire Fuel Treatments and Long-Term Carbon Storage in CA Forests

Summary

The central research question of this study is if fuel-reduction treatments can increase long-term net carbon storage by mitigating wildfire in California mixed conifer forest (MCF). More specifically, I aim to answer the following subquestions: (1) How do repeated fuel treatments (mechanical thinning, and/or prescribed fire) directly affect aboveground carbon stocks over time? (2) How do repeated fuel treatments (mechanical thinning, and/or prescribed fire) affect predicted aboveground carbon stocks following modeled high-severity wildfire? (3) How does the probability of wildfire affect net aboveground carbon stocks of treated forests? To assess these questions, my data collection objective will be to collect primary data (tree, fuels, and understory data) from the Fire and Fire Surrogate (FFS) Study of Blodgett Research Forest. I will also use this primary data to produce secondary modeled data using Forest Vegetation Simulator (Fire and Fuels Extension).

Study Site

Blodgett Forest Research Station (BFRS) is located near Georgetown, CA, USA (38°54045″ N; 120°39027″ W), between 1100 and 1410 meters of elevation. The soils are primarily sandy loam, composed mainly of Ultic Haploxeralfs (Alfisols), which are well developed, well draining, and highly productive. Slopes are generally less than 30%. The local climate is Mediterranean, experiencing long warm-dry seasons and cool-wet winters. Precipitation is experienced mainly in winter and spring, at 160 cm/year on average, and temperatures range from 0-8° C in winter, and 10-29° C in summer. The species composition is generic mixed conifer forest (MCF), including (but not limited to) *Abies concolor, Calocedrus decurrens, Pinus lambertiana, Pinus ponderosa, Pseudotsuga menziesii,* and *Quercus kelloggii.* The historical (pre-colonial) disturbance regime of the area was one of frequent low-to-moderate severity wildfires with mean fire return intervals of 8-25 years. The recent disturbance regime includes intensive logging in the early 1900s, and decades of effective fire suppression. The forest structure is consistent with California MCF with this altered disturbance regime: moderate to high canopy cover, heavy fuel loads, high density with more small trees and fewer large trees, and species composition shifting away from fire-resistant species (pines) toward less fire-resistant species (firs).

Treatments

The FFS study at BFRS includes 12 similar experimental units (compartments), which were randomly assigned one of four treatments (3 compartments per treatment): control, mechanical-only, burn-only, or mechanical and burn. The similarity of compartments was confirmed by pre-treatment measurements, and initial treatments were installed in late 2001 and 2002 (Stephen & Moghaddas 2005). The objective of the treatment design was to reduce fire severity using management practices common in northern Sierra Nevada forests (Agee and Skinner 2005, Schwilk et al. 2009).

Control compartments (40, 240, 590) were left unmanaged for the duration of the study period. Mechanical-only compartments (190, 350, 490) were commercially harvested using crown thinning (removing larger merchantable trees) followed by a thinning from below (thinning trees below a threshold diameter) between summer 2001 and summer 2003. The goal of these thinning treatments in the mechanical-only compartments was a target mean basal area of 28-32 m^2/hectare, which is slightly more than half of pre-treatment mean basal area of all compartments (53 m^2/hectare). Following the harvest, small trees with diameter at breast height (DBH, breast height = 1.37m) less than 25 cm were masticated. Mastication occurred following the initial harvest between 2001 and 2003, and new small trees with DBH < 25 cm were masticated again between spring 2017 and spring 2018. Residual activity fuels (tree foliage, limbs, and tops) from the initial harvest, masticated material, and residual small trees were distributed throughout the compartments in ~0.04-hectare clumps.

Burn-only compartments (60, 340, 400) were treated with prescribed fires in October/November of 2002, 2009, and 2017 with prescription objectives of reducing surface and ladder fuel loads, while limiting mortality to ≤10% of trees larger than 46 cm DBH. Fire weather conditions were similar for both burns, and are detailed in Kobziar et al. 2006. Fire behavior in all 6 burns (all 3 compartments, both years) consisted of lower than 2 meter flame lengths and occasional torching of live trees.

The mechanical and burn compartments (180, 380, 570) were treated using a combination of the two treatments detailed above. They received the same mechanical treatments as the mechanical-only compartments, then the residual fuels were broadcast burned using the same prescription as the burn-only compartments, except they were not reburned in 2009 (they were burned only once in 2002). The surface fuels in the mechanical and burn compartments were mainly masticated chips and residual materials from the mechanical treatment, which had cured for a season before being burned, resulting in a longer burn than in the burn-only compartments.

Field Measurements

Field measurements of all treatment compartments were taken by field crews in permanent 0.04 hectare plots in the summers of 2001, 2003, 2009, 2016, and 2020 as pre-treatment, 1-, 7-, 14-, and 18-year post-treatment measurements, respectively. Twenty circular plots were established within a 10 hectare core area of each compartment (to reduce edge effects), in a regular 60 meter grid formation. Tree species, DBH, height to crown base, and total height were measured and recorded for all trees ≥11.4 cm DBH within each plot. DBH and total height were measured and recorded for all standing dead trees (snags) ≥20.5 cm DBH. Data on snag limb condition, wood hardness, bark coverage, and estimated years since death were recorded in 2016 to determine a live:dead carbon ratio for snags.

