Repeat short-interval fires put carbon storage at risk in Interior Alaska via cumulative combustion of soil carbon

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Abstract

Fire regimes alter the distribution, accumulation, and stability of carbon stocks across multiple spatial and temporal scales, particularly in boreal ecosystems, which are globally important storehouses of terrestrial carbon stocks. In interior Alaska, increasing temperatures and snow-free times have resulted in a greater frequency of short-interval fires (fires occurring within 50 years or less of preceding fires), which depart from historic fire-interval norms, where fires were historically infrequent and severe, occurring every 100-300 years. Increasing fire frequency causes shifts in forest structure and composition that affect carbon storage; however, the extent, strength, and mechanisms of these effects remain unclear. Fast-growing broadleaf species may lead to greater aboveground biomass in reburned stands; however, the cumulative severity of multiple fires may burn into carbon-rich soil organic layers. Here, we quantified aboveground and soil carbon in boreal black spruce (*Picea mariana*) stands that burned once, twice, or three times in the last 70 years within short intervals (<50 years). We quantified the effects of cumulative severity, stand structure, and composition on both aboveground and soil carbon in upland and lowland stands. Total carbon in reburned stands declined with additional fires, even with increases in tree density of faster-growing deciduous trees. Cumulative severity had the largest effect on aboveground biomass and soil carbon stocks in both sites, but particularly in upland stands, indicating that the effects of continued reburning on carbon storage may differ across topographic position. This study expands our understanding of future carbon dynamics in boreal forests, particularly in the context of emerging reburning, and contributes to a larger body of knowledge on the effects of continued disturbances on carbon storage.

Keywords: Boreal forests, Carbon Stocks, Reburning, Soil Carbon, Forest composition, Fire frequency

Introduction

Boreal forests are globally important carbon storehouses; as much as 30% of the world's terrestrial carbon stocks are stored within the forest floor and soil (Pan et al. 2011, IPCC 2021). In interior Alaska, fire drives the distribution, accumulation, and stability of C across spatial and temporal scales (Kasischke and Stocks 2012). However, changing climate and wildfire regimes may threaten boreal carbon stocks at regional scales (Walker et al. 2019; Dieleman et al. 2020) with the potential to exacerbate global climate change (Mekonnen et al. 2022).

Soil carbon is the dominant form of carbon in boreal forests: limited aboveground productivity and cold and/or anaerobic soil conditions promote permafrost and the accumulation of "legacy" carbon (carbon that persists across fire events, Walker et al. 2019). Fires have been a feature of the landscape for 10,000 years, with return intervals within 100-300 years (Higuera et al. 2008, Hoecker et al. 2020). Fires consume surficial soil carbon, but following fire, soil carbon reaccumulates via several mechanisms, including increased input via litter from regenerating biomass, production of pyrogenic carbon, and decreased decomposition rates from physical shifts in porosity, pH, and stability driven by combustion (Pellegrini et al. 2022; Shabaga et al. 2022). Thus, after a single fire event, soil carbon recovers relatively quickly in black spruce stands, reaccumulating 20-40 grams per year (Harden et al. 2012; Kane and Vogel 2009; O'Neill et al. 2006). Consequently, soil carbon inputs from litter or pyrogenic carbon balance soil carbon losses from combustion within 7 to 15 years after fire (O'Neill et al. 2006; Shabaga et al. 2022). However, fires that reburn previous fire perimeters within short intervals (repeat fires or reburns) can burn more deeply into organic soils, releasing not only larger amounts of carbon but also combusting legacy carbon (Walker et al. 2019) and increasing the rate of permafrost thaw due to thin (or eliminated) insulating organic layers.

