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Forest Restoration Thinning Has Minimal Impacts on Surface Soil Carbon in a Second-Growth Temperate Rainforest

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Abstract: Forest restoration thinning may accelerate the development of structural complexity toward old-growth conditions faster than a natural forest, yet associated changes in forest carbon (C) are poorly understood. Old-growth forests are characterized by high levels of sequestered C in aboveground biomass and soil C pools, yet active management has well-recognized negative impacts on stored C. Effects of forest restoration thinning on forest C can be determined using longitudinal measurements and modeling based on stand conditions and tree growth. At Ellsworth Creek Preserve in Southwest Washington, forest restoration efforts in a second-growth temperate rainforest have been monitored using permanent plots since 2007. Here, we compare repeat measurements from 2020, modeled forest C, and measurements of O-horizon C pools from 2022 to determine C impacts of silvicultural treatments for old-growth restoration. We found good general agreement between empirical measurements and models of forest C using the Forest Vegetation Simulator (FVS). However, treatment alone was not a strong indicator for C conditions; rather, forest age and age–treatment interactions better predicted soil C responses to restoration treatments. These data may indicate that "light" forest restoration thinning can accelerate old-growth development with minimal effects on soil carbon—a win-win conservation strategy for old-growth forests and the climate.

Keywords: carbon; forest; FVS; modeling; old-growth; restoration; soil; thinning

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1. Introduction

The need to understand forest soils and their importance for ecosystem functions like carbon (C) sequestration is becoming more important with the growing threat of climate change [1]. A review of negative emissions technologies suggested that afforestation and reforestation is the most cost-effective approach to mitigating the effects of global warming, although forest preservation may have the most significant potential impact [2]. In many temperate rainforest systems, less than 18% of the world's original primary old-growth forests remain [3]. Land-use changes and short-rotation forestry over the last century have resulted in a deficit of these late-successional forests, and wildfire and insect disturbances associated with climate change may reduce intact primary forests even more [4]. There is an increasing need to understand the long-term impacts of old-growth preservation and restoration on timber production and biodiversity [5,6] as well as for carbon storage [7–9], especially regarding soil C [1].

Ecological restoration activities offer significant promise in restoring many structural attributes of temperate old-growth forest ecosystems through selective harvests, small patch cuts, thinning from below, and targeted species removal and release thinning [10,11]. Nevertheless, it is less clear how such restoration treatments will intersect with forest carbon (C) storage and uptake, especially given the well-known effects of harvests on long-term carbon balance [12]. Further, long-term research has demonstrated predictable trends in soil organic matter following harvests where organic matter declines immediately and then slowly recovers over time [13]. For example, in a 70-year-old white spruce forest in Fairbanks, Alaska [14], thinning had a negative relationship on soil C, influenced by microclimatic changes to decomposition rates. Soil respiration has been found to be higher than net primary productivity from regrowth in younger stands [15] due to high heterotrophic respiration. It is unclear how such trends might apply to the relatively light ecological forestry prescriptions typical of management designed to increase old-growth attributes in wet coastal forests of the highly productive Northwestern coast [16–19]. Showcase restoration projects, such as the silvicultural treatments in The Ellsworth Creek Preserve in Washington State, USA (hereafter referred to as Ellsworth), provide a unique opportunity to examine changes in soil C associated with ecological forestry in a temperate rainforest ecosystem [20,21]. Previous work in pacific coast temperate rainforests has addressed how aboveground structural attributes have responded to restoration treatments [9,21] and understory plant responses to restoration treatments [21,22], but responses of whole-ecosystem carbon storage and soil organic matter (OM) C have not been evaluated or modeled in detail. Quantifying the accuracy of modeled relationships for forest C over time, coincident with the comparison of C between managed and control stands, would help us understand how management decisions are impacting C pools and the predictability of their outcomes. Past studies have demonstrated the greatest proportion of C losses in the O-horizon soil layer (>30%) [23]. Although deeper layers are significant [24]), we chose to focus on aboveground carbon storage and potentially dynamic changes in the OM layer.

In this study, we (1) used measures of stand structure from 2007 and 2020 to model forest stand C and soil OM C at the Ellsworth site using the United States Forest Service's (USFS) Forest Vegetation Simulator (http://www.fs.fed.us/fvs/; FVS, accessed on 1 June 2022); (2) directly measured accumulated OM pools and OM C pools in treated and control stands more than a decade after restoration treatments; (3) compared modeled and empirical values for stand C, soil OM, and soil OM pools; and (4) evaluated differences in O-horizon soil C sequestration between treated and control (no treatment) plots. We hypothesized that treated plots would show a decrease in stand C and O-horizon soil C pools compared to control plots, driven by the removal of biomass and reductions in O-horizon C due to reduced litter inputs and increased heterotrophic respiration and decomposition [25].

2. Materials and Methods

2.1. Study Area and Experimental Design

The Ellsworth Creek Preserve (Ellsworth) covers approximately 2300 ha of forested and freshwater stream systems in the Willapa Hills region of Southwestern Washington, USA (Figure 1). The property was acquired by The Nature Conservancy (TNC) in the early 2000s and has an elevation range from 0 to 365 m and a mild, maritime climate characterized by cool, wet winters and relatively warm, dry summers (Western Regional Climate Data center, https://wrcc.dri.edu/, accessed on 21 September 2023). Ellsworth forests are typical of second-growth forests dominated by a mix of western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), and red alder (*Alnus rubra*) [26]). Ellsworth was previously managed for timber production, and ages typically range from 20 to 80 years old. Structurally, most stands are in the competitive exclusion stage of stand development—a common result of systematic re-planting after clear-cut harvesting [5,27].

A science advisory committee composed of academic and management agency representatives assisted TNC in implementing a watershed-scale experiment designed to evaluate the effectiveness of forest restoration efforts at Ellsworth in the early 2000s. Restoration treatments were replicated across the study area. Control sites are represented by areas of forest where no management interventions were implemented. Treated sites, however, are areas where restoration treatments were implemented to stimulate forest growth, lower tree density, increase species diversity and abundance, and accelerate the development of forest structural complexity. Our analysis focused on forest structure and vegetation plots within two treated sub-basins (C1 and N2) and two control sub-basins (C2 and N1). Each sub-basin contained 28 0.1 ha plots, for a total of 112 permanent plots, measured in 2007 (pre-treatment). Remeasurements took place in 2020 (post-treatment) and 60 plots were revisited for sampling. The plots consisted of 31 plots in control sub-basins and 29 in treated sub-basins. Among these, 16 young plots (15–30 years old) and 15 mature plots (60–71 years old) were in the control sub-basins, and 13 young and 16 mature plots were in the treatment sub-basins. Each permanent plot contained four subplots located 10 m from the plot center in each cardinal direction where soil carbon was measured. See Case et al. [21] for more information.

