Executive Summary: Fuels treatments and their impact on carbon stocks and fire severity in Boulder and Jefferson Counties and the City of Boulder.

25 January 2022

Authors: Brian Buma[1] , Anthony Vorster[2] , Erin Twaddell[1]

1. University of Colorado, Denver. Brian.Buma@ucdenver.edu & Erin.Twaddell@ucdenver.edu
2. Colorado State University, Fort Collins. Anthony.Vorster@colostate.edu

The 2020 Calwood fire burned in late fall, under intense weather conditions through areas treated to reduce fuels, creating a powerful opportunity to assess the impacts of fuel treatments on forest fire severity and carbon stocks. Using comparative, non-wildfire impacted locations on City of Boulder and Jefferson County land, we measured carbon stocks on 130 plots co-identified with land managers in each jurisdiction. All pools were measured, including soils. More entries/treatments did reduce fuels – locations which were thinned had more carbon than those that were thinned and burned. However, rather than result in higher carbon after the wildfire, this trend carried over. Treated plots had less carbon than untreated wildfire plots. It appears that reductions in carbon associated with the fuel treatments were not offset by reductions in fire carbon losses at the plot level. Prior wildfire, in contrast, was associated with higher C after the Calwood. Treated areas look less severe after the fire in the remote sensing analysis, potentially arising from more rapid recovery of groundcover. Long-term implications – potentially less erosional losses and faster regeneration – will be need to be followed. Management implications:

- Treatment (thinning and Rx burning) reduced fuel loads
- Carbon loss associated with treatment was not offset by reduced carbon losses in the wildfire; carbon stocks are still higher on untreated wildfire plots than treated.
- Fire wind speeds were extremely high, likely at a range where treatments should not be expected to be effective. When looking at the whole fire, satellite reflectance suggests either lower burn severity or more rapid recovery in treated areas.

Abstract: Carbon stocks are an important aspect of modern forest management. In fire prone areas, carbon loss due to combustion is a major concern. A common goal of fuels management is reduction in carbon loss if and when a fire occurs. Despite substantial amounts of modeling, there are relatively few studies that have actively compared burned and unburned plots with various treatments, especially those that incorporate soil carbon stocks. This study compared carbon on thinned and thinned/Rx burned treatments both with and without a wildfire (n=130). It also created a fire severity map based on remote sensing metrics to estimate the utility of those maps towards carbon stock estimation and to evaluate treatment impacts across the landscape.

Results indicate that at the plot scale, fuel treatments did not result in more carbon post-wildfire than untreated plots. Treated plots had lower overall and lower live carbon than untreated plots after the wildfire (approximately a 20-35% reduction). In contrast, fires that previously burned in a wildfire were relatively resistant. The comparison plots, outside the burn, were similar – less carbon with increasing treatment frequency. Soil carbon was relatively resilient, though any fire impact (Rx or wildfire) was associated with about 30% lower C in the upper organic layers. At the scale of the fire, remote sensing imagery showed treatments, particularly Rx fire, and previous wildfire were associated with lower reflectance change (RdNBR). Lower RdNBR impacts may be associated with higher survivorship and grass regrowth postfire.

In sum, the extreme fire conditions where the plots were located appear to have killed nearly all trees regardless of treatment. These results may not apply to lower intensity fires, as evidenced by the remote sensing averages and the edges of the burn. Management should consider the limitations of fuel treatment effectiveness, and for which management goals, in the context of future fire conditions.

Keywords (up to 12)

Fire, carbon stocks, fuel treatments, thinning, prescribed burning, Calwood, wildfire, remote sensing

Introduction

As more people move into the Colorado Front Range, residential areas and recreational resources are increasingly exposed to wildfires. A history of fire suppression and climate change only exacerbates the situation. Managing tradeoffs between fire mitigation and important ecosystem services like carbon storage is a key challenge to the region. There are important nuances to consider [Campbell et al. 2012]. Fuels management can be effective in reducing fire intensity and carbon losses at a given point, though very intense fires can reduce treatment effectiveness. High severity fires release about 30% more emissions compared to low/moderate severity fires [Campbell et al. 2012, Wiedinmyer and Hurteau 2010, Volkova et al. 2014, Krofcheck et al. 2019], although important questions about treatment effectiveness in future climates remain [Kalies and Kent 2016, Thompson et al. 2020]. High severity fires can turn a forest into a carbon source for years to decades [Hurteauet al. 2014]; for example, lodgepole pine stands typically take about 100 years to recover ~90% of pre-fire carbon [Kashian et al. 2013]. Low and moderate severity fires turn the stand into a carbon source for several years and the carbon lost is typically recaptured after 7 years [Hurteau et al. 2014, Hurteau and North 2010].

On the surface, it seems that fuels management is thus key to reducing fire losses of carbon. But fuels management also reduces carbon in and of itself, and may be less effective in high intensity fires. The efficacy of reducing carbon losses in a fire must be balanced against losses associated with fuels treatments which generally span larger areas then will actually burn and must be repeated over some time interval [Campbell et al. 2012]. The balance has the potential to be both positive or negative [Meigs et al. 2009, McCauley et al. 2019]. The fate of harvested carbon is also important [Finkral and Evans 2008, Stephens et al. 2012]. Clearly strong, ecosystem-scale data and multispatial-scale studies are needed to constrain the benefits and costs of fuels management for carbon.

One key unknown is the effects of fuel treatment on carbon stocks below ground (a recent review found only six quality studies on treatment+fire impacts on soil carbon; [Kalies and Kent 2016]). Reducing tree biomass can reduce soil burn severity [Fites et al. 2007] and it has the effect of increasing solar energy hitting the forest floor and reducing water usage by trees. The net effect is generally an increase in grasses, which sequester a substantial amount of carbon below ground via dense root networks. One field study reported more intact ground cover and deeper litter after fire in treated vs. non-treated areas [Stevens et al. 2014], and labile carbon forms and losses can be lessened with pre-fire fuels treatment [Choromanska and DeLuca 2001, DeLuca et al. 2020]. Thus there is the potential for fuels treatments to not only change overall carbon but to change above vs below ground allocations. This aspect of fuel treatments is extremely understudied, but has the potential to change how carbon is lost or maintained in fire events.

The forest management strategies on the Front Range of Colorado and the Calwood fire provide an excellent opportunity to investigate the impact of treatments with and without a wildfire. The Calwood fire, which started Oct 17, 2020, consumed over 10,000 acres, 5,000 of which were burned in only five hours and almost 9,000 acres in 24 hours. The fire coincided with very dry conditions and high winds with gusts of 50 miles per hour recorded nearby. Although no formal fire weather translation to percentiles (e.g. 95th percentile weather) is yet available to our knowledge, the conditions were certainly extreme, and the weather rasters that have been compiled were available for use here.

Methods

In summer 2021, 130 sites were completely surveyed and sampled for carbon content and burn severity (Fig. 1). Sites were randomly selected from pre-existing vegetative monitoring plots. Treatments spanned thinning (timelines from 2005-2015) and thinning/prescribed burning (similar times). Areas within the 2020 Calwood wildfire perimeter included areas that were thinned prior to the fire (2012 and 2020), areas thinned and burned prior to the wildfire (2012 and 2015, respectively), areas burned in the earlier Overland wildfire, combinations of the above, and areas without treatments at all. Although the initial design was balanced between a fewer number of treatments, later treatment maps revealed a more complex mosaic of treatment histories. Areas that were thinned twice prior the wildfire were grouped with the single thinning treatment, and areas that were Rx burned twice were grouped with the single Rx burn treatment. In total, 50 sites were unburned and 80 burned, composed of 1335 individual trees and approximately 1300 individual soil samples. Each site is 20x20 meters and GPS'd for long-term work.

At each site, all pools of carbon were measured: Aboveground live and dead trees were identified to species and measured for their diameter at breast height (DBH) and percent health, estimated visually. Shrubs were identified and measured for height and basal diameter. Downed woody debris were assessed via three 15m transect lines (methods from Brown 1974), oriented randomly from the plot center. Grass and herbaceous material was sampled at five random 50x50cm subplots – height was measured at five random sites within each subplot, and then the entire subplot was harvested to ground level and dried to estimate biomass. Tree measurements were converted to biomass using allometric equations developed for the Colorado Front Range [Vorster et al. 2020]. Uncertainty was propagated using published values (in main datafile). All biomass values were converted into carbon at a rate of 50% by weight, dry mass.

Soil was sampled at each subplot; soil samples were taken with a hammer corer to produce samples of known volume. Organic soil was sampled through the entire horizon, mineral soil was sampled to 10cm depth if possible (occasionally rocks made this depth inaccessible).

Within the Calwood fire perimeter, which represents burned aspects of each treatment, a composite burn index (CBI) score was also assessed at each site using the standardized protocol. In addition, max average wind speeds and minimum relative humidy were calculated from RAWS for each day of the fire progression and the topographic wetness data from topography– while not exactly the conditions during burning at a point, they provide an approximation average at the daily scale (Stephanie Mueller, CFRI; *personal communication*).

In fall 2021, the data was QA/QC'd. Soils were dried at 60 ^{0}C for 48 hours, sieved into coarse and fine components (2mm mesh), massed, and ground in a roller mill. Bulk density of all soils and all horizons (with a small fraction of exceptions where the soil conditions precluded accurate volume estimates) were calculated for both the coarse and fine fractions. After grinding, all samples were processed on a Costech 8020 elemental analyzer for percent carbon and nitrogen. All samples were calibrated using ultrapure standards, with a curve accuracy (r^2) of 0.999 or better.

Several treatment and disturbance datasets were combined to evaluate interactions between the CalWood Fire and previous treatments and wildfires. These included GIS treatment datasets from Boulder County, the Colorado Forest Restoration Institute (Colorado Forest Restoration Institute Treatment Library and CPF Treatment Interactions v2), U.S. Forest Service (FACTS and Hazardous Fuel Treatments), Colorado State Forest Service (Stewardship Mapping and Reporting Tool [SMART] and historical treatment data surrounding the CalWood Fire), and LANDFIRE

(Public Events Geodatabase). Historical fire perimeters were also incorporated from the National Wildfire Coordination Group. We merged and curated these datasets to remove redundant records, track overlapping treatments, and record treatment type, year, and size in a standard format and language. Confidence in treatment location, method, and year was highest in areas on the east side of the CalWood fire (Heil Valley Ranch), so we only used these treatment polygons provided by Boulder County evaluate treatment impacts on remotely sensed burn severity. We did, however, exclude treatment areas from all sources to identify untreated areas for comparison with Boulder County treatments. Burn severity was mapped using with Landsat 8 satellite imagery and compared across treatments, areas previously burned by wildfire, and untreated areas. Burn severity was quantified using the differenced normalized burn ratio (dNBR) and relative differenced Normalized Burn Ratio (RdNBR). The NBR ratio contrasts two parts of the electromagnetic spectrum (e.g., light) that, while invisible to human eyes, respond quite strongly to water and chlorophyl content in healthy vegetation. That ratio is a good proxy for vegetation health, and thus the difference (dNBR) between pre- and post fire is a useful metric of burn severity. We collaborated with and mentored a NASA DEVELOP team in the spring of 2021 on the remote sensing work. This program develops remote sensing products while providing training for four early career geospatial professionals. We mapped burn severity using cloud-free satellite images spaced as close to a year apart as possible and evaluated map performance of each burn severity map using CBI plot data. Three combinations of image dates were used: May (pre-fire image from May 31, 2020 and post-fire image from May 27, 2021), July (July 11, 2020 and July 5, 2021), and October (October 6, 2020 and October 18, 2021). The October burn severity map was used for comparisons across treated, untreated, and previously burned areas. Untreated areas were defined as forested areas more than 60 m from a treatment or previous wildfire edge.