Aboveground carbon is more dynamic than soil C and strongly mediates how changes in the fire regime will alter carbon stocks in the future, both above- and belowground. Black spruce forests cover nearly 45% of all forested area in Alaska (Calef et al. 2005; van Cleve et al. 1983), and store the greatest amount of carbon relative to other forest types in the region (Johnson and Kern 2002). Thick soil organic layers associated with black spruce forests prevent seed germination of broadleaf species, whose smaller seeds cannot survive in moss layers as long as larger black spruce seeds (Johnstone and Chapin 2006), maintaining “ecological inertia” at the landscape scale (Harden et al. 2006). In addition, coniferous forests regenerate strongly after a fire via serotinous cones, enforcing strong legacy seedbank conditions (Johnstone et al. 2010). However, a single reburn (a second fire that burns shortly after the first) can produce mixed regeneration stands, as slow-growing, dispersal-limited spruce are killed prior to maturity, particularly in the initial decades after fire. Continued reburning (multiple short-interval fires) can convert dense black spruce stands into open broadleaf stands (Hayes and Buma 2021). Fast-growing deciduous species produce greater overall aboveground carbon than black spruce 20-60 years after fire events (Alexander et al. 2012), outweighing losses in carbon from soil consumption (Mack et al. 2021). Over a third of Alaskan black spruce stands are considered susceptible to shifting to deciduous dominance via reburn-conversion (Kurkowski et al. 2008).

Given the above, resolving questions about fire frequency and its impact on the key drivers, soil, forest density, and forest composition, are key to resolving whether aboveground carbon pool increases will offset losses in belowground carbon pools under novel reburning conditions. In addition, drainage is important and topographically controlled, and most existing research divides the landscape into uplands (well-drained, drier) and lowlands (poorly drained, wetter). Taken together, investigating how carbon stocks are altered across topographic positions and comparing key drivers of soil, forest structure, and composition will be critical for understanding the future of carbon cycling across the North American boreal.

This study quantified aboveground and soil carbon in reburned stands and investigated the role of forest composition, forest structure, and cumulative fire severity in altering above- and belowground carbon pools. We asked the following questions: 1) What is the impact of continued reburning on carbon stocks (aboveground live, soil, dead, and total) in boreal forests? and 2) How do differences in tree density, forest composition and soil consumption correlate with total carbon storage in reburned uplands and lowlands?