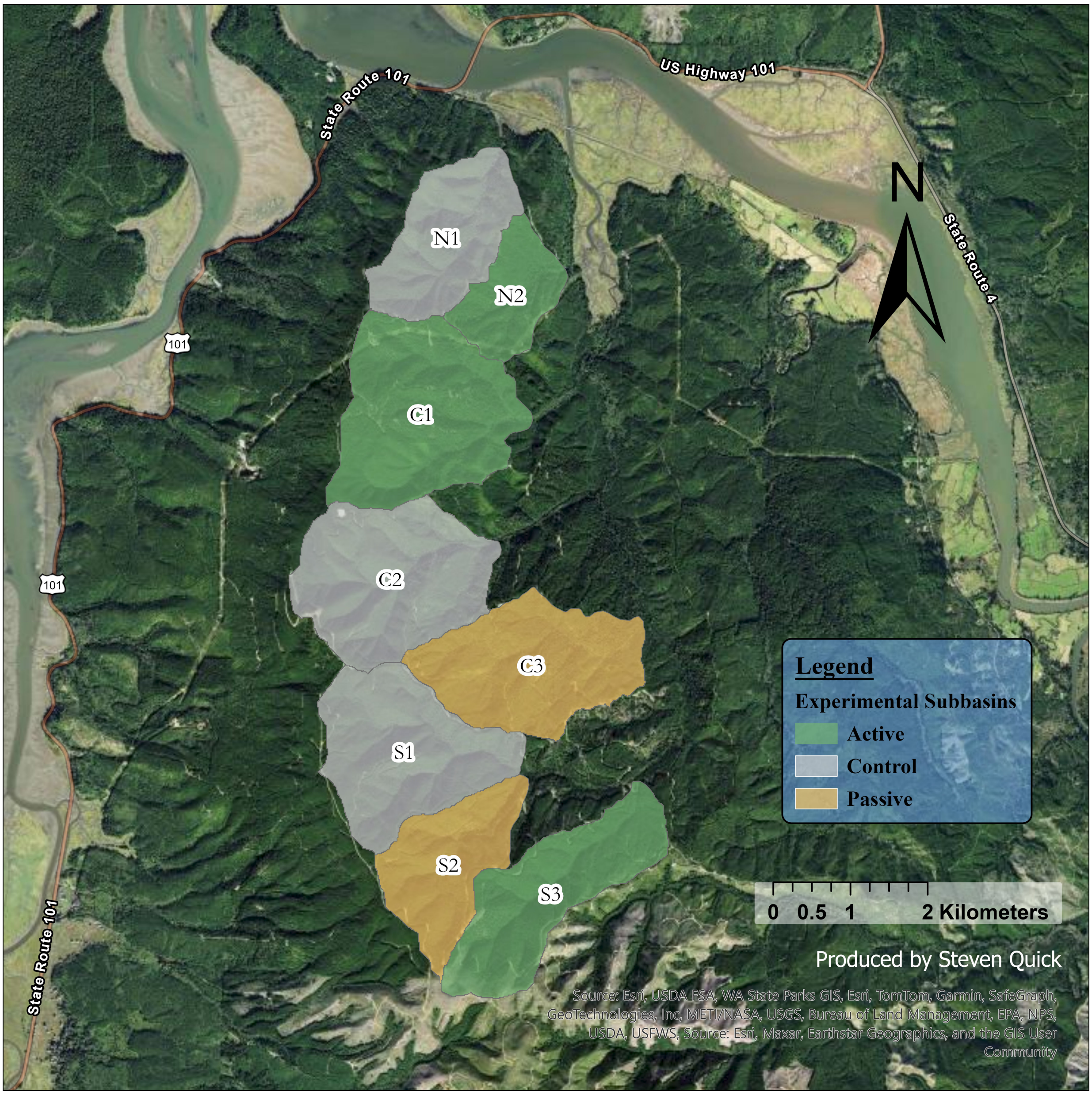

Figure 1. Map of Ellsworth Creek Preserve in Southwest Washington with sub-basins highlighted (polygons). Sub-basins that received treatment are colored in green (N2, C1, S3). Those that had roads removed but no thinning are colored in gray (N1, C2, S1), while a third group of sub-basins colored in yellow (C3, S2) still have roads intact but received no treatment. Passive sub-basins are part of the larger study design but not represented in this project.

2.2. Treatment Applications

Restoration treatments were applied in treated sub-basins in 2009 and 2013. Treatment blocks varied in size from 75 to 221 hectares. Mature stands received commercial thinning, and young stands received pre-commercial thinning. Species removal preference was applied in the following order: western hemlock, Douglas fir, Sitka spruce, western redcedar, and red alder; but unhealthy trees of any species were removed first. Treatments also avoided cutting hardwoods, tree saplings, and seedlings and minimized understory disturbance. See Case et al. [21] for detailed silvicultural prescription details.

2.3. Forest Structure Measurements

Within all plots, measurements in both 2007 and 2020 included overstory, understory, vertical and horizontal structures, forest health, regeneration density, and soil organic layer depth. Protocols were adapted from Cissel et al. [28], and measurements included tree diameter, tree height, and tree basal area (BA). Plots were randomly located within treatment blocks and sometimes were located in treatment areas. That is to say, some of the vegetation plots were thinned according to the treatment protocol. In 2020, repeat measures allowed an assessment of growth and changes in forest structure. All measured plots were located at least 30 m from the border of the associated treatment area. Geo- and topographic data were also collected for each plot, including slope, aspect, elevation, and topographic position. Elevation was derived from digital elevation models. See Case et al. [21] and Cissel et al. [28] for detailed forest structure measurement methods.

2.4. Soil Sample Collection and Analysis

Soil sampling was not conducted during the initial 2007 surveys, but organic litter (OM layer) depth was measured during the 2020 remeasurement survey (as reported in [21]. Organic litter depth was measured five times in each subplot and included all duff and litter less than or equal to 2 cm in diameter. Measurements were made along a 2.5 m slope-corrected transect at 0.5, 1.0, 1.5, 2.0, and 2.5 m from the subplot center, and the orientation of these transects corresponded with the cardinal direction of the subplot (e.g., transects ran north in the North subplot). Using a small trowel, a small hole was dug down to the A-horizon, and the OM layer thickness was subsequently recorded.