Data was summarized by carbon pool and treatment for all plots. For any sub-pool with missing data (e.g., a missing bulk density measurement for organic soil) the treatment average was inputed. This only impacted four plots, and only a single C pool per plot. The purpose is comparing treatments with and without wildfire, to see if effect differences between thinned and thinned + Rx burn are maintained through a wildfire.

To estimate the effect size of the treatments themselves if burned on forest carbon, mixed effect linear models were used with factorized wind speed categories as random effects and scaled (mean = 0 , sd = 1) topographic wetness index, scaled relative humidity, and factorized treatments as fixed effects.

Results

Overall, the 130 plots provide an look at initial treatment conditions and their response to a wildfire. The data here starts with the wildfire and treatment responses, and concludes with initial looks at unburned/burned site contrasts. The fire burned extremely hot and fast, resulting in a high proportion of severely burned forest (defined via satellite imagery, Fig. 2). First, carbon pools quantified from the sites chosen by both the research team and the land managers are presented (for averages and standard deviations by treatment, see Table 1). Note that while Rx burn + wildfire is presented as a treatment, there was only one plot, and so it is primarily for completeness that it is included, little can be drawn from that treatment sample. Then, the remote sensing results are presented.

Tree Carbon

The tree carbon pools dominate the aboveground C stocks. The highest total carbon (live and dead) was found in thinned only and wildfire plots, unsurprisingly. Plots with higher numbers or more intense treatments (e.g., thinned and Rx burned) had lower standing biomass C (live and dead); the lowest were in plots with the 2003 wildfire event (the Overland fire). When looking at live standing C only (live trees), Calwood fire impacted treatments all have a median of zero except the no treatment condition and plots that burned prior in the Overland wildfire, with only a subset of plots having a fraction that survived the Calwood (Fig. 3).

Groundcover Results

Ground cover carbon (grass, herbs, and shrub coverage) was approximately 3x higher (approximately 7.5 Mg C/ha) in plots that did not experience wildfire. There was no significant difference between thinned and thinned/Rx fire plots. The lowest groundcover carbon was observed in plots that were thinned before the Calwood fire (~1.0 Mg/ha), with the other wildfire impacted treatments only slightly higher (within those, the plots thinned in 2020 had the lowest groundcover values). This difference emerges from changes in cover on the plot, not average heights. In other words, grass, herbaceous, and woody plant coverage is higher in the untreated plots but plant sizes are not substantially different (Fig. 4).

Woody Debris Results

Plots that did not experience the Calwood wildfire had the highest median woody debris carbon; Rx fire after thinning appeared to lower woody debris fuels. The other wildfire treatments were generally lower, with the lowest C found in the plots that were thinned immediately prior to the Calwood fire (Fig. 5) and those that previously experienced the Overland wildfire.

Non-Soil Pools

When combining all non-soil pools, the thinned only and Calwood only treatments had the highest carbon (Fig. 6). Most of the wildfire C was dead, however. A few thinned, thinned+Rx burned, and prior wildfire plots had comparable live C, but the median values for the treatment were all substantially lower. When looking at only live pools, unsurprisingly the two non-wildfire impacted treatments, thinned and thinned – Rx burned, had the highest C (Table 1).

Soil pools

Bulk density was approximately 75% higher for both organic and mineral soils in the wildfire impacted plots, most notably in the organic layers (~0.5 g/cm^3 vs. ~0.85 g/cm^3), and this increased density was highest in mechanically treated plots. This was also broadly the same across the mineral soil, though less pronounced (Fig. 7). Organic soils were deeper in non-wildfire plots, with the thinned treatments having the deepest soils, the thinned+Rx burn slightly lower, and then the wildfire only treatments. Two unique treatments (Rx+Wildfire and Wildfire (Overland) + Thinning + Wildfire (Calwood) were of similar depths, but only represent three plots. Plots with treatments prior to the wildfire followed the same pattern as without the wildfire – thinned only (+wildfire) had slightly more than thinned+Rx burned after the wildfire (Fig. 8).

Total organic soil C density was higher in the non-wildfire plots, especially the thinned only plots, with the exception of the Overland fire + Calwood fire treatments. The organic soil stocks in the thinned and Rx burned resembled the wildfire only plots. Treatments that experienced wildfire had the lowest organic soil C stocks. Mineral soil had the opposite pattern, with slightly higher mineral soil C densities found in the wildfire impacted plots. The plots that had prior burned in the Overland slightly higher exceptions. Total soil C was largely balanced out by the two, however (Fig. 9), with the highest values going to plots that were impacted by the Overland fire prior to the Calwood.

Total carbon stocks were similar across all treatments, reflecting the significant amounts of C in the soil that overwhelmed the majority of differences between the treatments seen in the aboveground biomass components (Fig. 10). Wildfire only and the thinning only treatments, the two sets with the least amount of C removal (overall), had the highest live and dead C densities, and were roughly comparable, likely reflecting site differences. If only looking at live biomass and soil, which would be the C pools likely to persist, then the two non-wildfire treatments had the highest carbon, although the median wildfire only treatment was similar to the thin and Rx burn (non-wildfire) plots due to surviving trees. The plots that burned in the prior Overland fire had similar soil/live C densities (and similar to wildfire only), and those with prior fuels treatment the lowest in general.

Burn Severity and Forest Treatment

The RdNBR burn severity map created from October pre and post fire Landsat 8 imagery aligned best with burn severity field measurements ($R^2 = 0.60$). Increasingly severe burn severity generally had a corresponding increase in RdNBR (Fig. 11).

The Boulder County treatments and the Overland fire impacted nearly 21% of the Calwood fire (Table 2). Previous wildfire, thinning only, and thinning and Rx fire were most common, together accounting for nearly 90% of the treated and/or previously burned areas. Untreated areas in the Calwood fire had a wide range of RdNBR values and generally had higher RdNBR than treated or previously burned areas (Figure 12). RdNBR decreased from untreated areas to thinned forests to areas previously burned by prescribed or wildfire (with and without thinning).

Modeling

The mixed effect model takes day of fire wind into account when estimating differential effects of treatments on forest carbon (live and soil C). It should be noted that even still, the limitations of only having day-of-burn wind speed metrics meant that some treatments had little variation in wind speed, limiting the extent to which the model could discriminate based on that random effect. To put it another way, the treatments were not randomly distributed with respect to the spatial behavior of the fire. With that limitation in mind, the model was estimated effect sizes by treatments. All management strategies resulted in lower non-soil live carbon than the non-treated Calwood burned areas, though for the thinning+Rx burn treatment, the estimate (-0.85 Mg/ha) and uncertainty in that estimate ranges well across zero, meaning that while the best estimate was negative, there could reasonably be minimal or even a positive effect. (Note: the Rx burn only treatment represents only a single sample, and so should only be seen as an initial datapoint). In contrast, the plots that were impacted by the Overland fire had higher live and soil biomass estimates after controlling for wind, though with similarly large ranges of uncertainty. Higher relative humidities and wetter contexts were estimated to have positive effects on live carbon, though the estimated effect size was extremely small and uncertainty both positive and negative (Fig. 13).

Discussion

The treatments were roughly comparable, with slightly higher tree biomass on the thinned-only plots (City of Boulder) compared to the other treatments, assuming post-wildfire live and dead tree biomass estimates approximately represent pre-fire (mostly) live tree biomass.

The treatments appear to be doing as intended prior to a fire, at least in terms of reducing biomass (fuel). Lower fuels in the thin+Rx burn plots compared to the thinned only plots was expected, and it appeared to do so without increasing overall ground fuel loads. Grass and herbaceous coverage, which can carry a ground fire, was more widespread on thin+Rx plots compared to thinned only plots, and slightly taller, but less dense at any given point, meaning the overall biomass was essentially the same between thinned and thin+Rx burn plots. Tree biomass was lower, which we attribute to differential thinning prescriptions (see "Challenges" below), and is a management decision. There is substantial variation from plot to plot, as one would expect in patchy treatments – some plots had few to no trees, for example. This variation in aboveground biomass is useful for other management goals, but does have the effect of causing substantial point to point variation in aboveground carbon.

Organic soil depths were much higher (2-3x) in the non-wildfire treatments. The thinned only treatments had the highest depth, with some reduction apparent after thinning and Rx burning (assuming comparable starting points). This difference, which is reasonable after Rx fire, was carried over into the wildfire plots. Thinned and Rx burned plots had the lowest depths after wildfire as well. To the extent that starting depths are comparable, more treatments decreased organic soil depth, potentially a result of less inputs from hard to decompose needles and mechanical damage. The higher bulk densities, however, offset the lowest depths, leading to broadly similar total soil carbon stocks. The two "lighest" treatments, the wildfire only (untreated) and thinned (no wildfire), had the highest soil carbon (Table 1).

Belowground, the effects of the treatments were observable, though less substantial. Thinned only treatments had the least dense soil, with Rx burning + thinning being slightly more dense (though one must be careful comparing different locations). The wildfires followed the Rx burning trend towards denser soils. The wildfire plots all had denser organic soils, the mineral soils were less different. Interestingly the treated wildfire plots (thinning and Rx burn + thinning prior to the fire) had more dense soils, perhaps a legacy of compaction. Although the 2020-2021 winter was relatively quiet for erosion (USGS unpublished data), this should be watched in the future as a potential source of rapid carbon export from the system.

Overall, total carbon was highest in the untreated condition (the wildfire treatment) and in the lightest treatment, the thinned-only treatment. The thinned and Rx burned, and all the other wildfire impacted treatments, were similar, about 20% lower. When looking at live carbon and soil, the pools likely to be more stable over the next decade, the lowest carbon values are in the plots thinned immediately prior to the fire. Of those exposed to the Calwood fire, thinning treatments had higher C (primarily from soil, but also from some surviving trees), with average values very similar to the thinning and Rx treatments. Both, however, were about 1/3 lower than the wildfire only. Of the Calwood fire locations that previously burned in the Overland fire, carbon averages were broadly similar to wildfire only and higher than the manageria treatment plots within the Calwood perimeter. This suggests that at the plot scale, there was little benefit in regards to carbon from the treatments (but see “Challenges”).

Unfortunately, when exposed to an extreme wildfire, the treatment seem to have had little impact on carbon stocks, at least on the random plots sampled here. While we are still investigating some of the many metrics collected, the lack of clear effectiveness of the treatments at increasing surviving live biomass when exposed to a wildfire was surprising, even after controlling for wind in the statistical modeling framework, though high wind speeds were confounded with some treatments, especially thinning. Some of this could be a result of the limited nature of the plots, though the sample size was respectable for most treatments (and those that are low are, in a sense, subsets of the basic thin and thin/Rx condition). Treatments, by their nature, reduce carbon – an inherent part of fuel reduction. This results in lower C, with one objective frequently being a reduction in C loss if a wildfire occurs later. Although the carbon stocks (e.g., fuels) were reduced with increasing treatments (e.g., thinning vs. thinning+Rx burning), the end result was a not an increase in live C or soil C stocks post-fire. Part of this is likely related to fire intensity as it hit some thinning treatments; there was little variation within our random plot placement in wind speed, many were all the highest level in the dataset. However, it could also be partially that the high ground fuel loads and decreased tree density led to increased fire intensity as a result of easier wind movement, an unintended consequence seen in the 2010 Four Mile fire as well (USFS 2012, pg. 79). Similar lack of treatment effectiveness has been seen in experimental crown fires in Canada (Thompson et al. 2020).

