Impacts of Maintaining Fuel Treatments with Mechanical Methods on Soil Carbon & Nitrogen in a Sierra Nevada Mixed Conifer Forest

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ABSTRACT

Western North American forests are becoming increasingly vulnerable to high severity wildfire due to recent management practices, climate change, and altered fire regimes. Fuel reduction treatments are necessary to effectively mitigate wildfire hazard by altering forest structure and fuel loading. These treatments also have broader ecological impacts on wildlife habitat, soil properties, carbon storage, bark beetles, and forest diseases. This study considers the effects of maintaining mechanical thinning treatments on carbon and nitrogen stored on the forest floor and in the mineral soil. The maintenance treatments were applied 14-16 years after the initial treatments in 3 randomly assigned stands at Blodgett Forest Research Station. I used paired t-tests to measure the differences between pre-treatment means and post-treatment means of carbon and nitrogen on the forest floor and in the mineral soil. I found that all concentrations of carbon and nitrogen on the forest floor and in the mineral soil were significantly affected by the treatment. However, these changes in carbon and nitrogen concentrations were not reflected in the litter depth, bulk density, soil carbon stock, carbon to nitrogen ratio. My results somewhat differ from previous studies likely due to the inherent differences between initial and maintenance treatments, since maintenance treatments prolong the effects of initial treatments. Understanding the ecological impacts of mechanical thinning treatments is important, as mechanical treatments can be used in urban wildland interfaces and areas where prescribed fire is an unlikely management tool.

KEYWORDS

forest management, fuel treatments, soil science, carbon stocks, carbon sequestration

INTRODUCTION

As a result of recent forest management practices and changing climatic conditions, western North American forests are experiencing changes in structure, organization, and function (Hessburg et al. 2019). Given the effects of fire suppression, and therefore disruptions in ecosystem processes, mixed conifer forests have decreased in spatial complexity, now containing higher densities of single trees in smaller size classes and larger proportions of trees in patches of ten trees or more (Fry et al. 2014). Compared to historic mixed conifer forest conditions, present mixed conifer forests have higher tree densities, more canopy cover, higher proportions of true fir species, and lower proportions of pine species (Collins et al. 2011). These current forest conditions have stand density indexes that correspond to full competition to imminent mortality (North et al. 2022), which can be attributed to compounding stresses like drought, bark beetles, diseases, and high severity wildfire. Decreased precipitation and increased aridity during the fire season directly affect the burned area (Holden et al. 2018), while moisture deficits reduce tree vigor and resilience (Hessburg et al. 2019). The fire regime in mixed conifer forests is categorized as fuel-limited, frequent, and low to moderate severity; as the time since the last fire increases, forests with fuel-limited fire regimes are shown to burn with increasing rates of high severity fire (Steel et al. 2015). Fire suppression and selectively harvesting the largest trees over the past 100 years, changing precipitation and temperature patterns, and altered fire regimes present an urgent need to conduct fuel reduction treatments and promote forest resilience at a dramatically increased scale and rate.

To effectively mitigate wildfire hazard, fuel reduction treatments, such as mechanical thinning and prescribed fire, should aim to reduce surface fuels, increase height to live crown base, and decrease crown density (Agee and Skinner 2005). Mechanical thinning treatments are applied in many forms, with understory thinning being more effective at establishing a higher height to live crown base than overstory thinning, which also reduces the number of large trees below suggested historic conditions (Agee and Skinner 2005, North et al. 2007). Reintroducing fire to fire suppressed landscapes is accomplished with prescribed fire or managed wildfire, with prescribed fires effectively reducing ground and surface fuels, lowering the modeled wildfire rate of spread, predicted mortality, and fireline intensity (Stephens and Moghaddas 2005). Treatments can consist of combinations of thinning and fire to meet specific objectives. Mechanical understory thinning followed by prescribed fire can be used to reduce stem density and create a forest structure with a spatial distribution similar to historic conditions (North et al. 2007). Prescribed fire and managed wildfire are limited in their application, especially in areas close to wildland urban interfaces due to liability issues with smoke and escaped fire; in these areas, mechanical thinning treatments can be applied to achieve fuel reduction and ecosystem restoration objectives.

Forests are terrestrial carbon (C) sinks (Pan et al. 2011) that store terrestrial C in pools of live and dead, and aboveground and belowground biomass, actively capturing C through biomass growth. However, when large patches of high severity wildfire consume forest biomass, dead biomass is no longer able to increase C storage, therefore decreasing the forest's C sequestration potential. Compared to fuel reduction treatments utilizing fire, thinning treatments can be favorable in terms of maintaining the forest's capacity to store C. Prescribed fire only and mechanical thinning combined with prescribed fire emit significantly more carbon dioxide (CO2) than mechanical thinning only treatments, and models show that mechanical thinning treatments result in low vulnerability to live tree C losses from mortality in wildfires (Stephens et al. 2009). Furthermore, mechanical thinning treatments increase the stability of total forest C stocks, including live biomass, dead biomass, and sequestration in forest products (Foster et al. 2020). The reduction effects of thinning treatments on stand density, basal area, and coarse woody fuel loads have been shown to persist for ten years after the treatments (Low et al. 2021), working to restore stand structure to historic conditions and reducing fire hazard. However, fine woody fuels and ground fuels increase ten years after thinning treatments (Low et al. 2021), suggesting that continuous entries and maintenance treatments are needed to prolong the treatment effects. Proactive, continuous fuels management would reduce C losses and prevent CO2 fluxes from severe wildfire, ensuring long-term stability of C sinks in the form of aboveground biomass.