While OM layer thickness can be indicative of surface soil C changes, differences in OM bulk density can also result in changes in soil C that would not be reflected in thickness measurements alone. Accordingly, in 2022, we collected additional soil samples to directly measure OM layer C content. Soil core samples were collected to a depth of 10 cm (below the OM layer) from within 1 m of the subplot center using rigid 5 cm PVC soil cores, stored in a labeled brown paper bag, then sealed in a plastic bag for transport. Organic litter depth was subsequently measured in the field for comparison against 2020 depth measurements described above. After samples were dried (105 °C) for at least 48 h and weighed, organic matter was separated, and the remaining material was stratified by fragment size (>2 mm, <2 mm, and <5 mm) using mesh sieves. Organic matter and each fragment size were then weighed again before 5.0 g samples of organic matter were prepared in crucibles to estimate organic matter using loss-on-ignition methods (using a muffle furnace at 5 h at 500 °C). Ash mass was then recorded and compared to initial mass to derive approximate proportions of C. The remaining volume of organic matter was reduced to a similar particle size for elemental analysis for carbon/hydrogen/nitrogen ratios. Sample C and N content was determined using 3–10 mg samples analyzed using a Perkin-Elmer Series II 2400 CHNS/O elemental analyzer (Perkin-Elmer Inc., Waltham, MA, USA).

2.5. Forest Vegetation Simulator

To model changes in stand and soil OM over time, we used the Forest Vegetation Simulator (FVS) developed by the USFS. The base FVS model predicts changes in tree diameter, height, crown ratio, and crown width, as well as mortality and C storage estimates based on standardized national scale allometric biomass estimation equations [29]. Live tree metrics, including height, age, DBH, live crown ratio, and species, as well as stand metrics, including slope, elevation, and aspect, were formatted for use in FVS and comparisons on the sub-basin-level.

We constructed models using both 2007 and 2020 data. Initial runs constructed from 2007 data were used for comparison with remeasured data from 2020 and 2022 to FVS models (see statistical analysis below), validating the usefulness of the modeling approach produced with initial data from 2007. Once validated, models for forest C pools through 2040 were constructed using the remeasured data from 2020. Control models—"grow-only runs"—were generated by running FVS without any forest management activities to simulate our control plots. These runs were constructed with no management activities selected and were conducted in the Pacific Northwest Coast Variant. In active treatment models, management activities were represented by thinning and pruning operations with the thin-from-below component following the parameters described above for commercial thinning and pre-commercial thinning groups, respectively (Section 2.2, Treatment Applications). All models used a maximum stand density index (SDI) of 600 and a site index (SI_{50}) value of 98. In addition to stand visualization and standard tree list outputs, we enabled carbon and fuel outputs using the carbon reports and fire and fuels extension [29]. Specifically, we compared aboveground total, standing dead, down dead, floor, and total stand C pools for each stand in both treated and control groups. We also loaded summary reports from FVS to retrieve conventionally used metrics in forestry such as BA and Quadratic Mean Diameter (QMD).

2.6. Statistical Analysis

First, we compared empirical measurements of stand variables (TPH and BA) and C content (total aboveground C, stand total C, and OM layer C) in 2020 and 2022 to FVS modeled values (based on 2007 data) using a mixed-model restricted maximum likelihood (REML) approach. The REML methodology is used to analyze linear mixed models and may prevent nuisance parameters from having any effect and prevent false positive associations. Stands in the study were treated as random effects to account for repeat sampling within individual stands. Data type (model vs. empirical) and stand treatment were treated as main effects, stand age was used as a covariate, and data type by stand treatment interactions and age by model type interactions were treated as potential interaction effects. Means comparisons within significant model interaction terms were conducted using Tukey's Honestly Significant Difference tests ($\alpha = 0.05$).

For the comparison of empirical data on soil OM, simple nested Analysis of Variance (ANOVA) was used to examine the differences between treatments in the OM layer, OM bulk density, C content, and total OM C. In these analyses, samples were nested within stands, and the treatment type was used as a main effect.

Values among treatments were compared over time in long-term modeling (2020–2040) using repeated-measures ANOVA, where distinct stand structure (BA, TPH) and carbon (aboveground C, OM C, and total C) pools were treated as response variables; treatment type, year, and treatment by year interactions were treated as main effects; and individual stands nested within years were treated as random effects.

All analyses were conducted in the statistical program JMP Pro 16.2.0 with an α of 0.05 for determination of statistical significance.

3. Results

Forest Vegetation Simulator Models and Comparisons

Our data demonstrated nearly universal underestimation of TPH, BA, and C stocks ($p < 0.05$) in models developed from 2007 compared to empirical data from 2020, driven by poor modeling of tree regeneration. Variation was high for empirical measurements (CV = 26.5%–46.4%), but empirical data in 2020 were significantly different from the FVS models in TPH, BA, aboveground C, and total stand C ($p > 0.05$; Figure 2; Table 1). Values for BA, TPH, aboveground C, and total stand C were all lower in models based on 2007 data than in empirical inventories in 2020 in the active stands (Figure 2; Table 1). For BA ($p < 0.0001$, $R^2 = 0.92$), the factors treatment, run type, and stand age were all significant. The interaction between treatment and run type was not significant, but the interaction between age and run type was significant (Table 1), indicating that there was convergence among modeled and empirical stand BA in older stands but not younger stands (Figure 3). The overall model for TPH ($p = 0.006$, $R^2 = 0.74$) demonstrated significance for factors treatment and run type (Table 1) but not for other variables or interaction effects. Aboveground C results ($p < 0.001$, $R^2 = 0.95$) mirrored results for BA where treatment, run type, age, and age by run type were all significant, and convergence in modeled and empirical data occurred with age (Table 1, Figures 2 and 3). Interactions between treatment and run type were not significant (Table 1). Total stand C mirrored both BA and aboveground C results, and treatment, run type, age, and age by run type interactions were again significant ($p < 0.001$, $R^2 = 0.95$; Table 1, Figure 2). Convergence in run type results again occurred in older stands (Figure 3). Modeled data also reported that tree regeneration should have been lower, and carbon losses in the treated stands following thinning should have been higher than observed ($p < 0.05$). Accordingly, modeling results from 2007 data for control stands were much closer to empirical measurements in 2020 and 2022 than for active management stands.

Table 1. Mixed-model results comparing run type by FVS modeled (2007) data and empirical (2020–2022) results from Ellsworth Creek treatment stands across active and control treatments.

	Effect	df_{den} **	*F*	*p*
BA	Treatment	14.97	14.1182	**0.0019**
	Run.Type	14.97	50.4598	**<0.0001**
	Stand Age	15.23	36.5626	**<0.0001**
	Treatment:Run.Type	14.97	3.9925	0.0642
	Stand Age:Run.Type	15.03	4.7280	**0.0461**
TPH	Treatment	15.01	8.4556	**0.0108**
	Run.Type	16	12.1081	**0.0034**
	Stand Age	15.2	0.0711	0.7933
	Treatment:Run.Type	16	2.4303	0.112
	Stand Age:Run.Type	15.05	2.8498	0.112
Aboveground C	Treatment	14.97	11.5283	**0.004**
	Run.Type	14.97	63.2752	**<0.0001**
	Age	15.36	37.8432	**<0.0001**
	Treatment:Run.Type	15.04	4.1703	0.0592
	Stand Age:Run.Type	16	4.9621	**0.0416**
Total Stand C	Treatment	14.98	11.5921	**0.0039**
	Run.Type	14.97	58.8258	**<0.0001**
	Age	15.37	29.5479	**<0.0001**
	Treatment:Run.Type	14.97	2.5344	0.1323
	Stand Age:Run.Type	15.04	8.2344	**0.0117**
Soil OM	Treatment	2.083	5.9772	0.1294
	Run.Type	7.109	0.7224	0.4231
	Age	0.558	0.9083	0.5971
	Treatment:Run.Type	17.82	10.6954	**0.0043**
	Stand Age:Run.Type	3.681	2.1882	0.2191

Note: FVS modeled based on 2007 data versus empirical data from 2020–2022. ** Numerator is 1 for all *df* values. Only denominator is shown.