Interestingly, the plot level C metrics are not in congruence with conclusions that might be drawn from the remote sensing metrics alone, highlighting the importance of ground investigations. Remotely sensed burn severity measured across the entire burn area does show a reduction of burn severity as measured by RdNBR in treated and/or previously burned areas, particularly in areas that burned as a prescribed or wildfire, and treatment footprints are visible on the map (although see “Challenges” below). Thinning(s) alone were the least effective at reducing RdNBR values, and wildfire/wildfire+treatments the most effective (though the most variable).

RdNBR measures the difference between reflectance at the same time of year between pre and post fire imagery. As such, it can be sensitive to variation in weather, treatment effectiveness, and other factors, and is an indirect measure of actual fire impacts. RdNBR was correlated with burn severity field observations (Fig. 11). Although noisy, it was also correlated with total C (as total C, RdNBR increased suggesting that high biomass prior to the fire led to larger reflectance change) and live C (as live and soil C increased, RdNBR decreased, suggesting that lower RdNBR is associated with higher surviving carbon stocks; Fig. 14). Although statistically significant, meaning the effect is unlikely due to chance, the spread was very high, with r^2 values of 0.1 or less, and so point-level spatial uncertainty is relatively high. Soil and live biomass (including groundcover) resiliency is important going forward for erosion and ecosystem recovery, among other things. These could conceivably correlate with important management goals, such as fostering resilience (more regeneration, Shive et al 2013, though the native/non-native status of recovering vegetation is unclear from satellites) or resistance to things like post-fire erosion in coming years. For example, grass biomass (carbon per unit area) was correlated with RdNBR ($r^2 = 0.50$), with very little grass coverage on plots with RdNBR values above 200. Again, however, ground measurements are needed. Further geospatial analysis will be conducted to understand the role of treatment type relative to other variables such as topography, forest type, fire weather, and time since treatment.

Challenges: A major challenge is differences in treatment intensity between the jurisdictions. This is apparent in the tree biomass metrics, which Rx burning should not reduce (City of Boulder thinning only treatments, 51 Mg C/ha, Jefferson County: thinning and Rx burning, 30 Mg C/ha). The wildfire impacted plots, if we assume that standing dead were all alive prior, are somewhat intermediate, at 31-36 Mg C/ha, depending on specific treatment. So that difference (i.e., 21 Mg/ha between non-wildfire thinned and thinned-Rx fire) is likely due to treatment intensity as prescribed, rather than the treatment itself. The treatment itself, however, should be more directly comparable in the other pools – woody debris are lower on Rx burned plots, likely due to consumption, though potentially also production.

The comparison of RdNBR across untreated, treated, and previously burned areas should be interpreted cautiously. Treatments can reduce potential RdNBR change simply by lowering the pre-fire NBR values. Other differences between treated and untreated areas, such as potentially more rapid post-fire understory vegetation recovery in treated areas (either desired or undesired/invasive species), could exaggerate RdNBR differences between treated and untreated areas (as mentioned above). They could also impact other metrics like postfire erosion. Further exploration of the relationship between the carbon data and burn severity maps, including combination with other metrics, should improve spatial modeling. A related spatial challenge is the the non-random location of the plots with respect to the fire. In the statistical analysis, the thinned plots were, to a large part (and especially the ones thinned in 2020) confounded with high wind speeds, meaning discrimination of the effect of thinning vs. the effect of wind is difficult – this can be seen in the wide range of estimates around the treatments.

A complete carbon accounting is needed to understand the carbon implications of thinning in fire-prone landscapes. This would incorporate the ecosystem pools considered here as well as the quantities of carbon removed in thinning treatments and the fate of this biomass. It would also consider wildfire emissions differences between treated and untreated plots. Carbon removals in thinning treatments can be inferred from comparisons to untreated and unburned plots (planned for 2022), or could also be estimated from harvest records or comparisons of pre and post treatment inventories.

More work, especially the inclusion of untreated and unburned reference plots, will be completed in spring 2022 (and further analyses as part of Erin Twaddell’s MS thesis). Unburned/untreated plots were not part of the original plan as the focus was on treatment variation within the fire and reference to those treatments outside; however the magnitude of the carbon reduction prior to the wildfire appears to be important to interpretation. These will be shared with the funders as they become available. We will also be creating aboveground forest carbon maps across the study area. These maps and dNBR maps will be used to examine carbon and burn severity patterns relative to topography, forest type and structure, fire weather, and treatment and disturbance history. We plan on these surveys in spring 2022 and will continue to inform the parties here as to the updated results.

Extreme fire weather is likely to continue to occur in the Front Range, and given the proximity of people to burnable landscapes, understanding the relationship between fuel treatments and fire is important. It is especially important to understand the conditions at which they become less effective.

Acknowledgements

We thank the City of Boulder, Boulder County, and Jefferson County for funding this research. Dr. Amanda West Fordham and Sarah Osborne of the Colorado State Forest Service located and digitized historical treatment records included in this study. Their time and some of Anthony Vorster's time was supported by the National Institute of Food and Agriculture (NIFA) of the United States Department of Agriculture [grant number 2019-67019-29469]. The NASA DEVELOP program also supported this work — special thanks to the hard work of Neal Swayze, Christopher Choi, Garrett Knowlton, Jorune Klisauskaite, Brian Woodward, and Scott Cunningham. Mengfei Zhang also prepared data for this effort. We are grateful to the Colorado Forest Restoration Institute (CFRI) for sharing treatment spatial data and to Stephanie Mueller and Kelsey Newton at CFRI for compiling fire weather data.

Literature Cited

Brown, J.K., 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p., 16.

Campbell, J.L., Harmon, M.E. and S.R. Mitchell. 2012. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions?. Frontiers in Ecology and the Environment, 10(2): 83-90.

Choromanska, U. and T.H. DeLuca. 2001. Prescribed fire alters the impact of wildfire on soil biochemical properties in a ponderosa pine forest. Soil Science Society of America Journal, 65(1): 232-238.

DeLuca, T.H., Gundale, M.J., Brimmer, R.J. and S. Gao.2020. Pyrogenic carbon generation from fire and forest restoration treatments. Frontiers in Forests and Global Change, 3: 1-8.

Finkral, A.J. and A.M. Evans. 2008. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. Forest Ecology and Management, 255(7): 2743-2750.

Fites, J.A., Campbell, M., Reiner, A. and T. Decker. 2007. Fire Behavior and Effects Relating to Suppression, Fuel Treatments, and Protected Areas on the Antelope Complex: Wheeler Fire. Fire Behavior Assessment Team.

Hurteau, M.D. and M. North. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. For. Ecol. Manage. 260: 930–937. doi:10.1016/j.foreco.2010.06.015

Hurteau, M.D., Bradford, J.B., Fulé, P.Z., Taylor, A.H., and K.L. Martin. 2014. Climate change, fire management, and ecological services in the southwestern US. Forest Ecology and Management 327: 280–289. doi:10.1016/j.foreco.2013.08.007

Kalies, E.L. and L.L.Y. Kent. 2016. Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management, 375: 84-95.

Kashian, D.M., Romme, W.H., Tinker, D.B., and M.G. Turner. 2013. Postfire changes in forest carbon storage over a 300-year chronosequence of Pinus contorta -dominated forests. Ecological Monographs 83: 49–66.

Krofcheck, D.J., Remy, C.C., Keyser, A.R. and M.D. Hurteau. 2019. Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires. Journal of Geophysical Research: Biogeosciences, 124(10): 3075-3087.

McCauley, L.A., Robles, M.D., Woolley, T., Marshall, R.M., Kretchun, A. and D.F. Gori. 2019. Large-scale forest restoration stabilizes carbon under climate change in Southwest United States. Ecological Applications, 29(8): p.e01979.

Meigs GW, Law BE, Donato DC, et al. 2009. Influence of mixed-severity wildfires on pyrogenic carbon transfers, postfire carbon balance, and regeneration trajectories in the eastern Cascades, Oregon. Ecosystems 12: 1246– 67.

Shive, K.L., Kuenzi, A.M., Sieg, C.H. and P.Z. Fulé. 2013. Pre-fire fuel reduction treatments influence plant communities and exotic species 9 years after a large wildfire. Applied Vegetation Science, 16(3): 457-469.

Stephens, S.L., Boerner, R.E., Moghaddas, J.J., Moghaddas, E.E., Collins, B.M., Dow, C.B., Edminster, C., Fiedler, C.E., Fry, D.L., Hartsough, B.R. and J.E. Keeley. 2012. Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. Ecosphere, 3(5): 1-17.

Stevens, J.T., Safford, H.D. and A.M. Latimer. 2014. Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forests. Canadian Journal of Forest Research, 44(8): 843-854.

Thompson, D.K., Schroeder, D., Wilkinson, S.L., Barber, Q., Baxter, G., Cameron, H., Hsieh, R., Marshall, G., Moore, B., Refai, R. and C. Rodell. 2020. Recent crown thinning in a boreal black spruce forest does not reduce spread rate nor total fuel consumption: Results from an experimental crown fire in Alberta, Canada. Fire, 3(3): 28.

USDA. 2012. Fourmile Canyon Fire Findings. General Technical Report RMRS-GTR-289. https://www.fs.fed.us/rm/pubs/rmrs_gtr289.pdf

Volkova, L., Meyer, C.M., Murphy, S., Fairman, T., Reisen, F. C. and Weston. 2014. Fuel reduction burning mitigates wildfire effects on forest carbon and greenhouse gas emission. International Journal of Wildland Fire, 23(6): 771-780.

Vorster, A. G., Evangelista, P. H., Stovall, A. E., and S. Ex. 2020. Variability and uncertainty in forest biomass estimates from the tree to landscape scale: the role of allometric equations. Carbon Balance and Management 15: 1-20.

Wiedinmyer C, and M.D. Hurteau. 2010. Prescribed Fire As a Means of Reducing Forest Carbon Emissions in the Western United States. Environ. Sci. Technol 44: 1926-1932.

Tables

Table 1. Carbon stocks by treatment for various pools. Values are means. All values in Mg/ha (standard deviation). Note the Rx+wildfire treatment only has one sample, and the Overland+thin+Calwood only has two samples, and both should be interpreted cautiously.