Knowing the C impacts of fuel reduction treatments both aboveground and belowground is critical given the forest's role in the global C cycle. There are different pools of belowground C that form, persist, and respond to treatments in different ways, which can be influenced by soil texture and parent material (Haddix et al. 2020, Rasmussen et al. 2005). There is particulate organic matter (POM) that forms through decomposition of organic matter, and there is mineral-associated organic matter (MAOM) that forms by the binding of organic matter to mineral surfaces (Haddix et al. 2020). Soil C storage potential is linked to nitrogen (N) availability and the C/N ratio. Coniferous forests contain less C stored in MAOM than POM, which has a more variable C/N ratio and can be more vulnerable to disturbances, including fuels treatments (Cotrufo et al.

2019). Specifically in the Sierra Nevada, soil C storage capacity and partitioning is determined by the ecosystem fire regime and weathering of soil parent material (Rasmussen et al. 2018). Fuel reduction treatments have varying impacts on C pools and dynamics depending on the treatment type and intensity (Dore et al 2016), and there are important tradeoffs in terms of climate change and CO2 fluxes as a result of high severity forest fires.

Given the variability and vulnerability of C and N on the forest floor and in the soil, it is important to monitor the impacts of forest management and fuel treatments. To understand how maintaining fuel treatments with mechanical methods effects C and N on the forest floor and in the soil, this study explores three questions: 1) How do maintenance mechanical treatments impact C and N in the aboveground litter and duff on the forest floor? 2) How do maintenance mechanical treatments impact belowground C and N in the mineral soil? and 3) How have C and N changed on the forest floor and in the mineral soil since the initial treatment?

METHODS

Study Site

This study was conducted at Blodgett Forest Research Station (38°54'N, 120°39'W) near Georgetown, California. The elevation at Blodgett Forest Research Station (BFRS) ranges from 1100 to 1400 meters, and the temperature ranges from 0° to 8°C in the winter and from 10° to 29°C in the summer. The average total annual precipitation is about 160 centimeters. BFRS consists of about 1700 hectares with an overstory species composition that is characteristic of mid-elevation, mixed conifer forests in the Sierra Nevada, which consists of white firs (*Abies concolor*), Douglas-firs (*Pseudotsuga menziesii*), incense-cedars (*Calocedrus decurrens*), ponderosa pines (*Pinus ponderosa*), sugar pines (*Pinus lambertiana*), and California black oaks (*Quercus kelloggii*). Soils are well-drained, sandy-loam, Ultic Haploxeralfs, and the soil depth ranges from 85 to 115 centimeters, under which there is Mesozoic granitic material. BFRS was logged almost completely 100 years ago and excluded fire on the landscape until recently ("Blodgett Forest Research Station" 2020).

Maintenance Mechanical Thinning Treatment

The initial treatments occurred as part of the Fire and Fire Surrogate Study (FFSS) at BFRS that considers the effects of fuel treatments on different ecological functions (McIver et al. 2013). The initial treatments were applied in 2001 and 2002, and the maintenance treatments were applied in August and September of 2016 and 2017. The maintenance treatments were applied 14-16 years after the initial treatments in order to sustain the effects of fuel treatments.

I analyzed the results from the maintenance mechanical thinning treatment, which consisted of a thin from below and a mastication treatment. The thin from below was a commercial harvest to a residual basal area of 34.4 m^2 ha^{-1}, and the mastication focused on chipping small trees and shrubs in place. The mechanical thinning treatment focused on removing intermediate and codominant trees to promote the growth of large trees in the overstory with the overall goal of reducing fire severity by increasing height to live crown base and decreasing ladder fuels.

The FFSS applied treatments in 12 similar experimental stands with each treatment randomly assigned to 3 stands. The treatments consisted of prescribed fire only, mechanical thinning only, mechanical thinning and prescribed fire, and a control. The mechanical treatment was applied in stands labeled 190, 350, and 490, which were 22.7, 13.8, and 28.7 hectares in size. The area that received mechanical treatments in each stand was smaller than the stand size because of areas that were thinned from below but not masticated, so about 15.5, 9.6, and 20.9 hectares of stands 190, 350, and 490 received the full mechanical treatment. There were 18 plots in stand number 190, 20 plots in stand number 350, and 19 plots in stand number 490; the forest floor and mineral soil were sampled once at each plot.