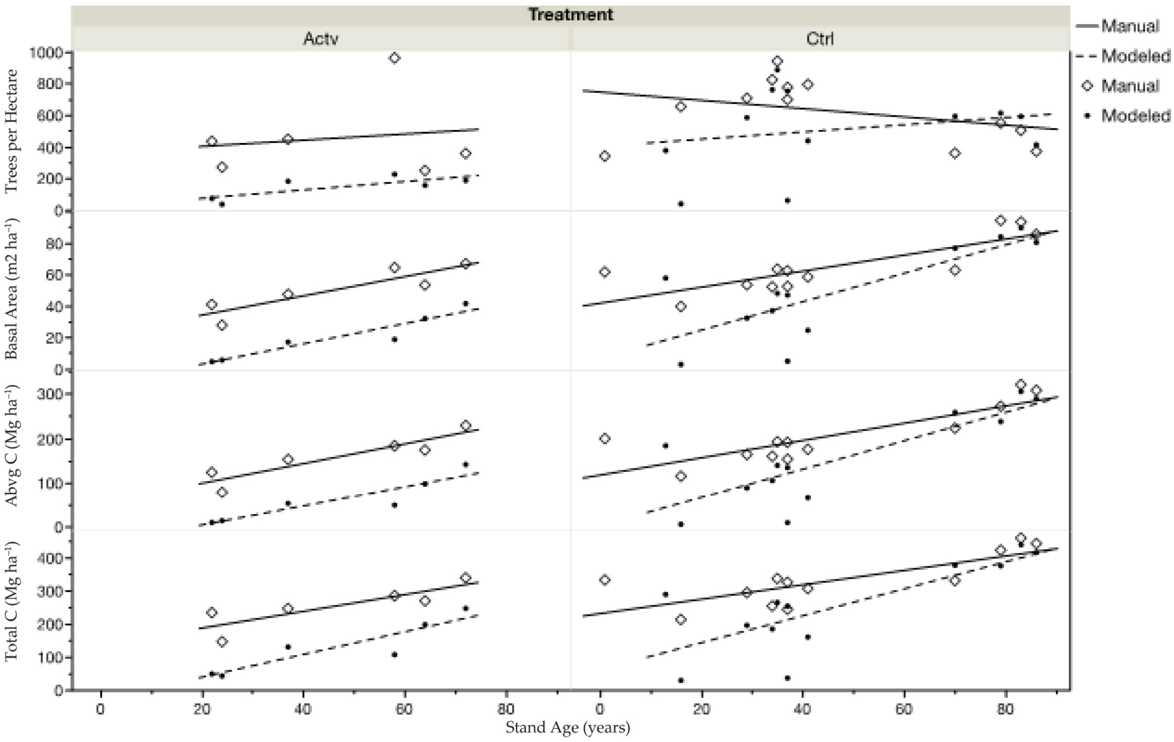

Figure 2. Comparison of empirical measurements (diamonds) and modeled values (points) based on 2007 inventory data versus stand age.

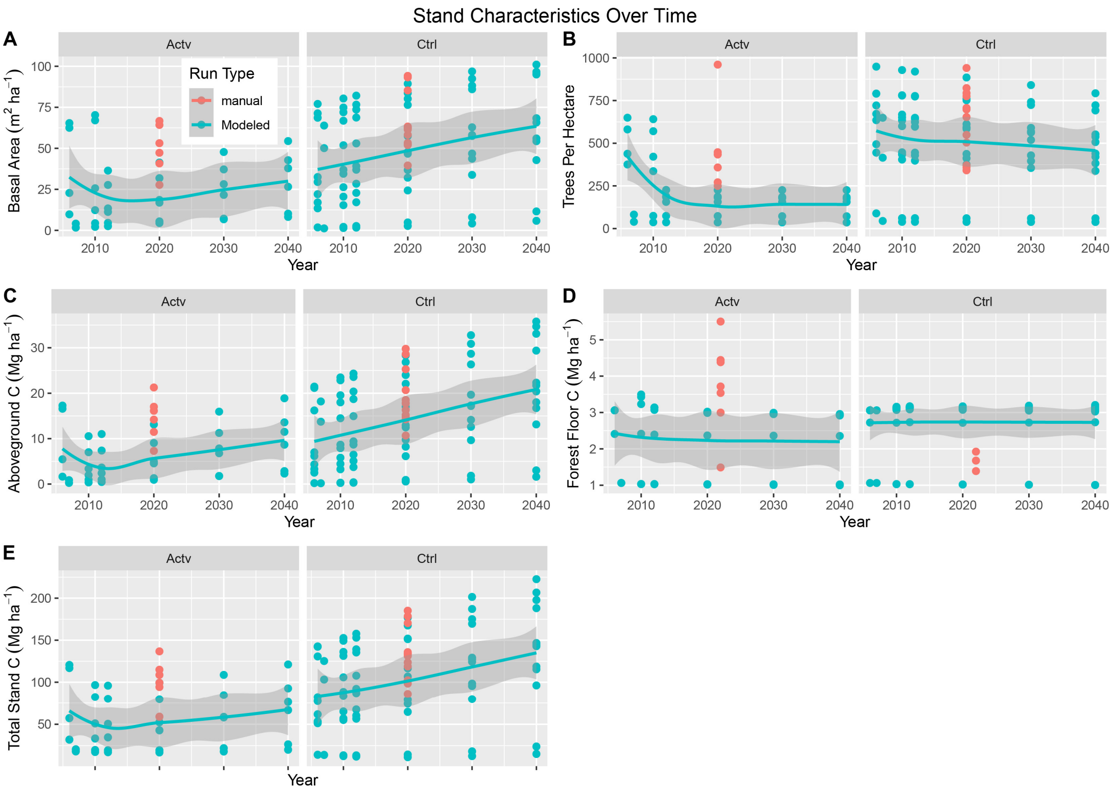

Figure 3. An overall comparison of data collected in 2020 and 2022 to FVS model estimates produced with 2007 inventory data. Panels show basal area (**A**), trees per hectare (**B**), aboveground C (**C**), forest floor OM C (**D**), and total stand C (**E**). Teal points show stand estimates by FVS, and orange points reflect manual measurements in 2020 and 2022.