Fuels data were measured and collected using Brown's line-intercept method (Brown 1974) on two 11.43 meter transects per 0.04 hectare plot. For each transect, litter and duff depths were measured at two fixed locations. Additionally, 1 hour (0-0.64 cm), 10 hour (0.64-2.54 cm), and 100 hour (2.54-7.62 cm) woody fuel particles that intersected with the transect were tallied along 1.83, 1.83 and 3.05 meter sub-transects, respectively. Diameter and decay class of all 1000 hour fuels (≥7.62 cm) that intersected with either transect were measured and recorded.

Ocular estimates of percent cover of understory vegetation was recorded for each plot by species, and binned into classes of <5%, 5–25%, and 25–100%, which were interpreted as 2.5%, 15%, and 63%, respectively. The species included were the following understory species common in BFRS: *Arctostaphylos spp., Ceanothus spp., Chamaebatia foliosa, Chrysolepis spp., Notholithocarpus densiflorus, Ribes roezlii, Rosa gymnocarpa,* and *Symphorocarpus mollis.*

Data Analyses

Table 1 - Abbreviations

Abbreviation	Term	Meaning
AFC	Aboveground Forest Carbon	Carbon in aboveground live and dead biomass (trees, understory, and fuels)
LTC	Live Tree Carbon	Carbon in aboveground stem, bark, and branches of live trees
SLTC	Stable Live Tree Carbon	Carbon in trees predicted to survive a wildfire
ELTC	Expected Live Tree Carbon	Mean of LTC and SLTC, weighted by wildfire probability
~~TAC~~	~~Total Aboveground Carbon~~	~~Carbon in aboveground live biomass, dead biomass, and offsite forest products~~
~~ETAC~~	~~Expected Total Aboveground Carbon~~	~~Mean of pre-fire TAC and post-fire TAC, weighted by wildfire probability~~

Observed Carbon Stocks

To calculate aboveground live tree biomass, BFRS researchers used regional biomass equations used by the Forest Inventory and Analysis (FIA) program. These equations use tree measurements (species, DBH, and height) to estimate each tree's cubic volume, and use species-specific wood density to estimate biomass of the entire tree stem. Aboveground live tree biomass is the sum of stem, branch, and bark biomass, and separate allometric equations were used to calculate branch and bark biomass.

To calculate snag biomass, the same equations (stem only) were used and adjusted using a live:dead biomass ratio of 0.88, based on the findings of Cousins et al. (2015). Plot-level biomass, in units of Megagrams per hectare (Mg/ha), was estimated as a sum of individual tree/snag biomass scaled by plot size. Conversion of biomass estimates to carbon content was accomplished by assuming a ratio of 0.48 Megagrams of carbon (MgC) per Mg biomass for live trees, and 0.5145 MgC per Mg biomass for snags, consistent with established literature (IPCC 2003, Cousins et al. 2015, Dore et al. 2016).

Understory carbon stocks were determined using observed percent-cover data and biomass equations from McGinnis et al. (2010). The number of average-sized individuals per species populating each plot was estimated from field data and multiplied by their species-specific per-individual biomass to estimate total observed biomass per species. These estimates were summed and scaled by plot size to determine understory biomass per hectare, then converted to MgC per hectare (MgC/ha) using a carbon density ratio of 0.49 (Chojnacky and Milton 2008).

Fuel loads were estimated from transect data using Sierra nevada-specific equations and species-specific coefficients (Van Wagtendonk et al 1998). For each plot, the species-specific coefficient used was determined as an average of coefficients of all species measured in the plot, weighted by species' basal area as a proportion of total plot basal area (Stephens 2001).

Plot-level fuel load estimates were calculated as an average of both transect-level estimates of total fuel load, and were converted to MgC/ha using a 50% carbon concentration for coarse (1000-hour fuels) and fine woody fuels (1-100 hour fuels) and 37% for litter and duff (IPCC 2003, Stephens et al. 2012). For analysis, I categorized fuel loads as coarse woody fuels (1000-hour fuels), fine woody fuels (litter and 1-100 hour fuels), and duff. I defined Aboveground Forest Carbon (AFC) as the sum of carbon stocks in live trees, snags, understory vegetation, coarse woody debris, fine woody fuels, and duff.

Wildfire Modelling and Carbon Stability

To assess the treatments' effect on carbon fluxes associated with wildfire, I modeled potential wildfire behavior for each plot in each observed year with the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (Reinhardt et al. 2003). Fire behavior and crown fire potential are modeled by FFE using established equations, and user-input tree data and real fire weather conditions from nearby wildfires, such as the 2013 American Fire and the 2014 King Fire. I assigned surface fuel models based on compartment characteristics, and ran both low and high fuel models to capture the uncertainty associated with surface fuel model assignment. The reported fire behavior for each plot was the average of the low and high surface fuel model runs.