Treatment Type (Number of Plots)	Live and Dead Standing Tree Carbon	Live Standing Carbon	Ground-cover Carbon	Woody debris Carbon	Non-Soil C (live only)	Non-Soil C (live and dead)	Organic Soil C	Mineral Soil C (top 10cm)	Total C	Total Soil and Live C
RxBurn+Wildfire (1)	0 (NA)	0 (NA)	1.5 (NA)	0 (NA)	1.5 (NA)	1.5 (NA)	11.4 (NA)	13.5 (NA)	26.4 (NA)	26.4 (NA)
Thin+RxBurn (25)	29.6 (25.0)	29.6 (25.0)	7.9 (3.0)	5.6 (8.7)	37.5 (26.2)	43.1 (25.6)	19.3 (7.5)	20.3 (8.1)	82.7 (25.7)	77.1 (27.2)
Thinned (25)	51.4 (32.6)	50.3 (32.0)	8.3 (4.4)	3.5 (2.8)	58.6 (34.6)	63.2 (35.5)	28.1 (13.1)	16.6 (6.6)	103.6 (48.1)	99.3 (46.9)
Thinned+RxBurn+ Wildfire (17)	35.3 (14.8)	13.6 (21.0)	3.3 (2.2)	1.6 (1.5)	16.9 (22.5)	40.1 (16.0)	18.1 (13.9)	24.8 (7.3)	83.1 (26.7)	59.8 (33.3)
Thinned+Wildfire (37)	32.4 (23.6)	5.7 (13.6)	2.0 (2.0)	1.2 (2.2)	7.7 (15.2)	35.6 (23.7)	14.9 (5.0)	27.7 (10.4)	78.3 (27.8)	50.3 (19.7)
Wildfire only (Calwood, 17)	51.1 (32.5)	25.4 (27.5)	4.4 (3.1)	1.4 (1.9)	29.8 (30.5)	56.8 (33.0)	16.2 (5.2)	28.2 (6.5)	101.2 (31.9)	74.2 (34.3)
Wildfire (Overland)+Thinned +Wildfire (Calwood) (2)	11.8 (16.6)	11.8 (16.6)	1.3 (0.1)	0.5 (0.4)	13.0 (16.8)	13.5 (17.1)	24.3 (4.4)	37.0 (1.5)	74.8 (11.3)	74.3 (10.9)
Wildfire (Overland)+Wildfire (Calwood) (6)	26.8 (34.0)	0 (0)	1.6 (1.0)	0.6 (1.0)	1.6 (1.0)	29.1 (33.4)	22.0 (5.0)	42.8 (17.9)	93.9 (41.9)	66.5 (17.4)

Table 2. Area of forest treatments in the Calwood burn area.

Treatment Type	Area (acres)	Percent of Burn Area	Percent of Treated Area
Wildfire and Thinned	45	0.4	2.1
Rx Burn	79	0.8	3.8
Thinned Twice	92	0.9	4.4
Thinned and Rx Burn	341	3.4	16.2
Thinned	398	3.9	18.9
Wildfire	1146	11.3	54.5
Total	2101	20.8	100.0

Figures

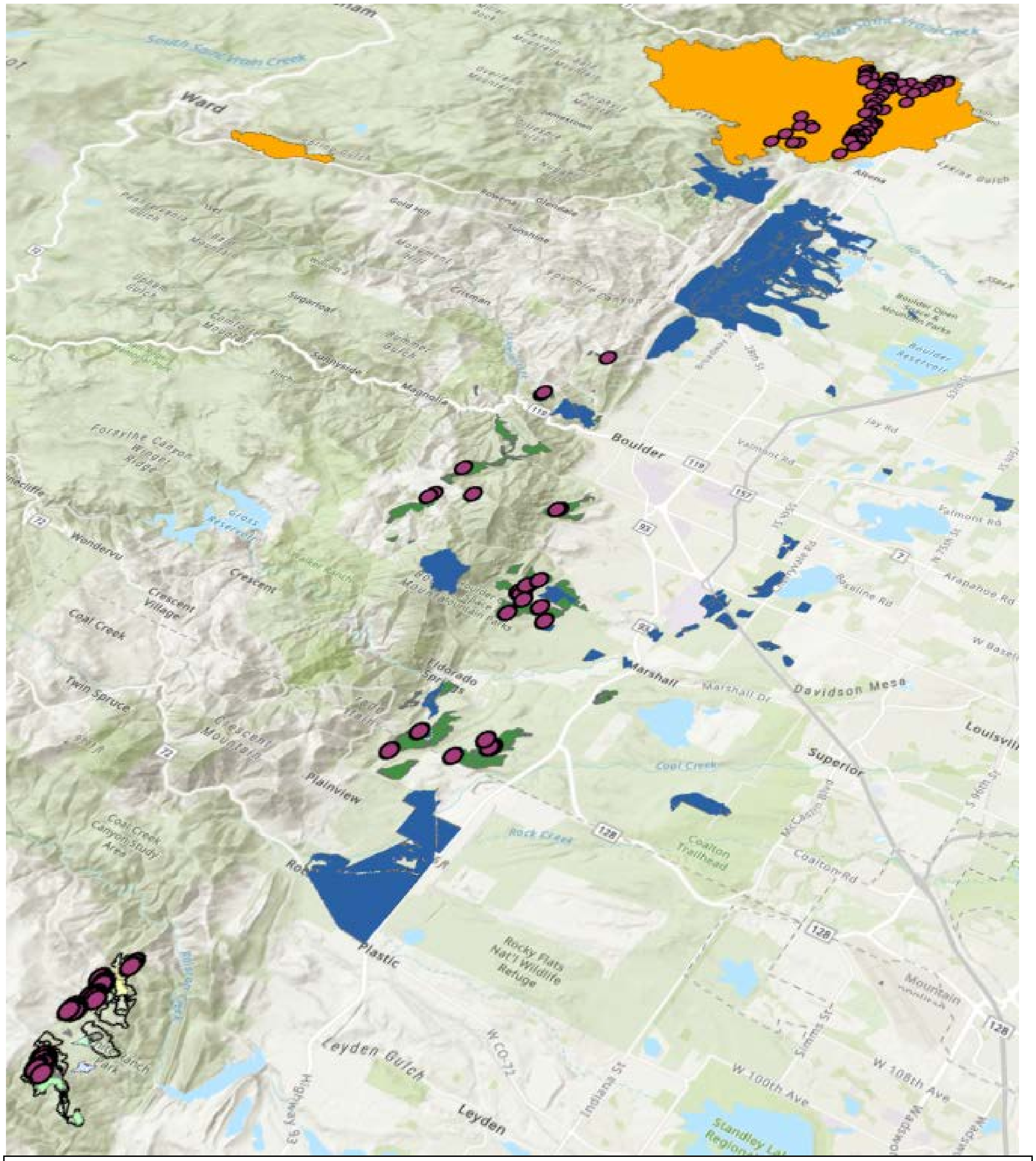

Figure 1. Sites (purple dots) visited across the study. Total number of locations sampled in 2021 is 130. Samples came from Jefferson County (n=25), City of Boulder (n=25), and Boulder County (n=80). Orange is the Calwood fire perimeter, other colors are various treatments across the jurisdictions involved in the project.

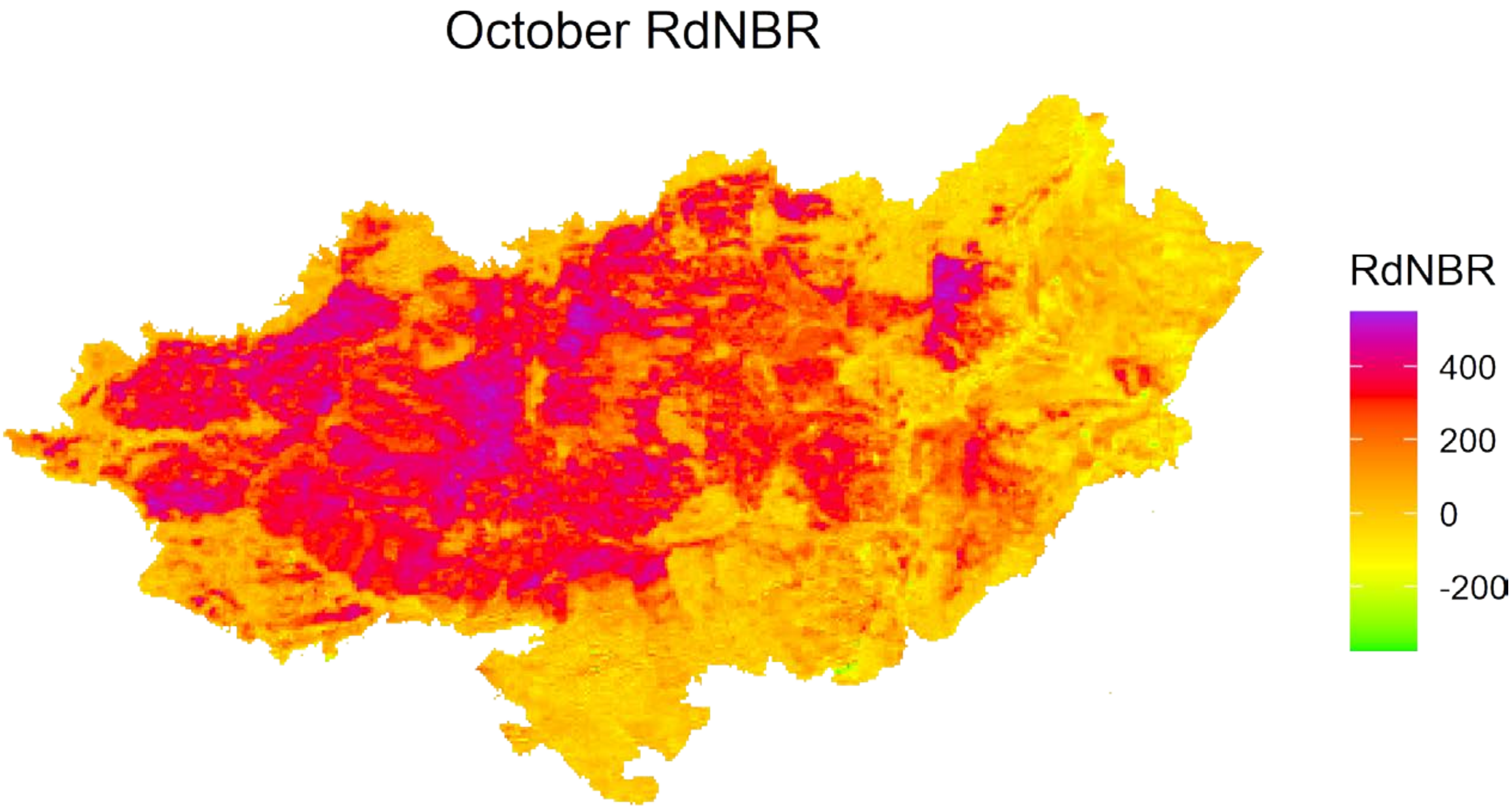

Figure 2. CalWood Fire RdNBR severity as mapped with Landsat 8 imagery. The majority of the fire was mapped as moderate-high and high burn severity. These areas largely burned within two days of the fire starting.