Forest Floor & Mineral Soil Sampling

Pre-treatment measurements of the forest floor layers (litter and duff) were collected in August and September of 2016. The litter layer includes dead and unattached plant debris, pinecones, dead foliage, pieces of bark, and fuels less than a quarter of an inch. The litter layer excludes animal scat, vegetation still attached to the parent stem, and fuels greater than a quarter of an inch. The duff layer is the partially decomposed organic material found between the litter layer and the mineral soil. The litter and duff were collected 14 meters away from each plot center from within a 30 centimeter diameter frame. The depth of the litter and duff was first measured and then collected from within the entire frame without mixing it with the mineral soil below. Post-treatment measurements repeated this process and were collected in September and December of 2017 after the mechanical thinning in August 2017.

Pre-treatment measurements of mineral soil were collected in August and September of 2016. The mineral soil samples were collected from inside the same 30 centimeter diameter frame from which the litter and duff were first removed. Once the litter and duff were removed from the frame, a slide hammer sampler was used to take soil cores from 0 to 30 centimeters in depth. Post-treatment measurements repeated this process. Post-treatment measurements were collected in September and December of 2017 after the mechanical thinning in August and September of 2016 and 2017.

Sample Processing and Analysis

To process the litter and duff, the samples were first oven-dried at 65 degrees Celsius until a constant mass was reached (usually 24 to 48 hours) and then weighed. The samples were ground in a Wiley mill (Thomas Scientific) in order to pass through a 1 millimeter screen. A subsample of this ground sample was then pulverized in a ball mill. The pulverized litter and duff subsample was used for elemental analysis of C and N concentrations using a Thermo Scientific FLASH 2000 elemental analyzer.

To process the mineral soil, the samples were first air-dried and then weighed. The samples were sieved through a 2 millimeter screen where the fraction that was less than 2 millimeters was then pulverized in a ball mill. This pulverized mineral soil subsample was used for elemental analysis of C and N concentrations using a Thermo Scientific FLASH 2000 elemental analyzer. To determine the soil C to N ratio, the percent C concentration was divided by the percent N concentration.

To calculate bulk density, the 30 centimeter mineral soil cores were used, following the core sampling technique used by Lichter and Costello (1994). Using this method, bulk density is determined by dividing the net weight of dry soil by the volume of the cylinder used to collect soil cores. To calculate soil C stocks, the Pearson et al. (2007) method was used, which multiplies the bulk density, percent C concentration, and the depth at which the mineral soil was sampled.

Statistical Analysis

I used paired t-tests to measure the differences between pre-treatment means and post-treatment means of C and N on the forest floor and in the mineral soil, litter depth, C to N ratio, bulk density, and soil C stock. I assessed the normality of the paired differences using Shapiro-Wilk tests. When the assumptions of a paired t-test were not met, I used Wilcoxon signed rank tests. I conducted the analyses using R statistical software, and differences for all statistical tests were considered significant when $p < 0.05$.

RESULTS

Forest Floor

For the litter and duff layer, the paired differences of both the litter depth and the average percent C concentration are not normally distributed. The results of the Wilcoxon signed-rank test for the litter depth showed that there is not a significant difference between the pre-treatment and post-treatment measurements of the litter depth, with little variation between stands (Figures 1a and 1b). In the litter and duff, the Wilcoxon signed-rank test showed that there is a significant difference between the pre-treatment and post-treatment C concentrations (Table 1). The sample mean for post-treatment percent C concentration (M = 72.471, SD = 21.376) was about 75% higher than the sample mean for pre-treatment percent C concentration (M = 41.400, SD = 5.414) in the litter and duff (Figure 2a). There is also a significant difference between the pre-treatment and post-treatment measurements of the average percent N concentration in the litter and duff layer, $t(32)$ = -6.800, p = 1.086e-07. The sample mean for post-treatment average percent N concentration (M = 1.226, SD = 0.315) was about 56% higher than the pre-treatment average percent N concentration (M = 0.784, SD = 0.225) in the litter and duff (Figure 2b). Each stand number varied in the percent C and N concentration found in the litter and duff; stands 350 and 490 had a greater difference between pre-treatment and post-treatment measurements than stand 190 (Figures 3a and 3b).

