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Article

Using Silviculture to Influence Carbon Sequestration in Southern Appalachian Spruce-Fir Forests

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Abstract: Enhancement of forest growth through silvicultural modification of stand density is one strategy for increasing carbon (C) sequestration. Using the Fire and Fuels Extension of the Forest Vegetation Simulator, the effects of even-aged, uneven-aged and no-action management scenarios on C sequestration in a southern Appalachian red spruce-Fraser fir forest were modeled. We explicitly considered C stored in standing forest stocks and the fate of forest products derived from harvesting. Over a 100-year simulation period the even-aged scenario (250 Mg C ha^{-1}) outperformed the no-action scenario (241 Mg C ha^{-1}) in total carbon (TC) sequestered. The uneven-aged scenario approached 220 Mg C ha^{-1}, but did not outperform the no-action scenario within the simulation period. While the average annual change in C (AAC) of the no-action scenario approached zero, or carbon neutral, during the simulation, both the even-aged and uneven-aged scenarios surpassed the no-action by year 30 and maintained positive AAC throughout the 100-year simulation. This study demonstrates that silvicultural treatment of forest stands can increase potential C storage, but that careful consideration of: (1) accounting method (*i.e.*, TC *versus* AAC); (2) fate of harvested products and; (3) length of the planning horizon (e.g., 100 years) will strongly influence the evaluation of C sequestration.

Keywords: additionality; carbon sequestration; fire and fuels extension; forest carbon accounting; Forest Vegetation Simulator; silviculture; spruce-fir

1. Introduction

As global awareness of the effects of climate change increases [1], so will the importance of management strategies for terrestrial ecosystems that maximize atmospheric/global CO_2 mitigation [2]. Though there is some debate over how managed forests sequester carbon (C) relative to their old-growth counterparts [3–5], managed forests have been shown to make valuable contributions to C sequestration efforts [6–8]. While managed forests are not expected to contain as much standing C as old-growth forests on similar sites, managed forests could potentially sequester more C when both live biomass and harvested biomass are considered, and depending on the fate of harvested biomass (e.g., biofuel *versus* structural wood products, [6,9]). Furthermore, if the rate of growth for live biomass is increased by active management for wood products, the potential C sequestration rates in managed forests might be increased. This begs the question, what role can silviculture play in the long-term C sequestration potential of forests?

Numerous factors influence growth and biomass accumulation as well as potential standing C pools in forested systems. These factors include site quality [10], stage of stand development [11] and stand composition [12], forest type and disturbance regime [2]. Realistically, one cannot control site quality; however, silviculturists can modify stand structure, species composition, and stand density. This allows the direct control of stand developmental stage and growing stock potential, and therefore rates of C sequestration. By maintaining stand stocking within a desired range of relative stand density associated with various levels of growth potential (*i.e.*, maximum tree growth *versus* maximum stand growth, [13]) silviculturists can potentially influence the rate of C sequestration.

In the southeastern United States, southern Appalachian red spruce (*Picea rubens* Sarg.)–Fraser fir (*Abies fraseri* Pursh.) forests were historically heavily cut over [14] and, although productive (7.7 Mg biomass ha^{-1} yr^{-1}, [15]), these spruce-fir forests can either be C sinks or C sources depending on the management regime, the dynamics of snags or coarse woody debris [15–17], or natural disturbance regimes. Historically, hurricane-induced windthrow and ice storm damage were common disturbances resulting in gap-phase dynamics in these forests [18]. In the last two decades southern Appalachian spruce-fir forests have been heavily influenced by a catastrophic insect outbreak of the non-native balsam wooly adelgid (BWA; *Adelges piceae* (Ratzeburg)). As a result of the BWA the high elevation spruce-fir forests of the southern Appalachians have experienced higher disturbance-related mortality and, have been set back to an earlier stage of stand development. In recent years the aboveground components of this system have shown a substantial increase in standing biomass [16].

The vast majority (74%; [19]) of southern Appalachian spruce-fir forests are within the boundaries of Great Smoky Mountains National Park, where active forest management has been precluded since National Park designation in 1943. It is therefore impossible to directly determine the effect of various management scenarios on C sequestration. However, modeling approaches provide an excellent vehicle to estimate the effects of hypothetical management treatments on C sequestration (*sensu* [4,9]).

There are several C accounting tools available to land managers and researchers and guidelines have been established to assist with field data collection and C accounting methods [20,21]. Smith *et al.* [22] provided estimates of standing C stocks for several forest types as a function of stand age and included a methodology for assessing the effects of harvesting on C sequestration. Although these estimates cannot incorporate stand-specific data, they are readily available and easy to use. The Carbon Online Estimator relies on USFS Forest Inventory and Analysis (FIA) data and can produce standing C pool as well as growth and yield estimates at the county scale and larger [23]. The US Forest Carbon Calculation Tool also relies on FIA data and can provide state and national estimates of stored C [22]. The most recent version of the US Forest Carbon Budget Model also relies mainly on FIA data. This model generates easily interpretable and useful outputs but the data input process can be complicated and may require a user with advanced programming or FORTRAN skills.