For forest floor OM C values, an interaction effect between run type and treatment was significant (Table 1), but no other effects were significant. Tukey's HSD tests showed active treatment manual measurements were significantly greater than control treatment manual measurements and all modeled values in 2022 (Figures 2 and 4). Based on manual empirical soil data only, thinning treatments had a significant effect on soil OM C ($p = 0.0272$) where OM C was marginally higher in the active treatment stands (Figure 4). Active stands largely had values between 10 and 20 Mg C ha^{-1}, while control stands tended towards a median value closer to 10 Mg C ha^{-1}. Stand age was significantly related to soil OM C for stands <70 years old, as OM C declined with age in a negative exponential fashion (LOG [soil OM C] = 6.13 − 0.09 × stand age]; $R^2 = 0.91$, $p = 0.003$; Figure 5). When all stands were included, soil OM C trends with stand age were better described by a polynomial function where OM C declined until approximately age 50 and then increased again towards the 70+ year old stands (soil OM C = 16.7 − 0.31 × [stand age] + 0.07 × [stand age]^2; $R^2 = 0.88$, $p = 0.0006$; Figure 5). Stands <50 years old suggested a trend where active treatments were generally higher in soil OM C compared to controls (Figure 5B). For stands greater than 50 years old, control and active treatments showed similar values (Figure 5C). Nevertheless, across all ages, the treatments were very similar in % OM C, and median values were generally between 47% and 49% C (Figure 4A). OM bulk density was also similar across treatments (Figure 4C).

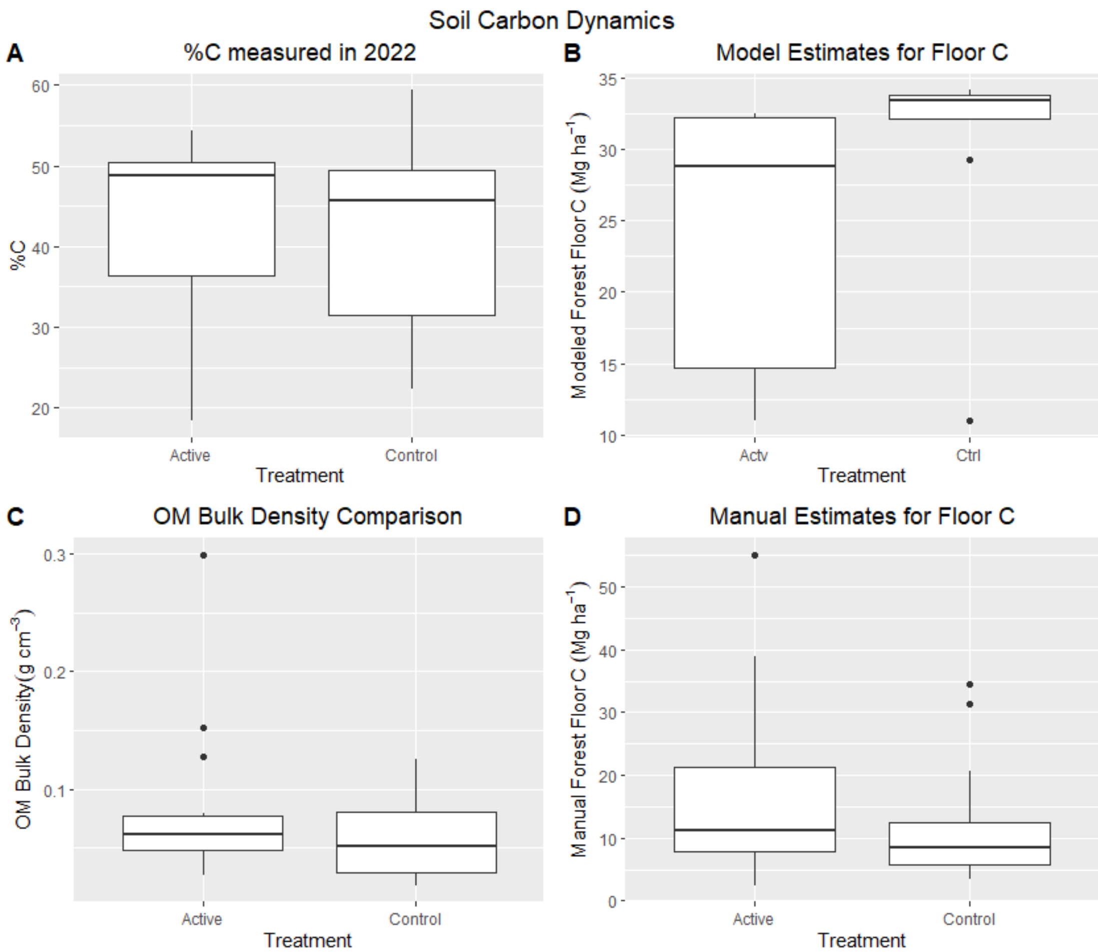

Figure 4. A comparison of forest floor C estimates from empirical versus modeled estimates. Panels show %C and bulk density (**A**,**C**, left side), and modeled and empirical forest floor OM C values (**B**,**D**, right side). Model estimates were produced using 2020 data and overestimated empirical observations (**D**).