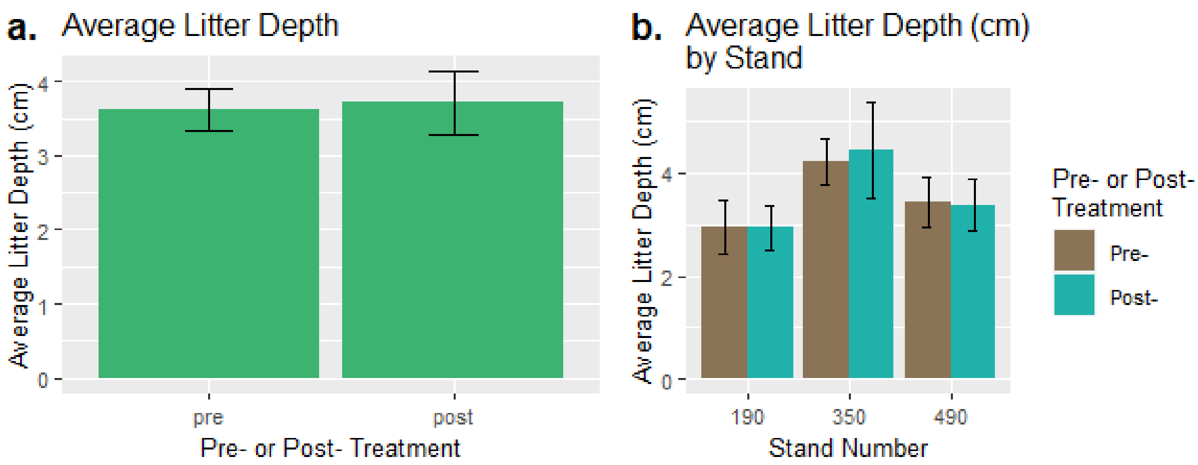

Figure 1. Average pre-treatment and post-treatment litter depth. The error bars represent the standard error of the mean. There is no significant difference between the pre- and post- treatment measurements of litter depth.

Table 1. P-value results from statistical tests. P-values from each statistical test where x is $p > 0.05$, * is $p < 0.05$, ** is $p < 0.01$, *** is $p < 0.001$, **** is $p < 0.0001$. For variables with paired differences that are not normally distributed, I conducted Wilcoxon signed-rank tests.

Statistical Test	Litter depth	Percent C concentration in litter & duff	Percent N concentration in litter & duff	Percent C concentration in mineral soil	Percent N concentration in mineral soil	C to N ratio	Bulk density	Soil C stock
Paired t-test			****	***	***	x	x	x
Wilcoxon signed-rank test	x	****						

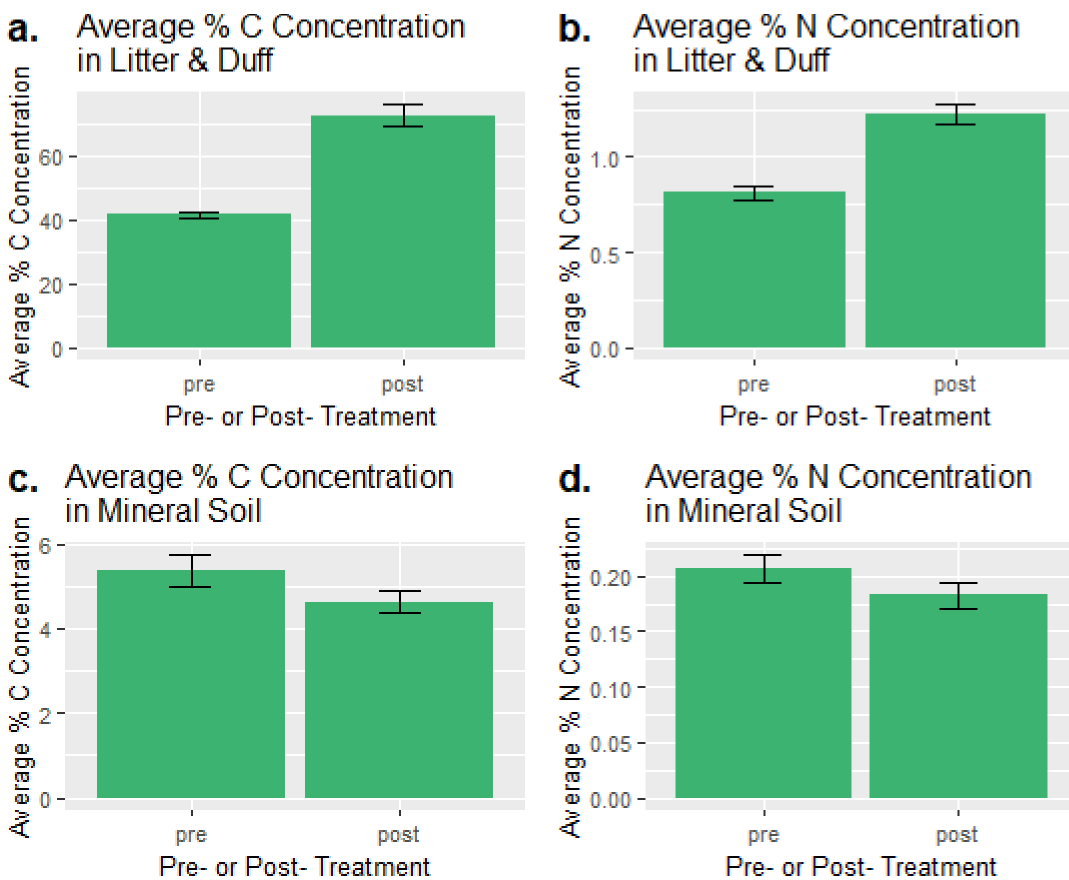

Figure 2. Average percent C and N concentration on the forest floor and in the mineral soil. The error bars represent the standard error of the mean.