Methods

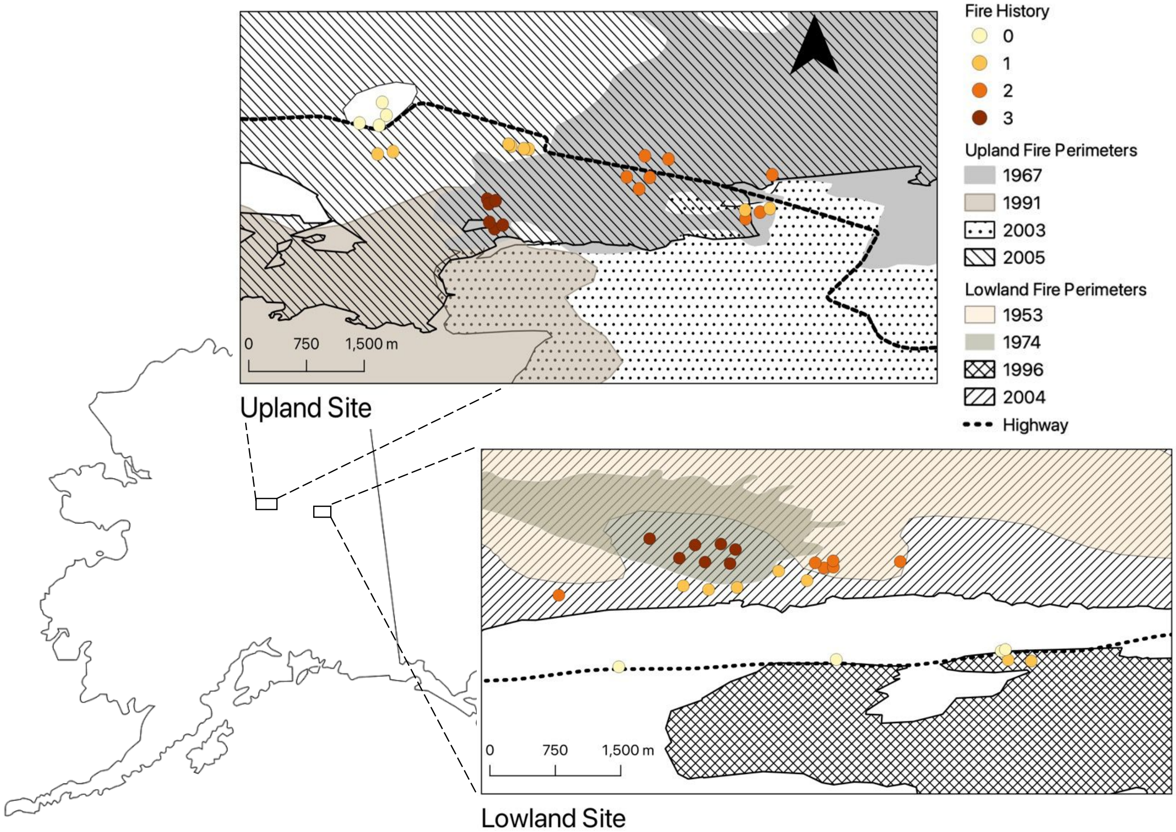

Figure 1. Map of Study Sites. Upper map displays location of upland study plots, lower map shows lowland study plots.

Study design

The study was conducted at two locations in Interior Alaska that have experienced 0-3 fires at intervals of < 30 years (the most recent burn in all plots was 2004 or 2005). Sites were originally dominated by mature black spruce stands, confirmed via aerial photography and remote sensing (Hayes and Buma 2021), and contain a mosaic of overlapping fire perimeters from 1953 to 2005, allowing for opportunistic, spatially constrained sampling of different fire frequencies in areas with the same initial composition. We established 50 400 m^2 plots in summer field seasons of 2018 and 2019, a minimum of 90 m apart (Fig. 1). Reburned plots (n = 42) were established a minimum of 100 m from burn perimeters, outside the dispersal distance of black spruce (~ 50 m; LeBarron 1939, Johnston 1971). All burned stands experienced complete aboveground mortality during each fire. We also established eight unburned reference plots within bordering unburned black spruce remnant forests.

We cored snags of each species represented in each plot to estimate the stand age of mature plots and to confirm the fire history in reburned plots, ensuring that no trees survived prior to fires. Cores were mounted, sanded, and then imaged using ImageJ to visualize fine rings (Schneider et al. 2012).

Estimating Aboveground Carbon

We estimated aboveground carbon in the field by measuring tree and shrub diameters above diameter at breast height (DBH, 1.37 m). At sites where very high densities precluded sampling the full 400-m^2, we sampled across a randomly selected 100-m^2 subplot and scaled up. We used regionally developed, species-specific allometric equations (Bond-Lamberty et al. 2002, Byrd 2013) to estimate total aboveground carbon within live and dead trees (see specifics in Appendix 1: Table S1). We were unable to locate local allometric equations for *Alnus viridis* *crispa* based on DBH, and relied on regional equations for *Alnus viridis sinuata* instead (Binkley et al. 1984). We assumed biomass was 50% carbon.

To account for carbon stored in dead or downed trees and debris, we measured downed woody debris (DWD, dead wood lying or standing at <45^0 angle) using two 28-m transects crossing the center of each plot and converted DWD field data into estimates of mass per area (grams per meter), following Brown (1974).

To estimate herbaceous and shrub understory plant biomass, we harvested all material in 10 randomly selected 1 m^2 subplots in each plot and dried samples at 50 °C. We scaled the resulting dry weight to estimate understory biomass.

Estimating Soil Carbon

We took soil cores at the corners and center of each plot ($n = 5$ per plot) using a 15-cm depth volumetric sampler, sampling the entire organic layer, and then 15 cm of the mineral. Mineral soil samples were sieved into two size classes (>2 mm and <2 mm) and homogenized in plastic bags. We ground soils using a roller mill before combusting in a Costech 8020 Elemental Analyzer to estimate the carbon content of each sample. We calculated the total carbon content within the organic and mineral soil horizons as the product of the depth, bulk density, and carbon percentage of each horizon.