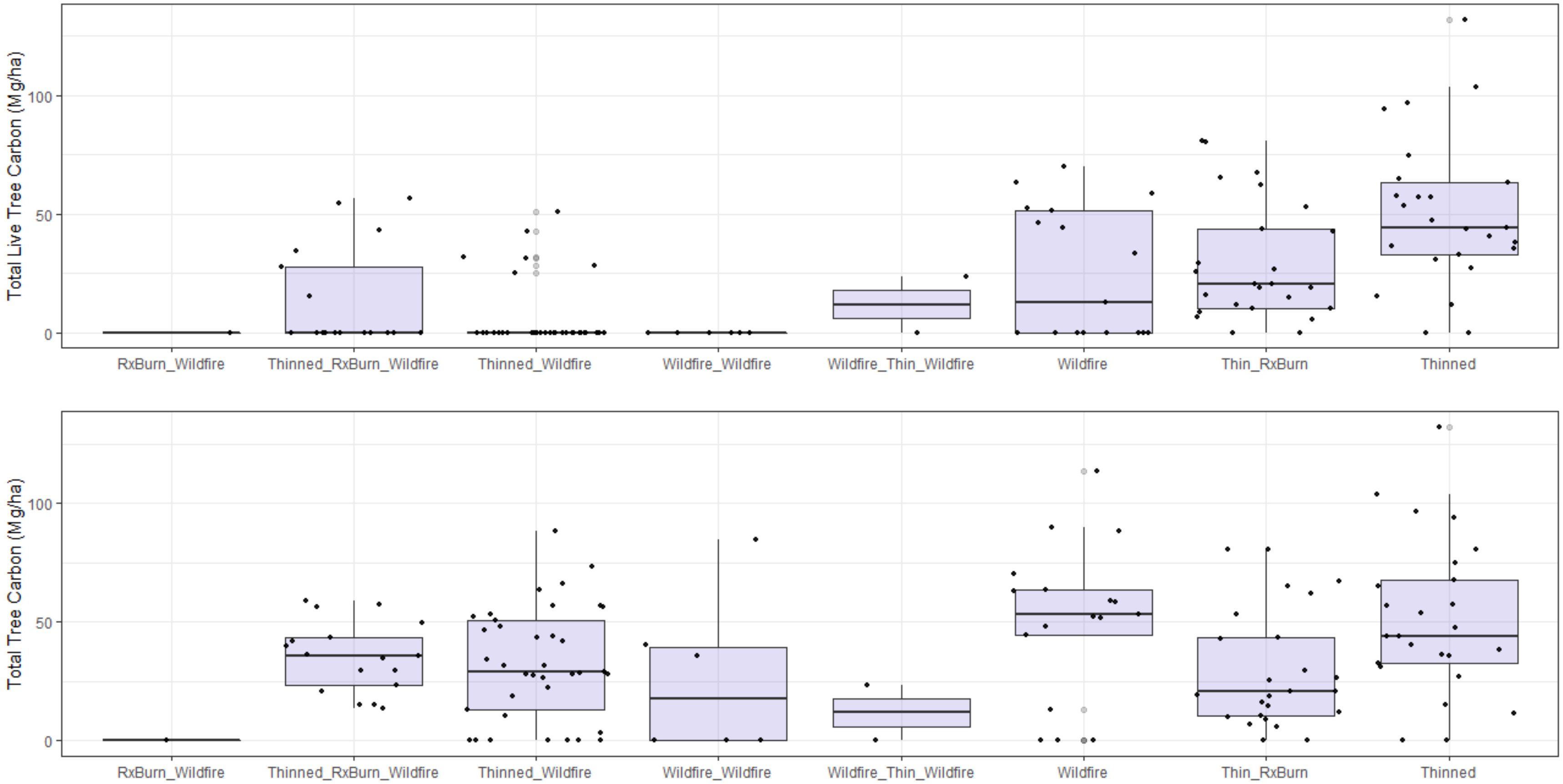

Figure 3. Carbon stocks found in tree biomass (live: top; all: bottom). Wildfire plots had very little live tree carbon on average, though a few had some surviving trees. When including dead carbon (bottom), the plots were generally similar, with previous wildfires having lower C on average, as anticipated. The cluster of higher C values associated with thinning and wildfire represent a break in location between those thinned in 2020 and those thinned earlier. RxBurn+Wildfire was only a single plot, with no trees.

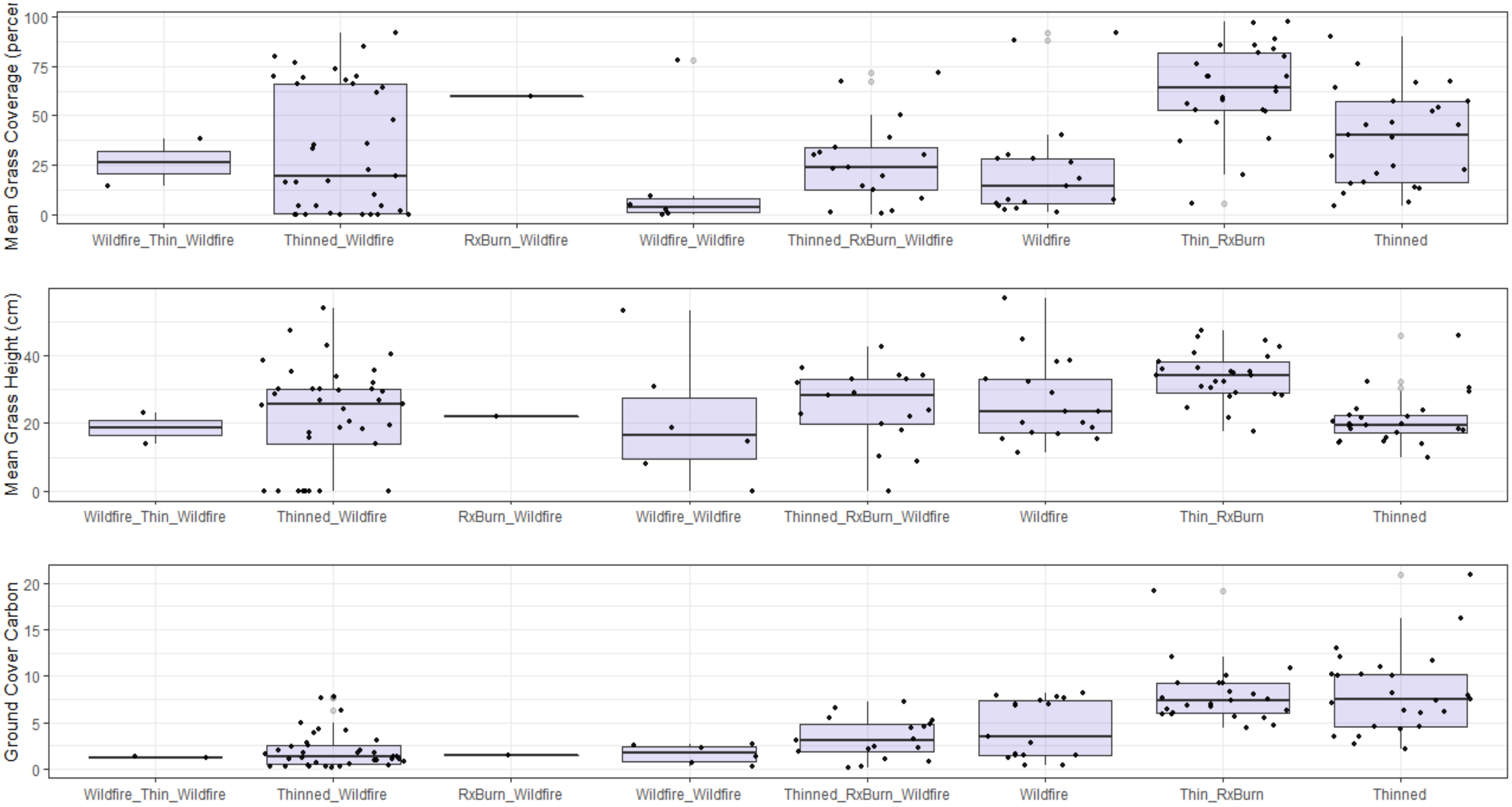

Figure 4. Ground cover coverage (top), ground cover height (middle), and ground cover carbon (bottom). Note the RxBurn+wildfire treatment only has one sample and should be interpreted cautiously.

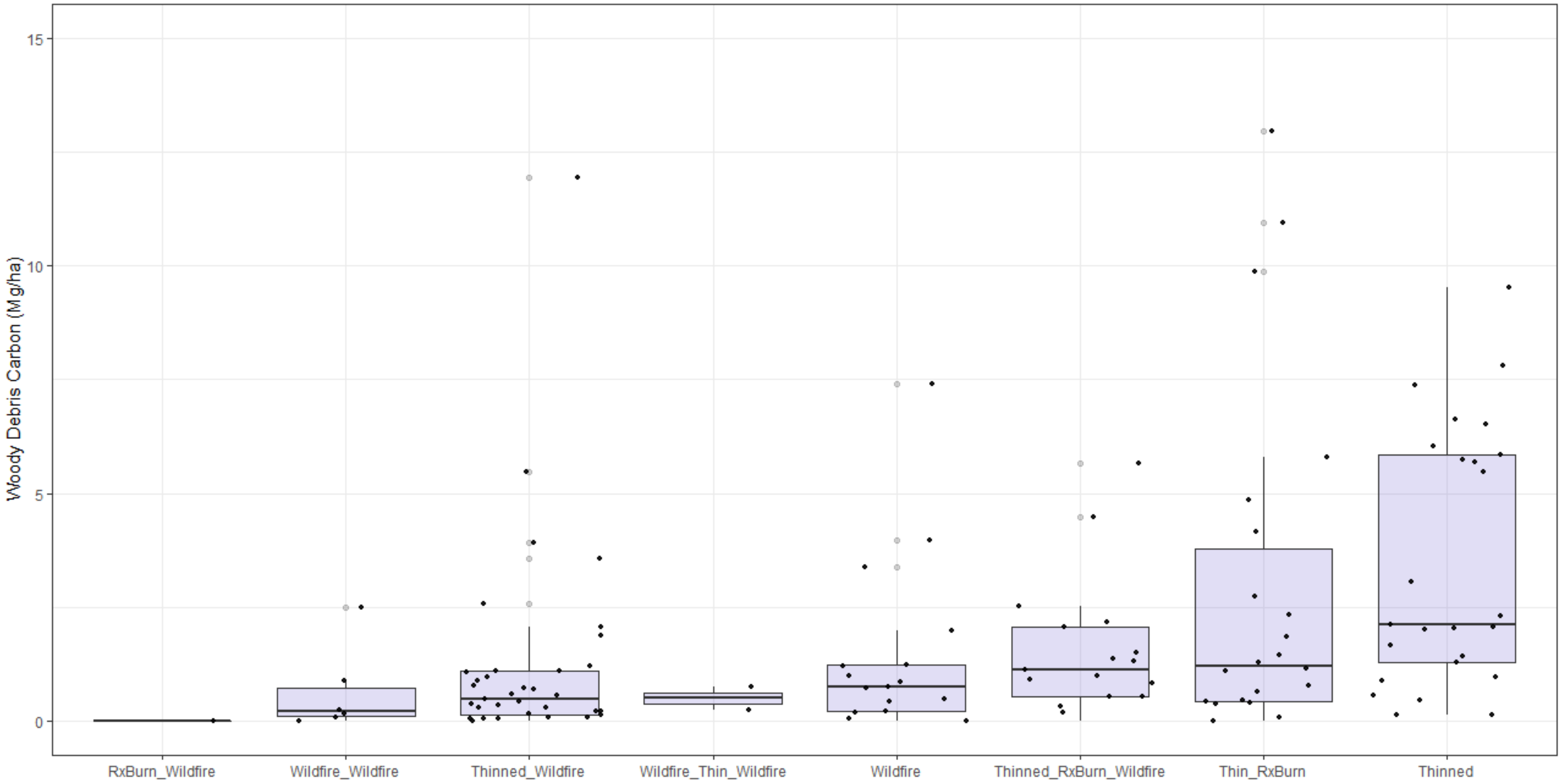

Figure 5. Woody debris on ground. The thinned treatment had the highest woody fuel loading on the ground, whereas the Thin+RxBurn was substantially lower. Note the RxBurn+wildfire treatment only has one sample and should be interpreted cautiously.