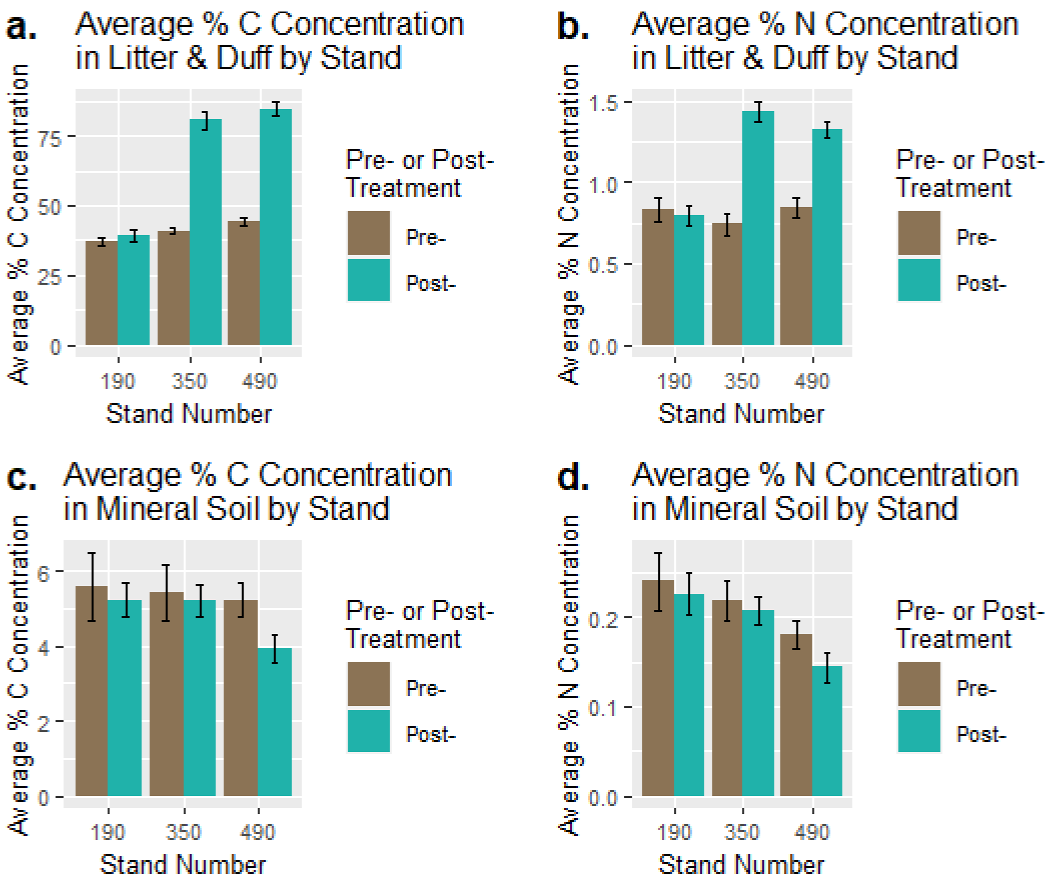

Figure 3. Average percent C and N concentration on the forest floor and in the mineral soil at the stand level. The error bars represent the standard error of the mean.

Mineral Soil

The paired differences for all mineral soil variables are normally distributed, so I relied on paired t-tests to evaluate differences in pre-treatment and post-treatment measurements. There is a significant difference between the pre-treatment and post-treatment percent C concentration in the mineral soil layer, $t(36) = 2.750$, $p = 0.009$. The sample mean for pre-treatment average percent C concentration ($M = 5.376$, $SD = 2.235$) was almost 14% greater than the post-treatment average percent C concentration ($M = 4.629$, $SD = 1.552$) in the mineral soil (Figure 2c). There is not a significant difference between the pre-treatment and post-treatment bulk density (g cm^{-3}), $t(46) = 1.563$, $p = 0.125$, with little variation between stands (Figures 4a and 4b). There is not a significant difference between pre-treatment and post-treatment soil C stock (mg ha^{-1}), $t(36) = -1.823$, $p =$

0.077, with the most variation between pre-treatment and post-treatment levels of soil C stock in stand 490 (Figures 5a and 5b).