Data Analysis

To quantify the impact of reburning on carbon and to test for the interactive role of topographic position, we directly compared major pools (aboveground, soil, DWD, and overall total carbon) across fire histories. To explore whether the direct and indirect effects of continued reburning (shifts in forest structure, composition, and soil organic layer) were good predictors of carbon storage in biomass and soil carbon, we used two hierarchical log-normally distributed multivariate Bayesian regression models to compare the effect sizes of site-level forest structure, composition, and cumulative severity on (1) live aboveground biomass and (2) soil carbon.

The model structure was the same for both response variables, with a slight difference in modeled sources of measurement error (see below):

$$\log(\mu_{ij}) = \alpha_j + \beta 1(Density) * x_{ij} + \beta 2(Deciduous\ BA) * x_{ij} + \beta 3(SOL) * x_{ij} + \varepsilon_i$$

where μ_{ij} represents the mean carbon in plot i within a given site, α_j represents the intercept, β represents the slope coefficients of each predictor variable and ε_i represents a normally distributed error term. We used the density of trees (trees per meter^2) to represent forest structure, given the importance of tree density as a mechanism in Mack et al. 2021. In addition, the short and consistent time since the last burn across all sites resulted in minimal variation in height or other similar metrics of structure. To represent the shift in species composition from conifers to deciduous trees, we used the sum of the basal area of deciduous species (basal area m^2 per ha). We selected soil organic layer depth (averaged within a plot in cm) to represent cumulative burn severity, given the role of soil consumption as a common proxy for fire severity in boreal forests (Harden et al. 2006). To compare effect sizes directly, we scaled each coefficient to a z-score between 0 and 1.

For both models, we used a Bayesian Markov Monte Carlo (MCMC) approach (Waller et al. 2003; Hooten and Hobbs 2015) to generate posterior values of coefficients. We ran 2,500 iterations across three chains and used trace plots to confirm that the Monte Carlo chains reached stationarity (Appendix: Figure S2). We intentionally selected vague priors (normally distributed, mean = 0, standard deviation = 1) to reflect the inherent lack of knowledge about the parameters, while still setting reasonable expectations (Kéry and Royle 2020).

All models were built using the “r2Jags” package (Su and Yajima 2012, version 1) and all analysis, model fit, and selection were performed in R version 4.1.2 (R Core team 2021, *code available online*). Additional information on the modeling approach and Bayesian inference used to estimate coefficient effect size including the specification of prior distributions and specifics on the MCMC sampler are provided in the appendix (S2).

Results

R1. How do carbon pools (overstory live and dead biomass, understory biomass, litter biomass and soil carbon) shift with continued reburning?