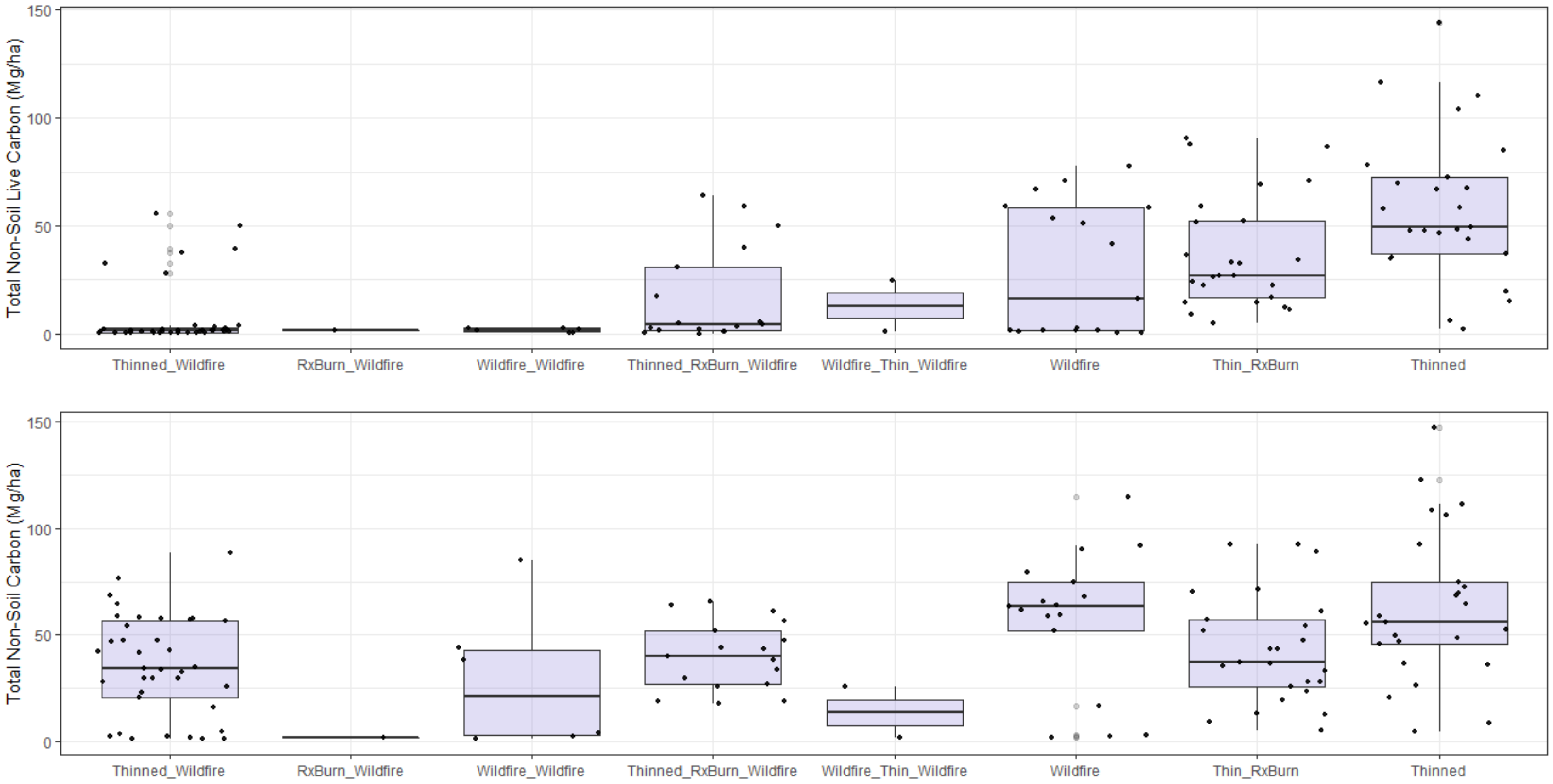

Figure 6. Totals for non-soil carbon (live: top; all: bottom). The nonwildfire plots had the highest live carbon, unsurprisingly, with Rx + thinned plots slightly lower than thinned only. The wildfire plots all had lower live carbon. To date, there were minor differences in non-soil live carbon across the treatments that burned in the Calwood fire, with the lowest being in the thinned + wildfire plots, though the older thinnings to the north had higher survivorship. Note the Rx+wildfire treatment only has one sample and should be interpreted cautiously.

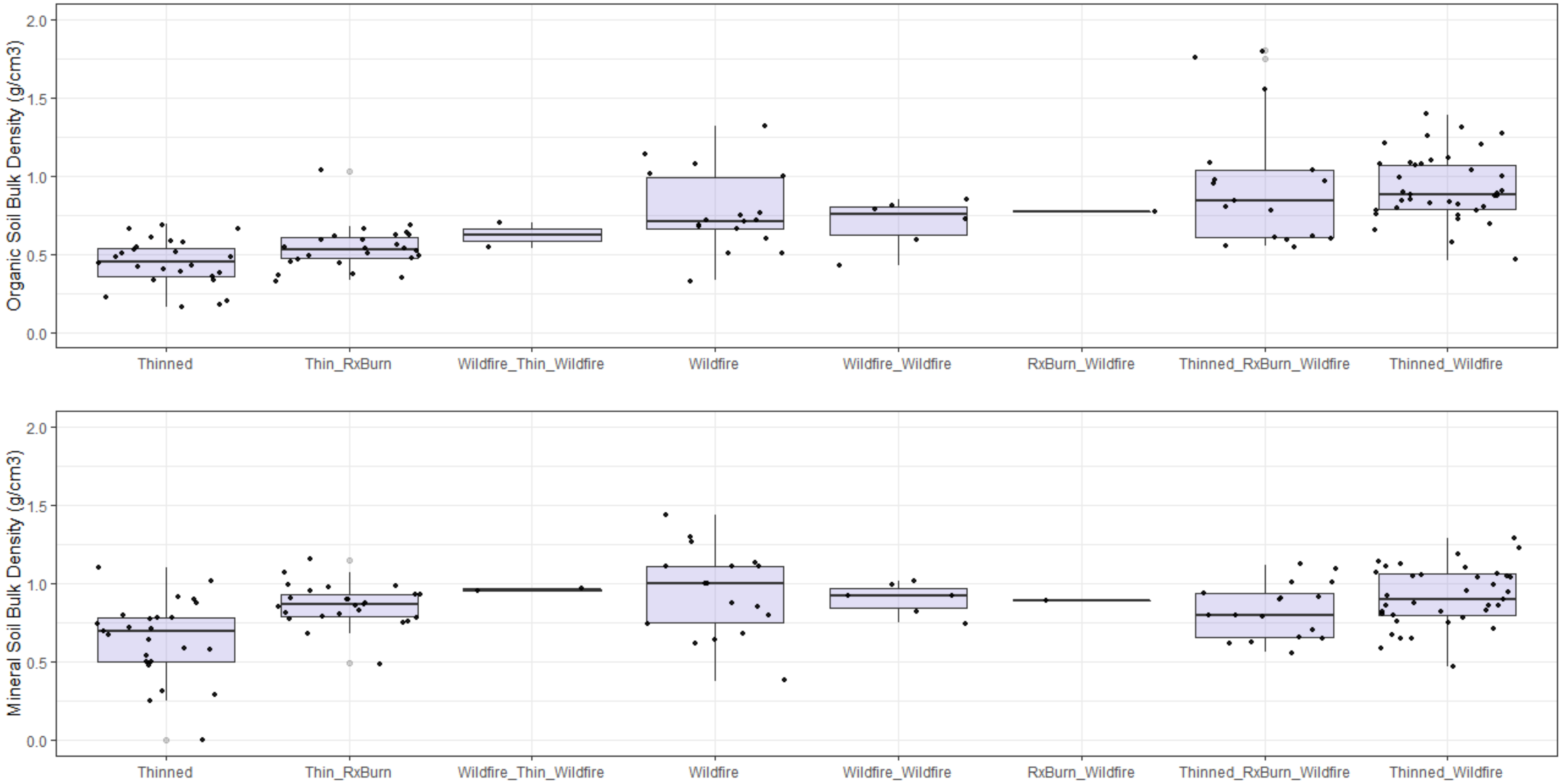

Figure 7. Soil bulk densities (organic layer: top; mineral soil: bottom). Lower values = less dense soils. Ashy combusted material from the organic layer prior to the wildfire was considered the organic layer for this analysis, to whatever depth was found. The mineral soil bulk density calculated for the top 10 cm of the mineral soil profile. Note the Rx+wildfire treatment only has one sample and should be interpreted cautiously.

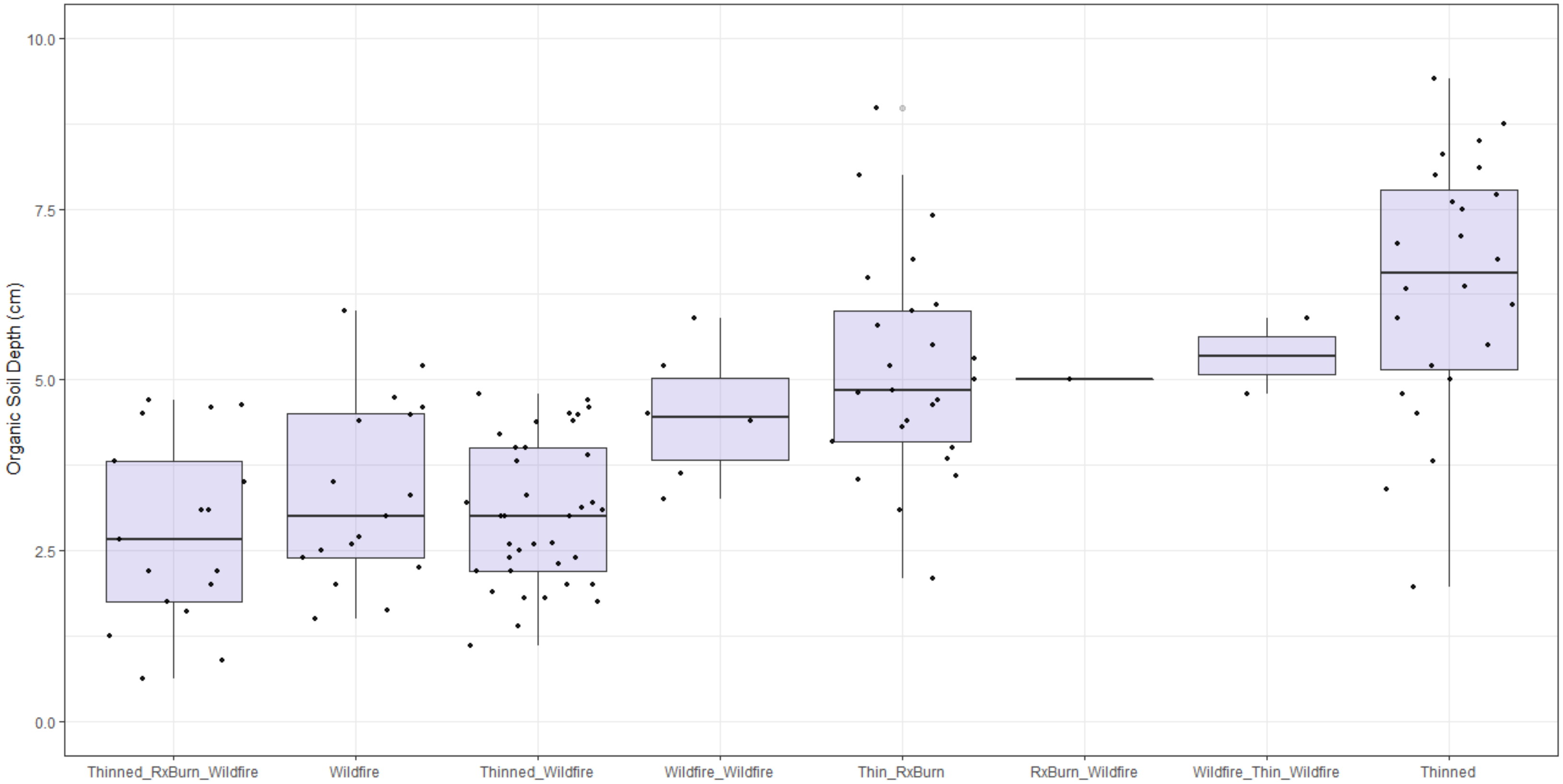

Figure 8. Organic soil depths (cm) for each treatment. Of non-wildfire plots, the thinning+Rx burned treatment was lower than thinning only; this pattern repeats, but at a lower overall level, in the plots impacted by the wildfire. The two wildfire plots with deeper organic layers are both very low sample size (1 and 2, respectively, so interpret with caution).