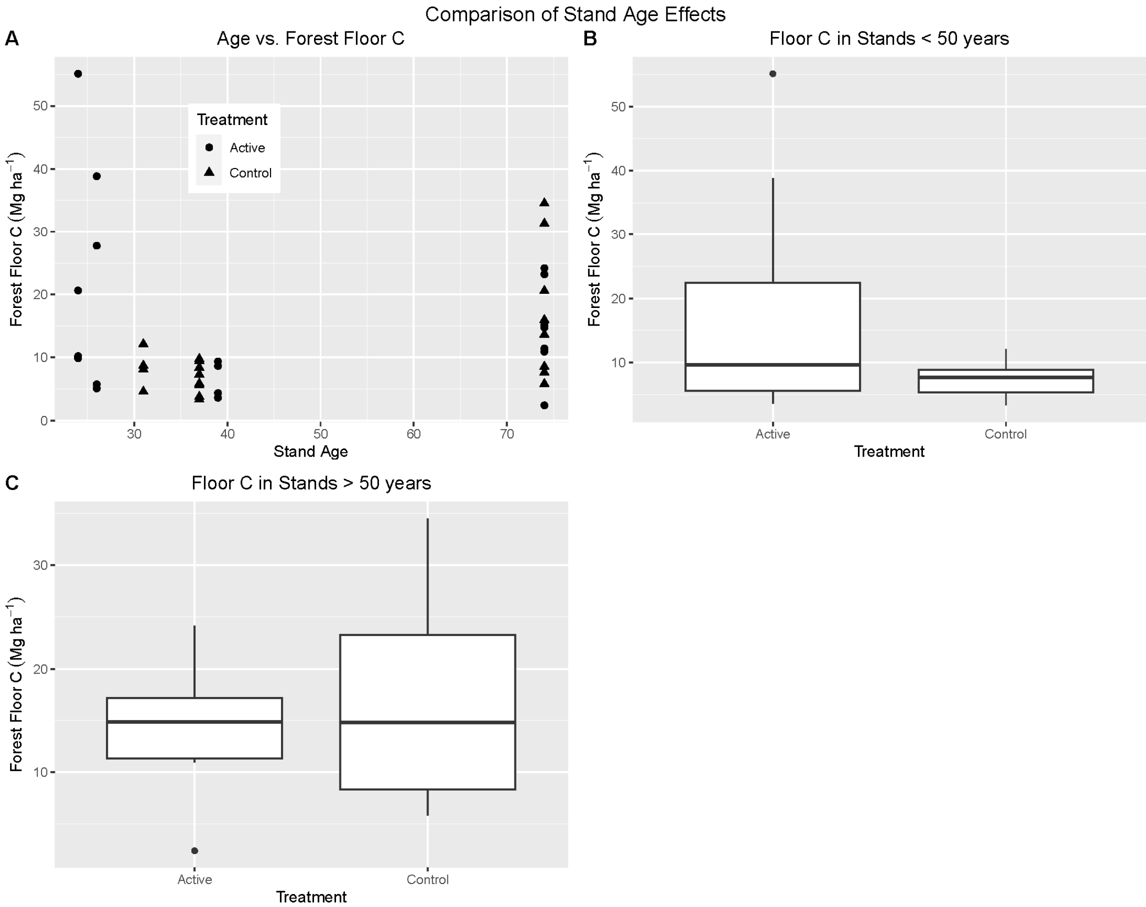

Figure 5. Comparison of soil C variables using empirical measurements from 2022, approximately 14 years after treatments began. Panel (**A**) shows a comparison of stand age effects. Comparisons between treatments are also shown for stands <50 years old (**B**) and greater than 50 years old (**C**).

The FVS Models based on 2020 data suggested that treated plots had reduced BA, TPH, aboveground C, and total C compared to controls (Table 2). Year was also a significant effect for BA, aboveground C, and total C (Table 2), as all variables except forest floor OM C increased with time (Table 2, Figure 6). There was no significant interaction between treatment and year for any response variable ($p > 0.05$). Interestingly, even when the FVS model was run through 2110 (90 years after the 2020 stand survey), results uniformly suggested a significant year and year by treatment interaction effect but no effect of treatment alone ($p > 0.05$). This result was apparently due to a convergence in values between treatments by about 2090 (Figure 7).

Long-term convergence among models suggested overlapping 95% confidence intervals and that the active plot C is likely to represent >80% that of control plots by 2040 and >90% of control plot C by 2100 (Figure 7). Since our early model comparisons suggested significant underestimation of model results, especially in active management stands, these estimates of model convergence are likely conservative, and convergence in C values among treatment types is likely to be sooner.

Table 2. Repeated-measures ANOVA results comparing FVS modeled (2020 data) over time from 2007 to 2040 Ellsworth Creek treatment stands across active and control treatments. Treatment and Year are main effects and Treatment*Year is an interaction.

	Effect	*df*	*F*	*p*
BA	Treatment	1, 50	9.0499	**0.0041**
	Year	1, 50	1.7505	**0.0019**
	Treatment*Year	1, 50	0.0331	0.8564
TPH	Treatment	1, 50	7.8758	**0.0071**
	Year	1, 50	0.5066	0.4799
	Treatment*Year	1, 50	0.0133	0.9088
Aboveground C	Treatment	1, 50	7.6966	**0.0078**
	Year	2, 50	18.7569	**<0.0001**
	Treatment*Year	2, 50	0.0063	0.9371
OM C	Treatment	1, 48	13.6534	**0.0005**
	Year	2, 48	0.0811	0.7770
	Treatment*Year	2, 48	0.0295	0.8643
Total C	Treatment	1, 48	12.4876	**0.0009**
	Year	2, 48	16.5111	**0.0002**
	Treatment*Year	2, 48	0.0123	0.9120