Total Carbon

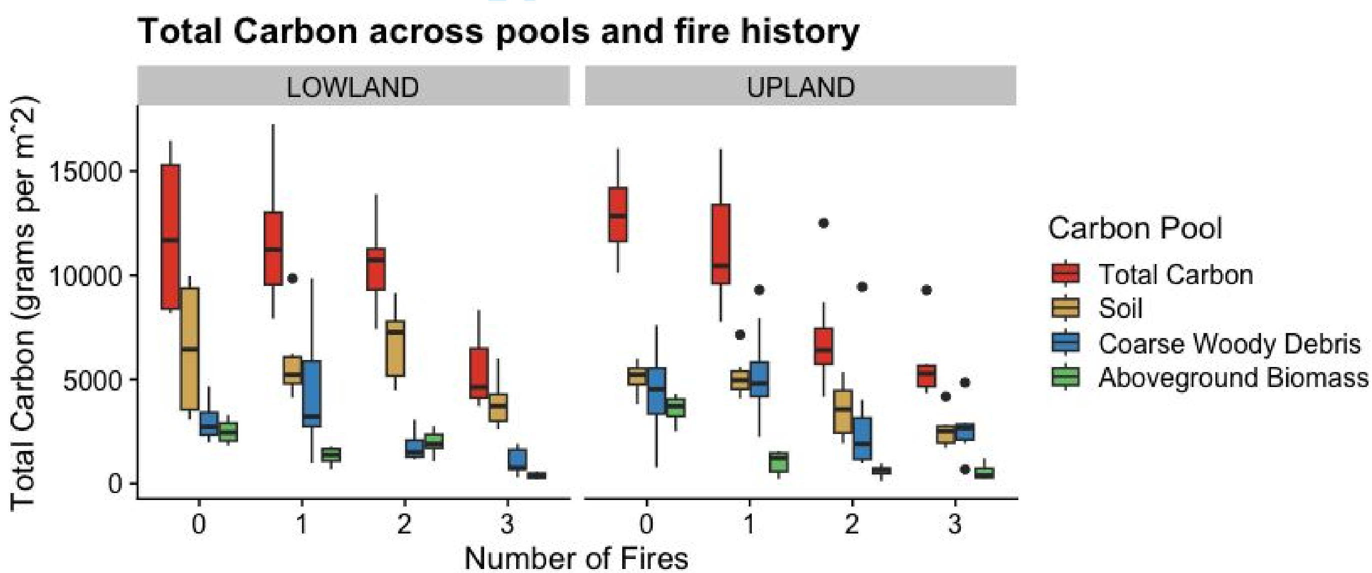

Figure 2. Total carbon across reburn history and within carbon pools. Green represents the combined pool of carbon within live overstory and understory biomass.

Across the plots, total carbon declined as fire frequency increased (Fig. 2) despite the similar age of all burned plots (13-16 years since last fire); all were less than the reference stands (86-106 years since last fire; Appendix Table S2). While the lowland and upland sites contained similar amounts of total carbon in sampled pools prior to burning (lowlands average 11,999 g/m^2, SD 4,299; uplands average 12,975 g/m^2, SD 2,075), that total carbon was distributed differently.

Aboveground Biomass

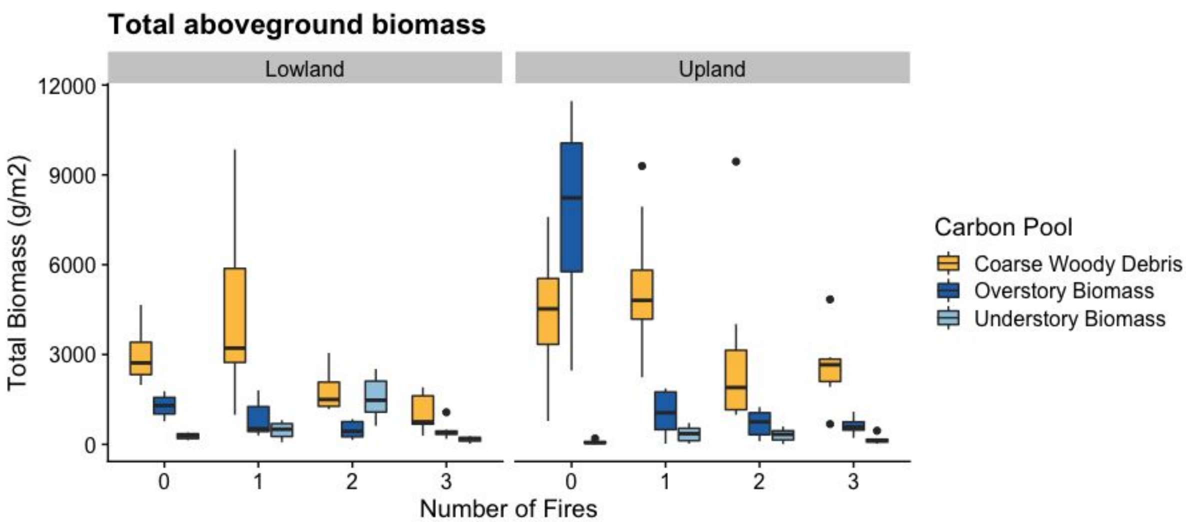

Figure 3. Aboveground biomass across reburn history and across pools.

Upland mature plots contained greater aboveground biomass prior to burning, due to both greater overstory and coarse woody debris biomass (Fig. 2). Coarse woody debris pools were relatively similar between mature and once-burned sites but were smaller in twice-burned sites (decreasing on average 27%). Higher coarse woody debris in some upland thrice-burned plots was associated with greater aboveground biomass overall in the three fire sites compared to two. Across both sites, understory biomass was the smallest carbon pool and did not appear to shift with reburning (understory biomass was an average of .09% of total carbon in unburned plots and averaged 0.46% in thrice-burned plots).