My analysis focused on the predicted mortality output (PMORT) from FFE, representing the percentage of plot basal area predicted to die within the first three years following the modeled wildfire. This metric incorporates both immediate and delayed mortality factors, using crown length, diameter, tree species, and predicted scorch height. FFE's estimates of mortality rely on empirical relationships (Reinhardt and Ryan 1988) adjusted by coefficients specific to tree species of the Western Sierras. I defined Stable Live Tree Carbon (SLTC) as the total Live Tree Carbon (LTC) expected to remain at least 3 years following a wildfire (note that this does not include the carbon stored in fire-killed snags, making it an underestimation of the total stable carbon stored in trees following a wildfire). I calculated SLTC as

(1) $SLTC = LTC \times (1 - PMORT)$.

Expected Carbon Stocks

To assess the expected carbon stocks considering direct treatment effects, wildfire-contingent treatment effects, and the probability of treated stands experiencing wildfire, I applied the concept of expected utility to risk-adjust the compartments' carbon stocks (Shoemaker 1982, Finney 2005, Ager et al. 2010). The expected carbon stock is a weighted average, combining both outcomes (observed carbon stocks and predicted post-wildfire stocks), weighted by the respective probabilities of their occurrence. For example, I calculated the Expected Live Tree Carbon (ELTC) for compartment n as

(2) $ELTC_n = [LTC_n \times (1 - P_{burned})] + (SLTC_n \times P_{burned})$

where P_{burned} represents the cumulative probability that the compartment will have been burned by the end of the study (2020). I calculated P_{burned} as

(3) $P_{burned} = 1 - (1 - P_{annual})^t$

where t is the number of years since treatment installation (t = 18 in 2020). To account for uncertainty in P_{annual} as climate change and altered disturbance regimes increases the frequency of wildfires in California's Sierra Nevada, I used three discrete values of P_{annual}: 0.01, 0.02, and 0.03. The P_{annual} value of 0.01 is accepted and used in established literature as the current annual probability of wildfire for a given area of forest in the Sierra Nevada (Foster et al. 2020). I chose to use P_{annual} values of 0.02 and 0.03 to assess the magnitude of change in ELTC given increases in wildfire probability, representing changes to long-term stable carbon storage in fuel-treated forests as wildfire frequency is predicted to increase (Stephens 1997, Westerling et al. 2006, Westerling 2016). I modeled a wildfire and calculated SLTC and ELTC for pre-treatment conditions and 2020 conditions of all treatment compartments, to compare the carbon stability before and after repeated fuel treatments. An increase in SLTC/ELTC would indicate an increased stability of aboveground live carbon stocks in these compartments as a result of the repeated fuel treatments.

~~To calculate Expected Total Aboveground Carbon (ETAC), I used an equation identical that of Expected Live Tree Carbon (Eq. (2)), but incorporated understory biomass, dead biomass, and offsite forest products:~~

$\cancel{(4)\ ETAC_n = [TAC_n \times (1 - P_{burned})] + (STAC_n \times P_{burned})}$

~~where TAC_n is the Total Aboveground Carbon in compartment n (sum of all observed carbon stocks, including trees, understory, and fuels), and $STAC_n$ is the Stable Total Aboveground Carbon for compartment n.~~

~~I made several assumptions in the calculation of $STAC_n$, namely regarding the efficiency of carbon sequestration in offsite forest products and the proportion of carbon in fire-killed trees/understory/fuels emitted to the atmosphere. An average of approximately 31.7 MgC/ha of live tree carbon was transported offsite as sawlogs from compartments undergoing a mechanical treatment (Stephens et al. 2009). For each mechanical-only or mechanical-burn compartment, I adjusted this estimation of carbon~~

~~sequestered offsite using a range of sequestration efficiencies (1%, 34%, 67%, or 100%) to account for variance in lifetime of wood products and the stability of their carbon stocks. I included these offsite carbon stocks as a part of STAC, since they remain unaffected by modeled wildfire within the study. To estimate STAC, I added the other estimated carbon stocks (understory, fuels, pre-fire snags, and fire-killed trees) to my estimation of SLTC. I assumed that some proportion (1%, 34%, 67%, or 100%) of the carbon in fire-killed trees would be emitted to the atmosphere, and the rest would become a part of the snag pool. For each of the other pools (understory, fuels, and pre-fire snags), I assumed some proportion (1%, 34%, 67%, or 100%) of the pre-fire carbon stocks would be emitted to the atmosphere if burned in a wildfire.~~

~~I used an envelope approach to calculate ETAC for each treatment under each unique combination of assumptions. To make my analysis more robust and resistant to bias from these assumptions, I used a wide range of values for each assumed parameter. With three levels of wildfire probability and four levels each of (1) sequestration efficiency, (2) proportion of fire-killed tree carbon directly emitted, (3) proportion of duff carbon stocks combusted, (4) proportion of fine fuel carbon stocks combusted, (5) proportion of CWD carbon stocks combusted, (6) proportion of understory vegetation carbon stocks combusted, and (7) proportion of pre-fire snag carbon stocks combusted, there were 49,152 unique sets of assumed parameters ($3 \times 4^7 = 49{,}152$). I iterated over the entire set of combinations and calculated ETAC for each treatment under each combination of parameters.~~

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