The Forest Vegetation Simulator (FVS) is an individual-tree distance independent growth and yield model that is widely used by managers and researchers to model forest change and stand dynamics over time in response to management activities [24]. FVS allows the input and analysis of user-collected stand data and produces easily interpretable output through the Suppose graphical user interface. In addition, FVS can track the simulation of various management scenarios at the tree- or stand-level for a user-specified time interval. Recently, C accounting has been incorporated into FVS through the Fire and Fuels Extension (FFE) [25,26]. Although publicly available and easily implemented, relatively few studies have utilized FVS-FFE to assess the long-term temporal dynamics of C sequestration at the stand-level (but see [27,28]).

The goal of this research is to simulate the possible effect of silvicultural activities on long-term C storage potential of managed forests compared to their unmanaged counterparts using a large comprehensive re-measurement data set from the Great Smoky Mountains. By pairing this data set with the readily available and easily used FVS, we attempt to provide a straightforward demonstration that active management may well be a better strategy for C sequestration than passive management. Current greenhouse gas accounting protocols require any management action intended to offset CO_2 emission to exhibit "additionality", *i.e.*, to be additional to the "business-as-usual" scenario [29]. Carbon accounting protocols further require management-caused changes in carbon stocks to be assessed over a 100-year planning horizon [30]. The potential influence of silvicultural activities on the C sequestration potential of southern Appalachian spruce-fir forests was examined using FVS-FFE to simulate forest growth and associated C dynamics for 100 years under three scenarios: (1) a no-action scenario (*i.e.*, business-as-usual); (2) an even-aged silvicultural system; and (3) an uneven-aged silvicultural system. Total C sequestration (TC) and the average annual changes in C sequestration (AAC, [26]) are calculated to compare the three scenarios. While TC demonstrates the overall difference in C sequestration between management practices over the life of a project or rotation, AAC can be used to demonstrate the additional C sequestered on an annual basis and has application in C accounting protocols such as the Regional Greenhouse Gas Initiative [31] We hypothesize the no-action scenario will exhibit the highest TC, but that the even-aged management scenario will exhibit the highest positive AAC.