Soil Carbon

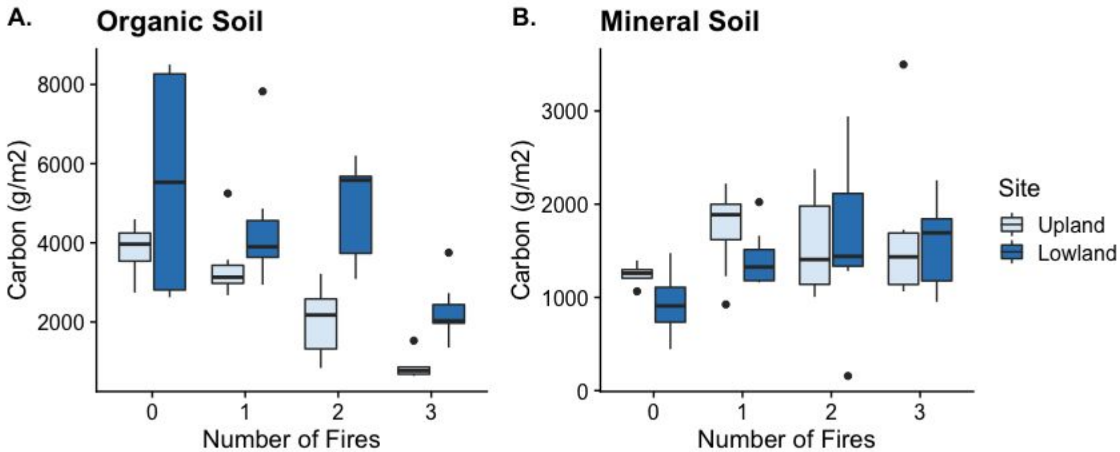

Figure 4. Carbon abundance of mineral (A) and organic (B) soil layers across reburn history and between sites.

Generally, soil organic layers contain more carbon than mineral soil. Carbon in mature plots in both locations was primarily stored as soil carbon (soil carbon was 39% of total carbon on average in uplands, 54% in lowlands). Trends in mineral and organic soil carbon pool size differed between lowland and upland sites (Fig. 4). Organic layer soil carbon was lower in reburned plots in both locations, but particularly lower in upland stands (Fig. 4A). Estimates of soil organic layer carbon were higher in lowlands after two fires to levels similar to mature plots (average 5,546 g/m^2 in twice-burned plots vs 4,880 g/m^2 in unburned plots). In three fire plots, organic soil layer was consumed altogether in some plots (soil organic layers in uplands contained twice less carbon on average than corresponding mineral soils – 874 g/m^2 in organic vs 1,707 g/m^2 in mineral).

R2. What are the effects of species composition, regeneration density, and cumulative severity on the abundance of aboveground and soil carbon in reburned stands?

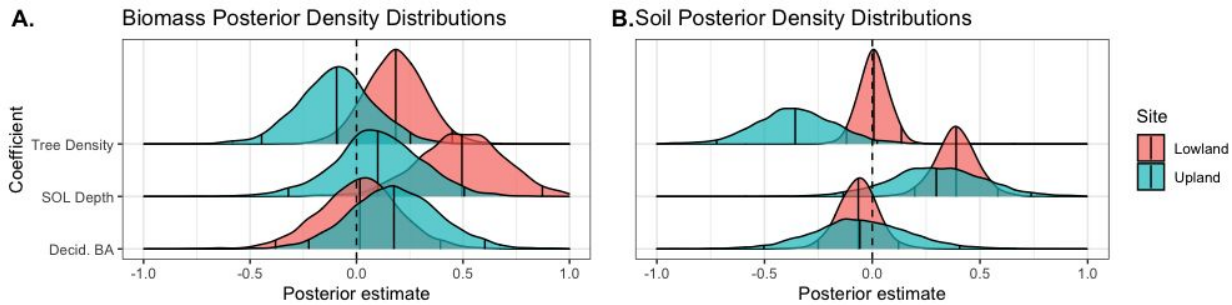

Figure 5. Posterior density distributions for site-level variable coefficients within upland and lowland field sites. Center line indicates median, ridge lines mark the edges of a 95% interval. Coefficients are z-scores, scaled to values between 0 and 1 – thus posterior estimates occur within the same range. (A) Posterior density distribution for aboveground live biomass model. (B) Posterior density distribution for soil carbon model.