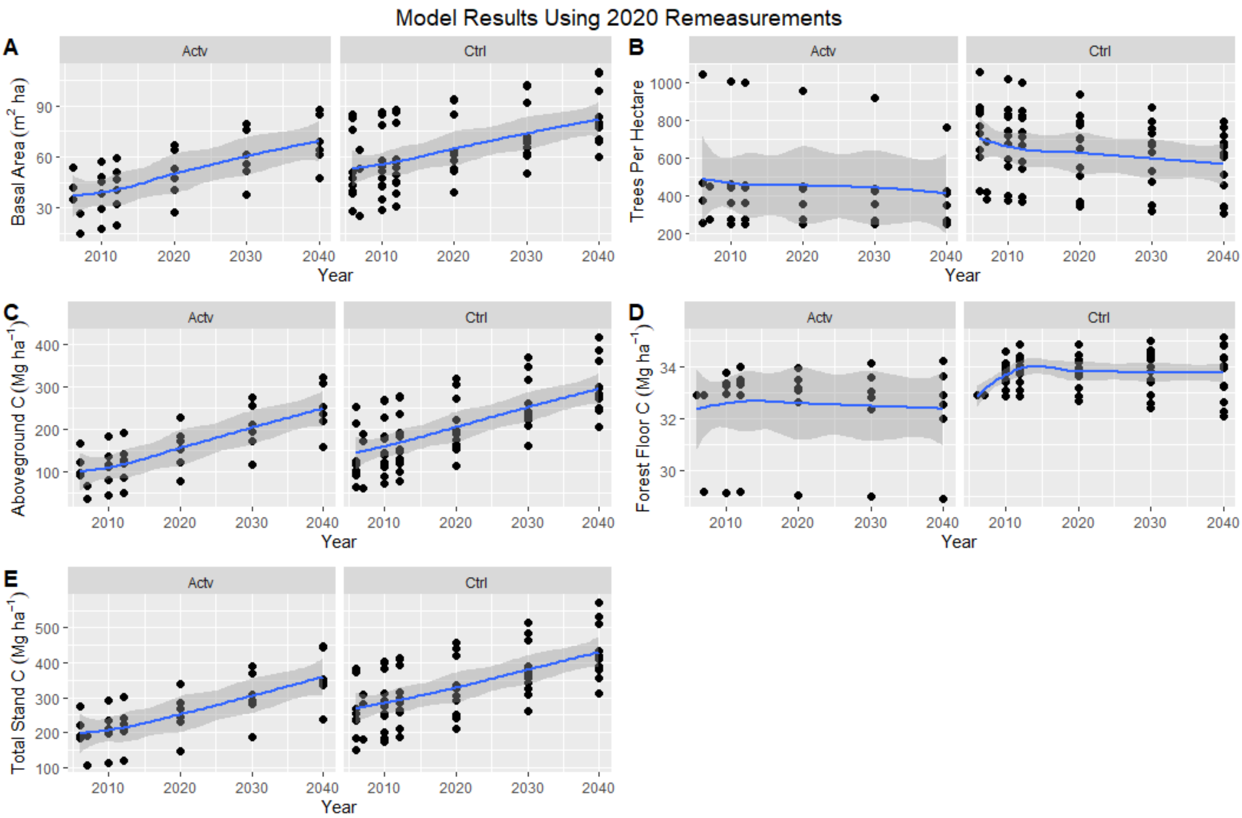

Figure 6. Model results from FVS using data taken in 2020. Panels are divided by active treatment (Actv) and control stands (Ctrl). Panels show basal area (**A**), trees per hectare (**B**), aboveground C (**C**), forest floor C (**D**), and total stand C (**E**). Blue lines represent the mean for each metric.

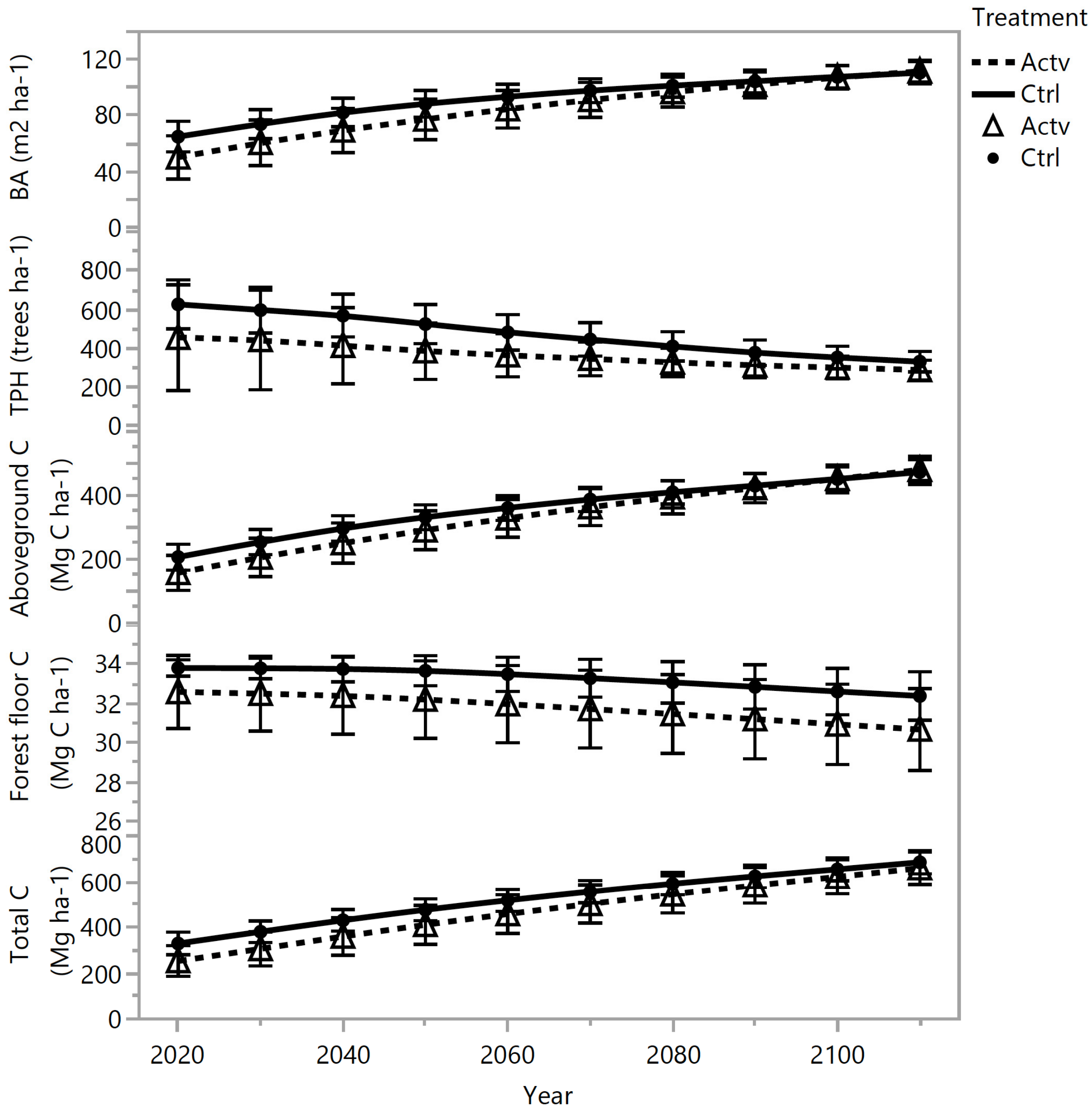

Figure 7. FVS model results from 2020 data modeled through the year 2110. Means are represented along with 95% CI bars. Note the convergence in lines over time as managed stands approach control stands in structure and C content. Each error bar is constructed using a 95% confidence interval of the mean.

4. Discussion

Previous work focusing on aboveground structure and understory species found quick recovery of aboveground canopy cover, tree growth, and sapling density in response to restoration treatments for old-growth restoration at Ellsworth Creek [21]. Nevertheless, modeling efforts in Northwest forests have long demonstrated the carbon consequences of active management, as thinning and gap treatments that remove aboveground carbon and photosynthetic biomass have an intuitively obvious effect on reducing stand C—even over the long term [12]. The C consequences of silvicultural practices for restoration of old-growth structural attributes are not well modeled or understood, but reduced C storage in treated stands is expected in the short term. In our analysis, we found statistical differences between modeled and empirically measured values of TPH, BA, and total aboveground C and total stand C in 2020, where the modeled values tended to be lower, especially for treated stands.

A more detailed analysis of aboveground stand metrics at our site [21] found higher-than-expected regrowth and sapling density following restoration treatments. The data from 2020 reflect this higher-than-expected sapling growth and density; however, the statistical results suggested that models built on existing forest structure (e.g., control plots) may more reliably project carbon stores aboveground, and simulated management projections (active treatments) are more challenging. This might be due to insufficient regeneration establishment models developed for the Pacific Northwest Variant of FVS [30]. Forests in the PNW tend to respond to disturbance with rapid regrowth. Measuring the growth of saplings and seedlings is often separate from tree measurements, and trees smaller than 14.5 cm DBH were not cut according to our treatment methods (also represented in the model) and may have been present in 2007 and then became much larger by 2020. Treatments indeed varied in timing (2009 and 2013) and may affect our empirical data, which can be a source of error, but this effect was not a clear driver in our study.