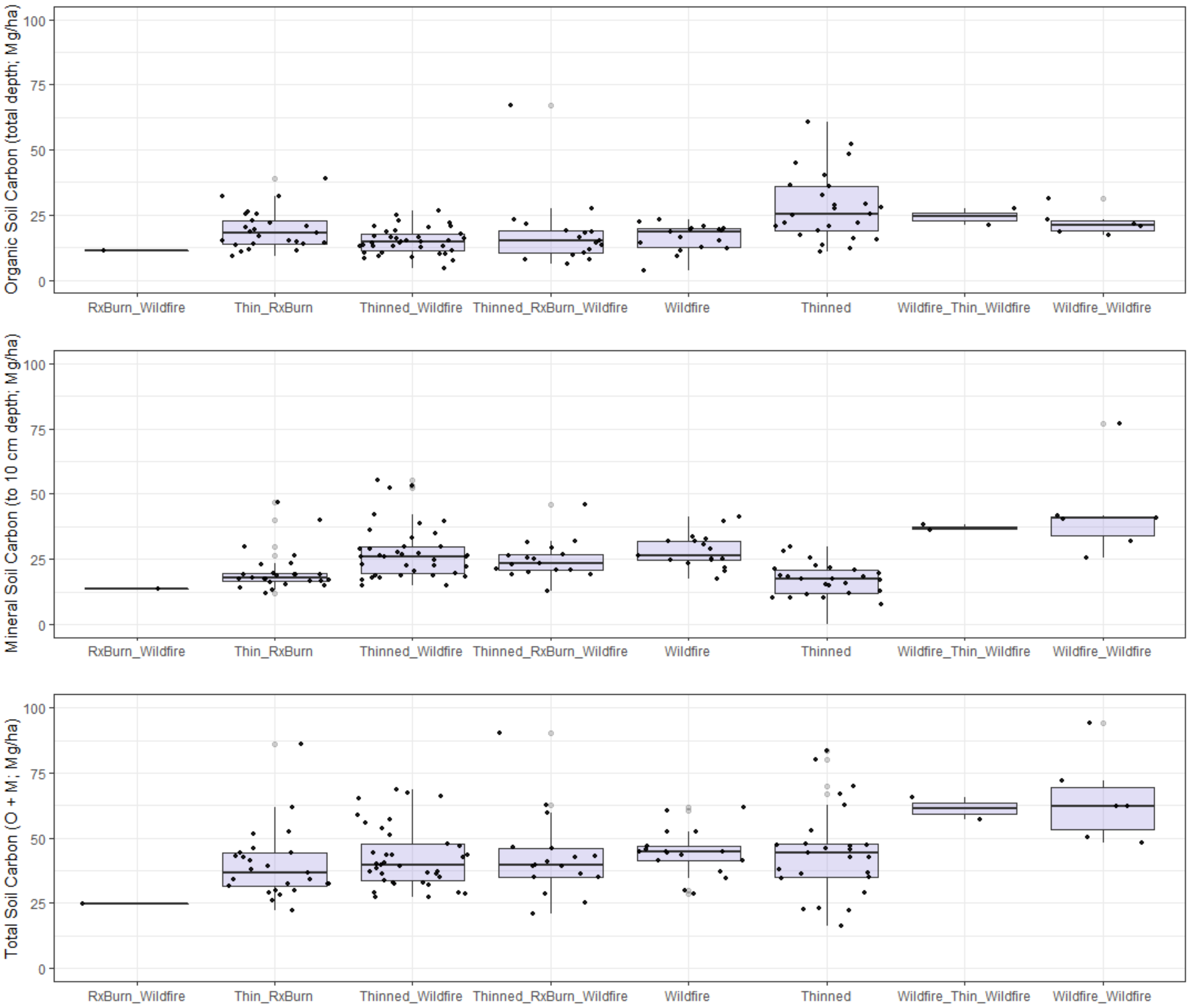

Figure 9. Total soil C stocks. Top: Organic soil C stocks, full depth of the layer. Middle: Mineral soil C stocks, to 10cm depth. Bottom: Total (organic + mineral). All units in Mg/ha. Note the Rx+wildfire treatment only has one sample and should be interpreted cautiously.

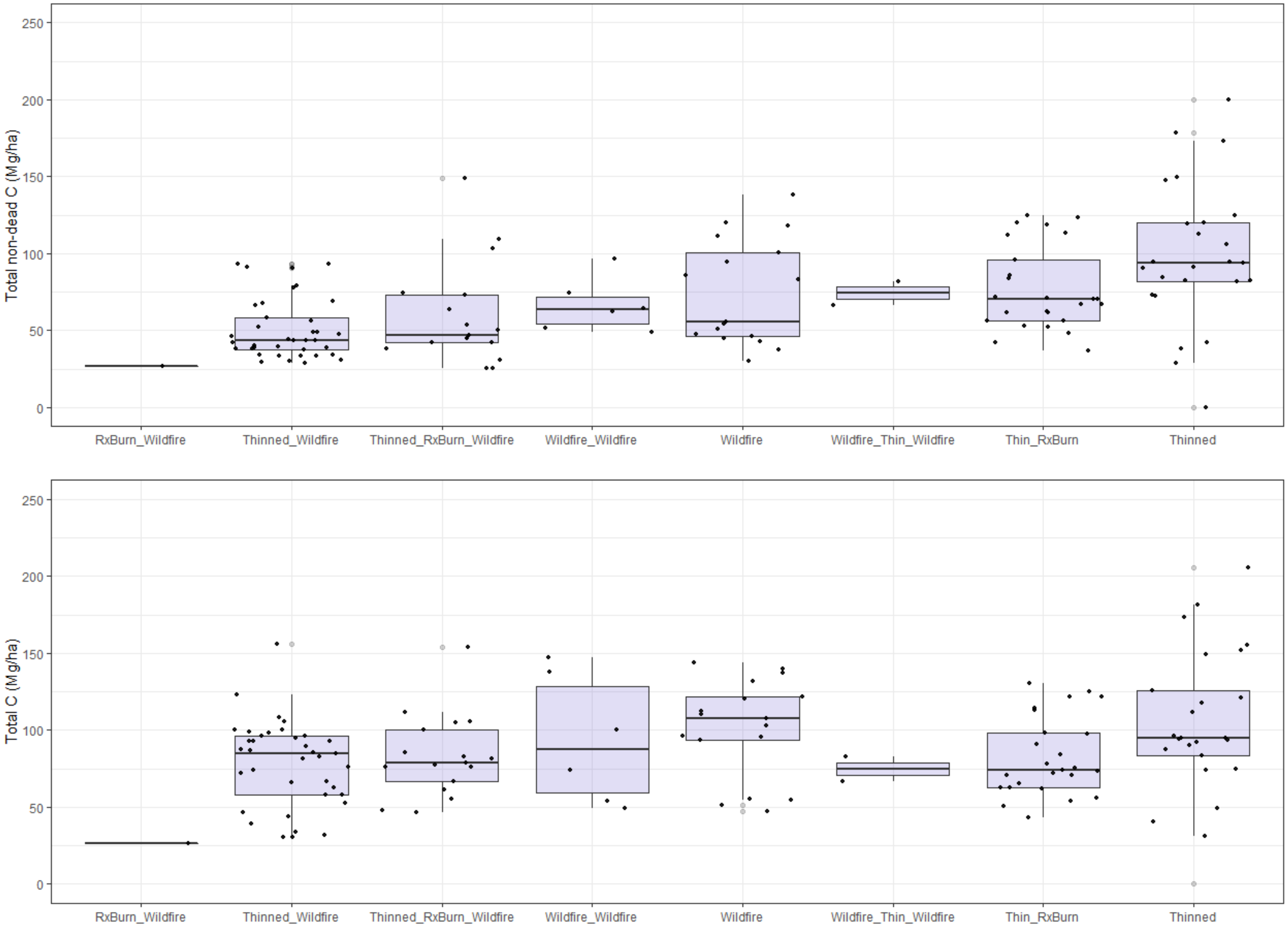

Figure 10. Total carbon stocks (Mg/ha) for each treatment. Top: Live carbon and soil stocks. Bottom: Total carbon (live and dead), also including soil. Full organic soil profile included, and top 10cm of mineral soil. Note the Rx+wildfire treatment only has one sample and should be interpreted cautiously.

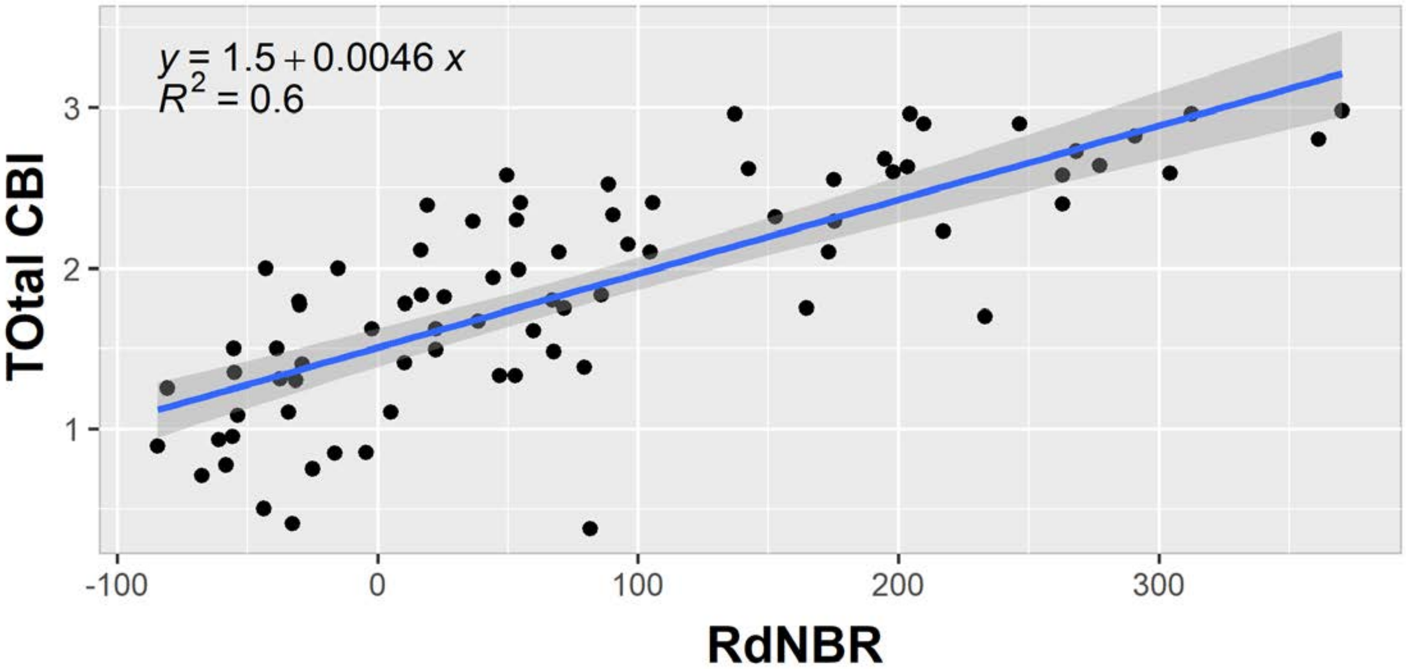

Figure 11. Relationship between RdNBR mapped with October Landsat 8 imagery (Fig. 2) before and after the CalWood fire and burn severity field observations.