The effects of tree density, soil organic layer depth and deciduous basal area on carbon followed similar trends across aboveground and soil pools but differed between sites (Fig. 5). Soil organic layer depth displayed the strongest positive effect size in both sites and both pools, but particularly in lowland plots. Tree density had negative effects on aboveground biomass and soil carbon in uplands, but no apparent effect on lowland soil carbon (median centered around 0) and a slight positive effect on lowland aboveground biomass. Deciduous basal area was not a strong predictor of either pool of lowland carbon; its strongest effect is on upland biomass, which increases as deciduous basal area increases.

Discussion

We found that both aboveground and soil carbon declined with reburning in upland and lowland stands. Tree density and deciduous basal area in reburned stands did not appear to meaningfully shape variability in carbon storage, either aboveground or in soil. Rather, soil organic layer depth, a proxy for cumulative burn severity, had the strongest positive effect on total carbon, particularly in lowlands. Within the limited timeline of study (stands 15 years postdfire), the impact of soil loss did appear to outweigh the increase in deciduous species despite their faster growth over the observed timescales. Together, these results suggest the importance of increased fire frequency and their cumulative severity, especially of multiple fires and their potential to drive ecosystem carbon storage past documented norms.

Our mature upland stands had greater aboveground biomass than regional averages and our lowlands had lower (average aboveground biomass in 60 year-old black spruce stands is 27.7 Mg per hectare, Yarie and Billings 2002). This is in line with expectations: lowlands are generally less productive than uplands (Jafarov et al. 2013).

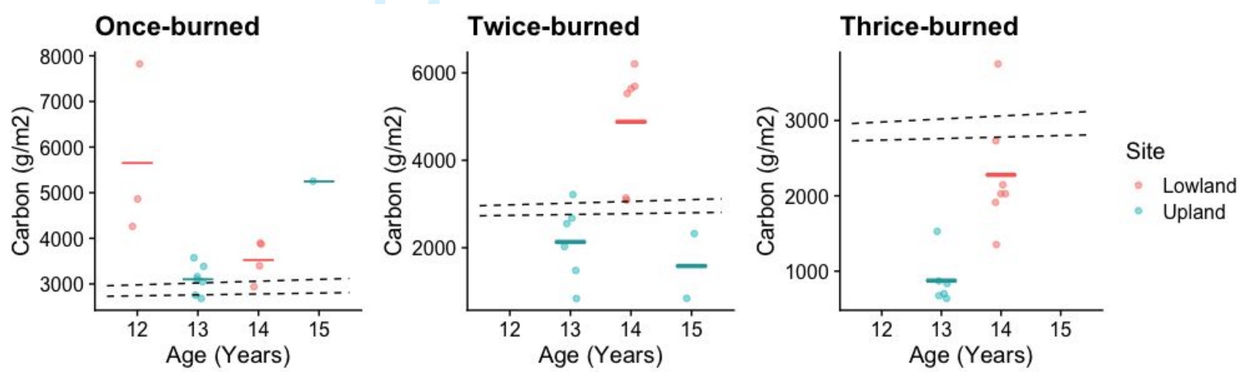

Figure 6. Observed vs predicted soil organic layer carbon across reburns. Colored horizontal averages represent averages of sites according to age in years. Dotted lines represent the range of predicted soil carbon accumulation after fire as predicted by Harden et al. 2012 and others.