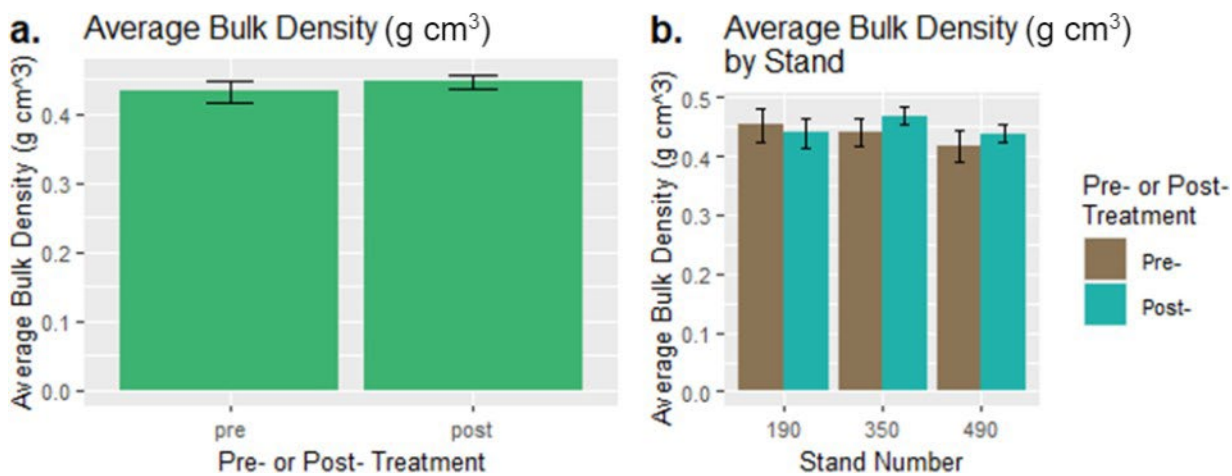

Figure 4. Pre-treatment and post-treatment dry bulk density. The error bars represent the standard error of the mean. The sample mean for the pre-treatment bulk density was 0.429 g cm^{-3} (*SD* = 0.088), and the sample mean for the post-treatment bulk density was 0.449 g cm^{-3} (*SD* = 0.059). There is no significant difference between the pre- and post- treatment measurements of bulk density.

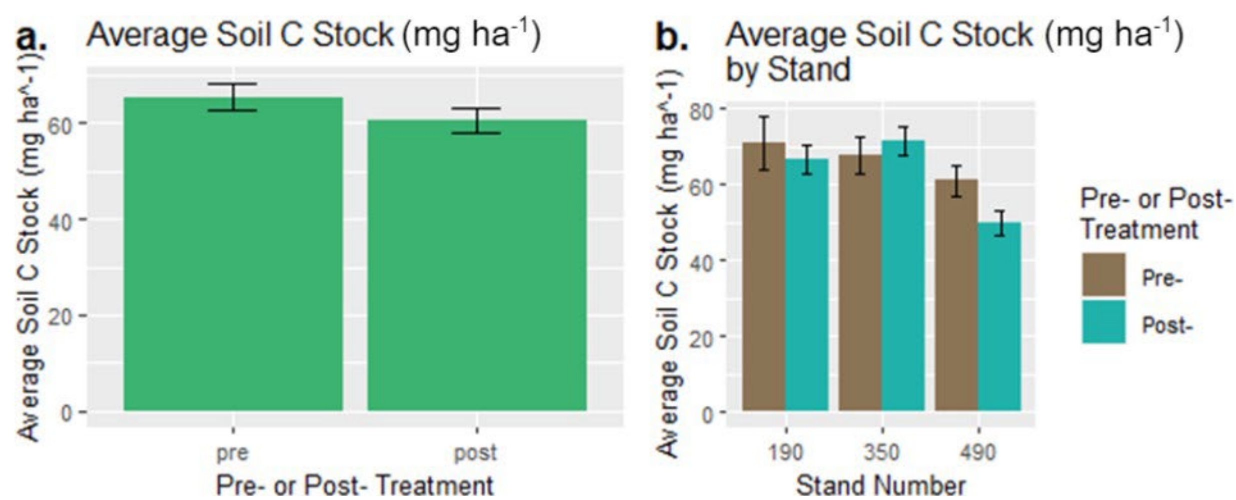

Figure 5. Pre-treatment and post-treatment soil C stock. The error bars represent the standard error of the mean. The sample mean for the pre-treatment soil C stock was 65.475 mg ha^{-1} (*SD* = 17.887), and the sample mean for the post-treatment soil C stock was 60.520 mg ha^{-1} (*SD* = 15.946). There is no significant difference between the pre-treatment and post-treatment measurements of soil C stock.

I found a significant difference between the pre-treatment and post-treatment measurements of the average percent N concentration in the mineral soil, $t(36) = 2.790$, $p = 0.008$.

The sample mean for pre-treatment average percent N concentration ($M = 0.206$, $SD = 0.078$) was about 11.5% greater than the post-treatment average percent N concentration ($M = 0.183$, $SD = 0.071$) in the mineral soil (Figure 2d). Each stand varied in the percent C and N concentration found in the mineral soil; stand 490 had the greatest variation in both percent C concentration and percent N concentration (Figures 3c and 3d). I found that there is not a significant difference between the pre- and post- treatment soil C to N ratio, $t(36) = -0.058$, $p = 0.954$, with little variation between stands (Figures 6a and 6b).