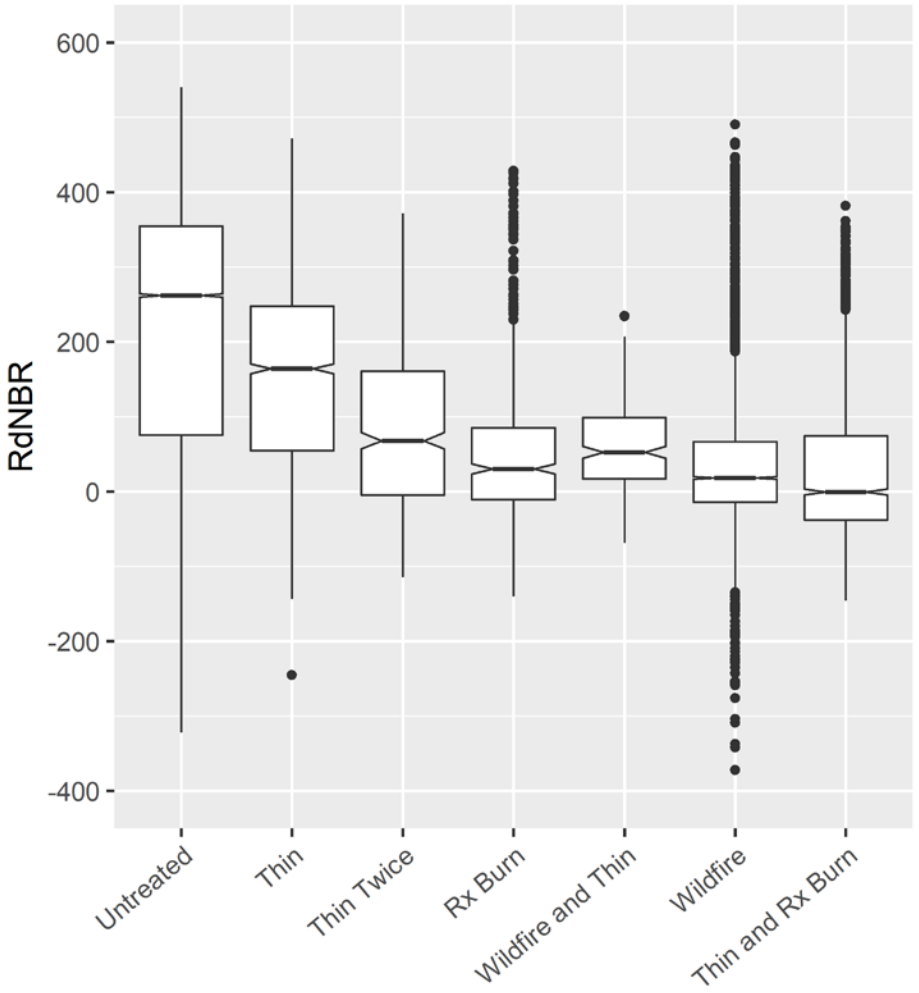

Figure 12. Remotely sensed burn severity (October RdNBR) summarized for untreated, previously burned, and various treatment combinations within the Calwood perimeter. “Untreated” refers to wildfire-only plots, no treatment prior to the Calwood event. “Wildfire” refers to locations within the prior Overland fire perimeter. Negative values correspond to unburned or lightly burned areas or areas that recovered by the time of the October 2021 satelite image collection. .

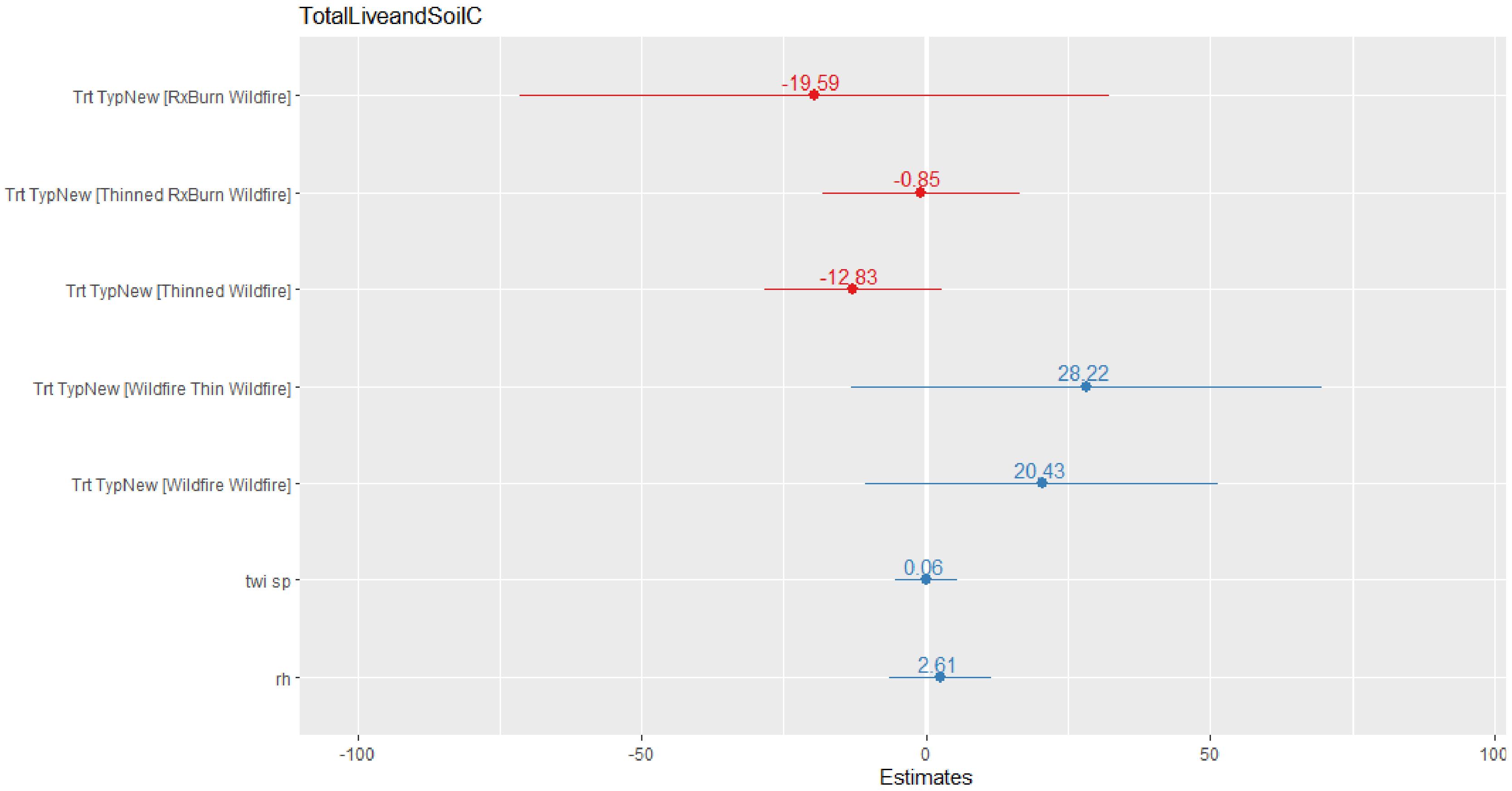

Figure 13. Effect sizes of treatments, humidity (rh), and topographic wetness (twi) on soil and post-fire live carbon (groundcover and surviving trees). In general, although the range of potential values is wide, prior wildfire resulted in higher estimated live and soil C, and prior human treatments resulted in lower. Wind speed was used as a random effect in the modeling structure.

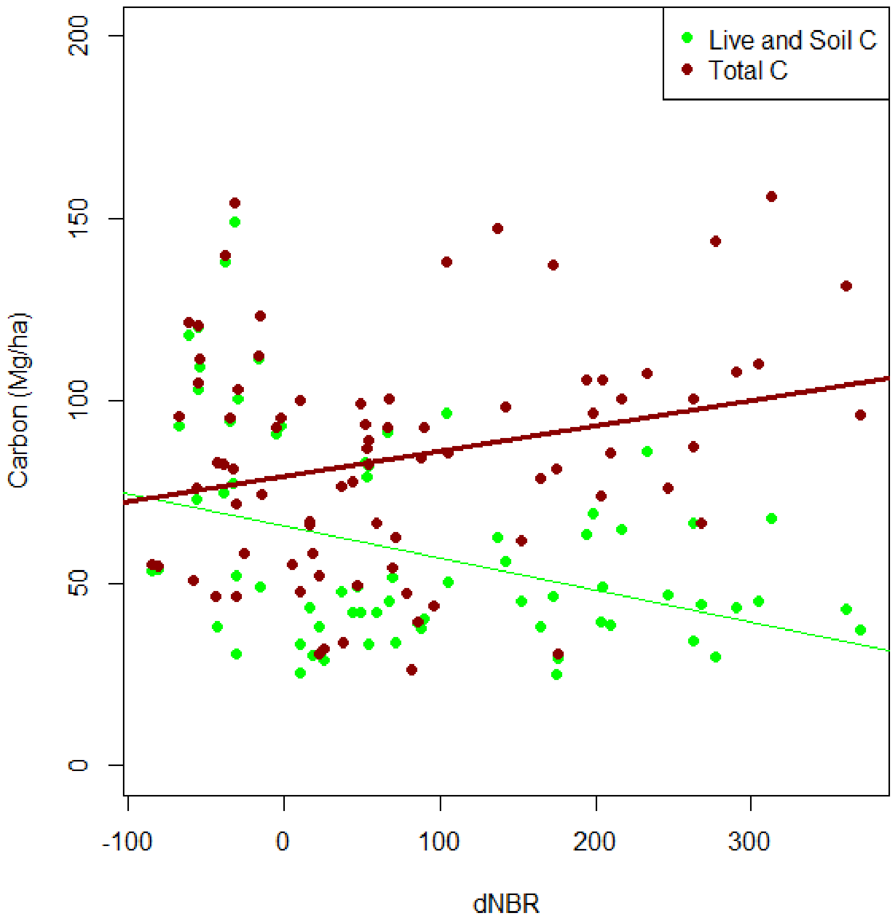

Figure 14. Corrleation between carbon stocks and dNBR. The relationship between live and soil C is nonsignificant (essentially flat) with substantial scatter. The relationship with total C (including dead) is significant and positive ($p = 0.02$, effect = 0.069, SE = 0.029) as is the relationship with live/soil C ($p = 0.001$, effect = -0.09, SE = 0.025).

Appendix

The associated zip file contains several datasets.

“plot data.csv” contains the plot-level summary data for carbon calculations.

The “fire_weather” folder contains wind data associated with the fire, and was provided by CFRI.

The “remote_sensing_severity” folder contains RdNBR maps created for the fire. The October map was used in the analysis presented here.

R code for the figures above.