Historically in the boreal, soil organic layer carbon recovers relatively quickly after fire events, accumulating an average of 20-40 grams of carbon per m^2 per year (Harden et al. 2012; Kane and Vogel 2009; O'Neill et al. 2006). Our estimates of soil organic layer carbon in reburned stands roughly correspond to predicted carbon accumulation rates initially (once burned Fig. 6). Upland average soil organic carbon is lower than predictions after two fires (Fig. 6B). Furthermore, when we move into burn frequencies that have not been observed before (our three-fire sequence), our observations of soil organic layer carbon depart from expectations after three fires (Fig. 6C). The difference between upland and lowland may be because of topographic differences. Lowlands have poor drainage and thus greater soil moisture and greater amounts of organic layer are consumed if the layer is drier (Kasischke and Turetsky 2006). While we sampled only the top 15 centimeters of mineral soil, reburning may make even deeper soil organic carbon pools available to mobilize. Shabaga et al. (2022) found that reburning increased active layer depth, leading to higher respiration likely from decomposition of previously unavailable soil organic carbon.

Not only are the losses in carbon crucial, the implied loss of soil organic matter itself has large implications for future boreal forest characteristics. Soil organic layers help maintain “ecological inertia” at a landscape-scale (Harden et al. 2006) by favoring black spruce regeneration. Studies like Alexander et al. (2012) and Mack et al. (2021) found that increases in the relative density, basal area and abundance of deciduous species are correlated to increases in aboveground biomass, attributing the relationship to higher annual primary productivity and faster accumulation of stemwood and bark in deciduous species compared to black spruce, but make no distinction between deciduous species. However, the impact of species-specific trends in deciduous regeneration may be important - deciduous regrowth in our reburned upland sites was primarily birch, while aspen dominated in reburned lowland plots (Hayes and Buma 2021). Both grow relatively fast after fire, but aspen is far more productive than birch (Van Cleve 1975, Viereck et al. 1986). Neither typically exist in high density pure stands in Interior Alaska currently (birch is common in gaps, Uchtyil 1991; aspen occurs across 2 – 10% of the interior, largely in floodplains; Viereck 1975), so our understanding of their longer-term dynamics and the resulting impact on carbon in these landscape contexts is limited. Given these findings, there is the potential for divergence in carbon stocks dynamics at the deciduous species level as well in the future. Given species differences in their tolerances for differing climatic, edaphic, and hydrological conditions (Viereck et al. 1986), this could become significant as warming continues.

Because of the inherently opportunistic nature of post-disturbance sampling, this study has a few key limitations. This study design, similar to chronosequence but varying frequency across space, samples two mosaics of fire histories, and each fire within that mosaic was shaped by various factors such as microtopography, fire weather at the scale of days or hours, or local microclimate, all factors that remain unquantifiable within the context of this study but may still all influence subsequent forest establishment and soil development. To interpret these results in the context of future carbon dynamics of the boreal ecoregion and the global carbon cycle more broadly, results from this study and from others like it (Melvin et al. 2015, Alexander et al. 2012) should be investigated further in approaches that allow for broader generalizations beyond these specific study sites (i.e., modeling and meta-analyses).

Our empirical evidence shows that repeated fires enable departures from historic norms of carbon storage and cycling in interior Alaska. Future increases in fire frequency and short-interval fires, which are already observable in the rapidly warming Arctic (Buma et al. 2022), will greatly alter that dynamic.

Conclusion

Declines in aboveground and soil carbon occur in reburns regardless of landscape position. Our results are consistent both with other empirical estimates of carbon storage after extreme fire and with simulations, which predict the transformation of the boreal into a net carbon source via increases in fire frequency and severity. Additionally, our study illustrates how cumulative severity of soil organic layer consumption shape carbon stocks in regenerating stands, even in historically more resilient landscape positions. Continued research into the susceptibility of the interior to landscape-scale reburning will be critical to understanding how shifts in fire frequency will shape carbon cycling at a larger boreal scale.

Data Availability

All code used in the analyses of this paper are publicly available as a repository on GitHub (https://github.com/k8hayes/Biomass) and datasets are available on Zenodo (https://doi.org/10.5281/zenodo.7401461).

Acknowledgments

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Conflict of Interest

The authors have no conflict of interest to declare.

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