The relatively light treatments associated with old-growth restoration coupled with rapid tree growth and sapling responses [21] resulted in similar stand C storage over time, even when differences between treatments remained significant through 2040 projections. Our long-range projections suggest that average differences in TPH may converge in the different treatments relatively rapidly, and agreement in BA, total tree C, and total stand C will occur even faster. For example, by 2040, models suggest both active and control stands will average within ~25–50 Mg C ha^{-1} of each other in total stand C, though individual plots may have higher or lower values in control and treatment stands, respectively (Figure 2). By 2107, projections indicate that total stand C may be near within 10% of each other for both treatments, approaching the anticipated ceiling for C storage in PNW forests [31]. Total tree C (Mg ha^{-1}) similarly is projected to range around 50–300 Mg ha^{-1} in active treatments by 2040, and 200–400 Mg C ha^{-1} in control treatments, with both treatments approaching 400–500 Mg ha^{-1} by 2100. Meanwhile, the C stores in trees are likely to be associated with larger trees (stands with larger QMD) and fewer trees (lower TPH in most stands).

Caution should be employed when interpreting these data, and differences among treatments are likely conservative. Regrowth models for FVS are notoriously inaccurate, especially for Western Washington, where forests are characterized by explosive regrowth and individual tree maturation is highly variable. Our analysis did not include any regrowth calibration to the base partial-establishment model in FVS, which is insufficient for modeling regrowth by itself in the Pacific Northwest [30,32]. Generally, FVS underestimated aboveground C in both active and control stands, but especially in active stands (Figure 3). These known errors suggest that our models of future C may overestimate the treatment differences and further suggest that the gap in C storage between active and control stands may be negligible within decades. A caveat is that this is for stands where ecological restoration was the goal, treatments were light and variable, and tree regrowth is rapid due to high rainfall and moderate temperatures. These results are unlikely to apply to more extreme production-oriented cuts, and we note that our results did still indicate less C over time in treated stands—consistent with well-documented effects of timber harvests on C storage.

Earlier work at our site found no difference in soil OM litter depths [21]. Similarly, our results suggest treatments were conducted at the Ellsworth Creek Preserve 10–14 years ago and may have already recovered to pre-treatment soil OM and C levels. We expected thinning treatments to result in reduced C because of reduced litter inputs, but microclimatic changes resulting from canopy reductions have been found to drive recovery of soil C pools in coniferous forests within a couple decades [33]. Although we also expected age to play a role in the accumulation rate and recovery of soil C following treatments, the interaction of treatment by age had a much stronger effect than treatments. Both young and mature control plots represent forests in the stem exclusion phase of succession, but mature control forests possess significantly greater soil C than their younger controlled counterparts. In active stands, higher OM C in young stands was likely an artifact of post-harvest debris and reduced decomposition during dry conditions.

Forest floor OM C was much more variable in our empirical measurements than in model projections (Figure 4), and this is likely due to overly simplistic assumptions in the soil OM content associated with a given stand age in FVS. Soil OM C is notoriously variable, and variation is much likely more predictable when accounting for microsite effects and species composition differences that can result in fast or slow decomposition [32]. Additionally, though, soil OM C was underestimated by models in the treatment stands and overestimated by models in the control stands. Underestimates may have been associated with low initial tree density, underestimated litter contributions to the forest floor during harvests, and overestimated increased decomposition of litter following harvest [34,35]. Additionally, the high moisture and leaf litter quality associated with trees in a high rainfall temperate rainforest could result in faster litter decomposition, and hence lower OM C, in the untreated stands than predicted by FVS. The lack of a reliable regeneration model also reduces the accuracy of modeling new recruitment unless a planting event occurs, and in many stands, regeneration was higher than expected following harvests at our sites [21]. Early in stand development, these results may emphasize the need for better modeling of regeneration and OM inputs associated with harvest treatments.

Nevertheless, averages of soil OM C from both modeling and empirical measurements were within one 95% confidence interval of the empirical measures in both managed and unmanaged stands. Empirical measurements may give higher OM C estimates when high litter inputs associated with harvest activities are not properly accounted for. Our direct measurement of values in 2022 suggested similar % C between treatments, and similar bulk density of the OM layer between treatments, and any differences in soil OM C (e.g., higher in the active treatments) were likely associated with higher OM inputs or reduced decomposition, rather than differences in OM quality or density. Over longer periods of time, realized climate changes could result in drier conditions, further reducing decomposition.

Logging debris following treatments typically results in high OM values, followed by rapid decomposition, and therefore soil C declines [35]. Interestingly, our study design (where active and control treatments were variable in age) resulted in an opportunity to examine the data in the context of stand age where our data align well with traditional interpretation of curves in soil OM content though time following harvest—the "Covington Curve" [36]. Both active and control treatment stands had OM C values that suggested a curve where initial high OM C was followed by a reduction by stand age 40–50, followed by a gradual increase in soil OM C by age 80 (Figure 5A). Again, our results suggested far more variability between plots within treatments than between treatments. Importantly though, our analysis was limited to surface soil OM C, and we did not examine patterns with soil depth. Soil OM leaching and depth profiles in mineral soils may either exaggerate or nullify patterns in soil C found by looking at the OM layer only [36]. Further analysis of soil C at greater sample depths [23,25] would also help inform our understanding.

5. Conclusions

These data from the Ellsworth Creek Preserve suggest that light-prescription ecological forestry treatments aimed at restoring old-growth conditions have resulted in small differences in above-ground stand C but have not resulted in significant differences in forest soil surface OM pools. Our comparison of modeled values and empirical measurements suggest that modeled estimates of C pools were frequently underestimated. Our model projections suggest that convergences in future stand C and OM C content are likely in coming decades and may occur sooner than expected. Small differences in stand C pools among treatments may be explained based on the relatively light harvest activity associated with skip and gap silvicultural prescriptions for old-growth structural development, rapid regrowth by retained trees and saplings, and high soil OM variability based on microsite conditions. Additionally, the role of stand age since complete harvest may have played a more dominant role in the response of soil OM C storage. We expected to see greater reductions in soil C for young managed stands. Indeed, soil OM C was lower in managed stands, but mature stands suffered greater C losses compared to younger counterparts.

The combined effect of age and treatment was significant, indicating that C resilience to disturbance may change with age. Future projections greatly simplify variation, but our comparison of modeled and field data over thirteen years suggests that projections give realistic values within 95% confidence intervals of empirical measurements. Accordingly, the projections of rapid C recovery following small-scale treatments suggest that lost soil OM C associated with harvest disturbance and altered microclimate may be rapidly recovered in subsequent decades.

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