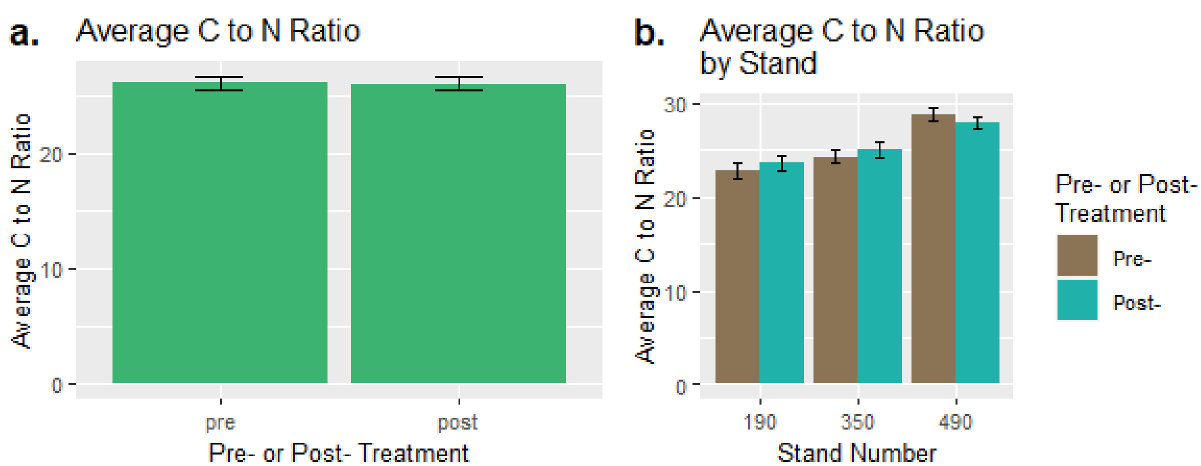

Figure 6. Pre-treatment and post-treatment soil C to N ratio. The error bars represent the standard error of the mean. The sample mean of the pre-treatment soil C to N ratio is 26.030 ($SD = 3.766$), and the sample mean of the post-treatment soil C to N ratio is 25.999 ($SD = 3.115$). There is no significant difference the pre- and post-treatment measurements.

DISCUSSION

Overall, my results somewhat differ from the initial treatment results (Moghaddas and Stephens 2007) and from the available literature on fuel treatment effects on soil C and N. This is likely due to the inherent differences between initial and maintenance treatments. Because the data I used were from a maintenance treatment, the initial thin from below probably already reduced the basal area to near 34.4 m^2 ha^{-1}, and the initial mastication probably removed and shredded most of the small trees and shrubs present in the stand. The purpose of the maintenance treatment was to sustain the effects of the initial treatment, but the maintenance treatment probably did not have as drastic of an effect on forest structure and composition as the initial treatment did.

Changes in the Forest Floor

The maintenance mechanical thinning treatment did not result in a significant difference in the litter depth; however, there was still a 13 percent increase in litter depth after the treatment was applied (Figure 1). This increase is likely due to the nature of the mechanical thinning treatment, which consisted of a thin from below followed by a mastication, leaving the slash on the forest floor. Mechanical thinning treatments have been shown to increase 1, 10, and 100 hour surface fuel loads, therefore increasing the fuel depth (Stephens and Moghaddas 2005). Because this was a maintenance treatment, there were likely fewer trees and shrubs to be removed in the mechanical treatment, so the impact on the litter depth was minimal, though still a 13 percent increase. My results are similar to the results from the initial mechanical treatment, where mechanical thinning did not significantly change the litter depth when compared to control (Moghaddas and Stephens 2007).

There was a significant (75 percent) increase in the percent C concentration in the litter and duff layer, but there is high variability in the C concentration of each stand. Stand 190 experienced less than 7 percent of an increase in percent C concentration, and stands 350 and 490 both experienced over 90 percent of an increase (Figure 3a). This variability in the forest floor layer is common, especially in mechanically treated sites where differences in harvesting operations may mix organic material that would normally be considered litter into the mineral soil layers below the forest floor (Johnson and Curtis 2001, Yanai et al. 2003). This implies that there could have been differences in the application of mechanical thinning treatments, resulting in the C concentration differences between stands. The results from the percent C concentration in the litter and duff in initial treatment were not significant (Moghaddas and Stephens 2007). Across all FFSS sites, forest floor C storage was not significantly affected by a mechanical thinning treatment in either the first post-treatment year or the subsequent sampling years (Boerner et al. 2008). These findings differ from the results of the maintenance mechanical treatment that I analyzed.

Similarly, to the C concentration, there was a significant (56 percent) increase of percent N concentration in the litter and duff layer, but there is high variability in the N concentration between stands as a result of differences in the mechanical thinning application. Stand 190 experienced about 1.5 percent of a decrease in percent N concentration between the pre-treatment and post-treatment, and stands 350 and 490 experienced about 100 percent and 60 percent, respectively, increases in average percent N concentrations (Figure 3b). My results differ from the initial treatment where total N concentrations did not differ between the four applied treatments (Moghaddas and Stephens 2007). This general increase in N concentration could be a product of soil organic matter decomposition, which can promote gross and net primary productivity (Alberti et al. 2015). Given the 15-16 years between the initial and maintenance treatments, there was time for the slash from the initial treatment to partially decompose, which could partially explain the increase in percent N concentration in the litter and duff layer.

Changes in the Mineral soil

I found that there was a significant difference in the percent C concentration in the mineral soil, with the C concentration decreasing by almost 14% after the mechanical thinning treatment was applied. In coniferous forests, there is proportionally more C stored in POM, which is vulnerable to disturbances, than MAOM (Cotrufo et al. 2019), which implies that the mechanical thinning treatment disrupted the C storage in the mineral soil. However, these results differ from the initial treatment, which did not experience a significant difference in the C concentration in the mineral soil (Moghaddas and Stephens 2007). I did not find a significant difference in dry bulk density, which is similar to the results from the initial treatment where average soil bulk density did not differ among treatments (Moghaddas and Stephens 2007). Furthermore, I did not find a significant difference in soil C stock after the mechanical thinning treatment, which is similar to the results from the initial treatment (Moghaddas and Stephens 2007). Despite there being a significant difference in the percent C concentration, this did not translate into a significant difference in the total soil C stock. The soil C stock did experience about a 7.5 percent decrease between the pre-treatment and post-treatment, but this was not statistically significant. Across all FFSS sites it was found that soil C was highly variable from year to year with the largest changes in soil C occurring in the first year after treatment, and meta-analysis of all FFSS sites revealed that there were no significant, network-wide effects on soil C (Boerner et al. 2008). Johnson and Curtis (2001) performed a meta-analysis on the effects of forest management on soil C and N storage and reported that the overall average percent change in soil C and N, compared to the control or pre-treatment values, was near zero, but they also found significant differences in the type of harvest. Sawlog harvests significantly increased soil C and N, and whole tree harvesting slightly decreased soil C and N (Johnson and Curtis 2001).

There was a significant difference between the pre-treatment and post-treatment percent N concentration, which is different from the results from the initial treatment, where there were not any significant differences in total N concentrations or pools in mineral soil among treatments (Moghaddas and Stephens 2007). There was not a significant difference in the soil C to N ratio, which was not a variable considered in the initial treatment. Despite not having a significant difference in soil C to N ratio, stands 190 and 350 experienced an overall increase in the C to N ratio, while stand 490 experienced a decrease in the C to N ratio (Figure 6b). This variation may be due to high levels of variation in the soil C to N ratio in coniferous forests (Cotrufo et al. 2019), and there are wide C to N ratios in POM (Haddix et al. 2020). The share of carbon between MAOM and POM and the soil C to N ratio mediate soil C stocks and the effects of other variables on soil C stocks (Cotrufo et al. 2019), suggesting the importance of maintaining the soil C to N ratio. It has also been shown that the soil C to N ratio exerts a strong control on gross primary productivity while gross primary productivity increases with decreasing soil C to N ratio.

Limitations & Future Directions

A major limitation for my project was data availability because the data that I analyzed came from an incomplete dataset. There were maintenance treatments applied to all fuel treatments at BFRS that were a part of the FFSS. The forest floor and soil samples from the prescribed fire treatment, mechanical thinning followed by prescribed fire treatment, and the control are still being processed in the laboratory, so I only had access to the pre- and post-treatment mechanical thinning data. Another limitation is that the data do not contain the same variables that were measured from the initial treatment. In comparing my results to the initial treatment results it would be useful to have soil strength, exposed bare soil, cation exchange capacity, and base saturation, as were measured in Moghaddas and Stephens (2007). Because of the available data, I used paired t-tests to analyze the data, and Moghaddas and Stephens 2007 used ANCOVA to evaluate soil properties. Because of the differences in statistical tests, I could not directly compare the results. The initial treatment soil cores were collected from 0-15 centimeters, while the maintenance treatment soil cores were collected from 0-30 centimeters.

Furthermore, this study also does not consider the emissions associated with fuel treatments, and there is no risk modeling of what the C and N storage would look like after a fire on the landscape. Some studies consider emissions from prescribed fire and from the machinery used in mechanical thinning treatments as C losses (Stephens et al. 2009). Other studies have used risk-sensitive C accounting and modeling to understand the effects of forest management on C stability (Collins et al. 2013, Foster et al. 2020). These modeling results suggest that treatments reduce hazardous fire potential but only if maintained with additional treatments (Collins et al. 2013). Overall, in accounting for C in forests, it is important to monitor C stocks over time, which could be modeled alongside emissions and C stability.

Broader Implications

Using mechanical treatments alone can potentially reduce fire intensity in some cases, but in order to effectively alter stand structure and reduce fuels, mechanical thinning followed by prescribed fire is recognized to be the most effective (McIver et al. 2013). Using mechanical treatments is important, especially in California where there are increasingly more wildland urban interfaces and areas where it is unlikely to apply prescribed fire or allow wildfire to burn. Modifying forest structure and density can be accomplished with mechanical methods, and mechanical only treatments could be designed to have a staggered treatment schedule and integrate prescribed fire to increase the longevity of the reduced fire hazard to up to 20 years (Stephens et al. 2012). Maintenance treatments are important in preserving the effectiveness of the initial fuel treatments, especially in forests that historically experienced frequent fire. These continuous treatments stabilize carbon stocks in forests and minimize the threat of carbon losses due to high severity wildfire. Furthermore, the carbon in the forest floor and the mineral soil represent a significant portion of these forest carbon stocks and must be monitored as treatments are applied, especially since these pools of carbon may persist even when carbon in the form of tree biomass is harvested. Understanding the impacts of fuel treatments and long-term management plans on forest carbon stocks is extremely important given the imminent threats of climate change and high severity wildfire in western North American forests.

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