2. Methods

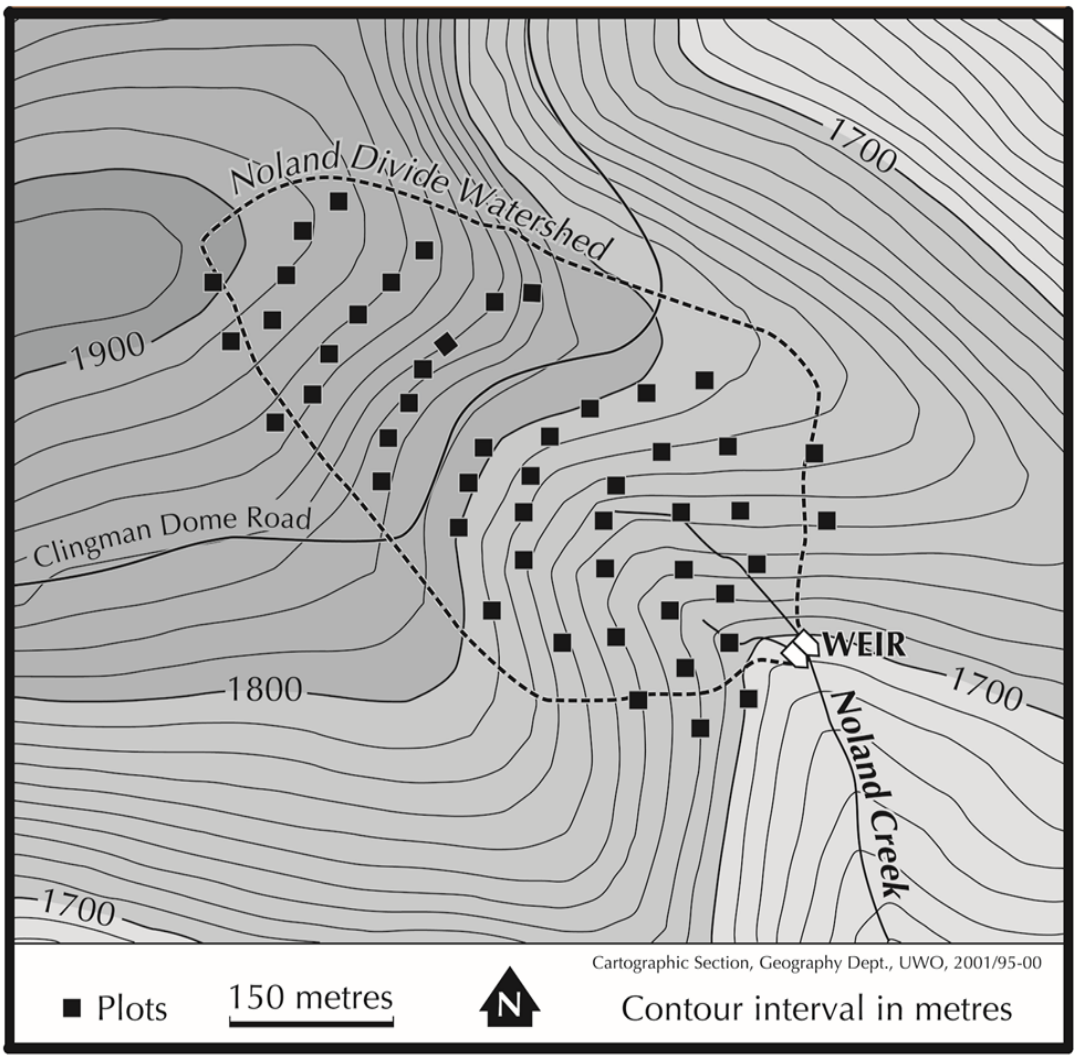
2.1. Study Area

Data for the study were collected in the Noland Divide Watershed (NDW, 35°34'N, 83°29'W) a 17.4 ha, high elevation catchment within Great Smoky Mountain National Park. This catchment was chosen because of the broad elevation gradient (1700–1910 m) and resulting variability in overstory species composition thought to represent much of the range of forest conditions occurring within southern Appalachian spruce-fir forests. Access to previously collected data as well as a pre-existing plot infrastructure allowed improved modeling and interpretation of model results through control of some potentially confounding factors (parent material, aspect, and climate). The NDW is dominated by red spruce at lower elevations transitioning into Fraser fir at higher elevations with a component of yellow birch (*Betula alleghaniensis* Britton) and various other hardwoods distributed across the range of elevations. The NDW has not been impacted by logging or fire [32], but has been severely impacted by the BWA [33,34] and wind related events [15,18]. The soils are mainly Inceptisols, occasionally with spodic characteristics [35,36], are generally shallow, (<50 cm depth to bedrock) and have a silt loam to sandy loam texture [37]. Precipitation is >200 cm annually and is distributed evenly throughout the year [38]. Mean air temperatures range from −2 °C in February to 17 °C in August with a frost-free period from May through September [38,39].

2.2. Data Collection

Overstory forest inventories were performed in the NDW in 1993, 1998 and 2003 on a system of 50–400 m^2 plots stratified along a series of nine elevation bands (1700, 1725, 1755, 1785, 1800, 1835, 1865, 1890 and 1910 m, Figure 1). For the analysis, these are divided into three elevation groups; low (1700, 1725 and 1755 m, 19 plots), medium (1785, 1800 and 1835 m, 19 plots) and high (1865, 1890, and 1910 m, 12 plots). All trees ≥5 cm diameter at breast height (DBH, 1.37 m) were measured using protocols described by [40], and tagged with a permanent and unique ID tag. Species, DBH, and status (live or dead) of each overstory tree were recorded. In 1998 and 2003, ingrowth was tagged as trees entering the 5-cm diameter class. Live trees that had fallen since the last inventory were considered windthrow. On each plot in 2003, all trees >2 cm and <5 cm DBH were sampled on a system of 4–16 m^2 subplots in order to estimate saplings. Trees <2 cm DBH were sampled on a system of 16–1 m^2 nested plots within each 16 m^2 sapling subplot and averaged across elevation bands in order to estimate natural regeneration [16].

Figure 1. Map of the Noland Divide Watershed and the systematic network of 50 permanent plots.



2.3. Data Preparation

Although the southern variant of FVS (SN-FVS) is capable of running simulations with very limited data (e.g., DBH, species [41]), additional tree and stand information can improve model estimates (e.g., height, diameter increment, site index [42]). Also, while included in the western variants, the eastern variants of FVS have not yet been modified to take into account forest dynamics under climate change (*i.e.*, Climate-FVS). SN-FVS has not been explicitly evaluated for spruce, fir or yellow birch; however, it has been validated and analyzed for other species [43–45] that displayed its ability to effectively simulate stand dynamics. Trees in the NDW watershed are generally shorter than in other southern Appalachian (or nearby) spruce-fir forests [33]. To estimate tree height for red spruce, Fraser fir and yellow birch, we used site-specific allometric equations fit from the height-diameter data in Barker *et al.* [33]. This resulted in at least three modeled individual tree heights for each species, on any given plot, the minimum necessary for SN-FVS to modify height growth to reflect local conditions. In addition, SN-FVS will modify the large-tree (>7.6 cm DBH) growth model to reflect local conditions if the user specifies the diameter increment for 3 or more individuals of a given

species on a particular plot in the input data [42]. We calculated 1998–2003 diameter increment for all live sampled trees measured during both the 1998 and 2003 inventories, assuming bark thickness was constant, and included them in our FVS input tree list. While assuming constant bark thickness potentially introduces bias, this will not affect comparisons between scenarios. In addition, five-year changes in bark are likely to be marginal. To incorporate natural regeneration into each management scenario, when appropriate, we calculated average understory stocking (stems/ha) for each of the dominant tree species in each of the three elevation groups from the 1 m^2 subplots. SN-FVS uses site index (height in feet at base age 50, SI) to model the site productivity potential of individual stands. Because site index was not measured in the field, we incorporated the influence of site quality into the model simulations by identifying a range of SIs consistent with Nicholas *et al.* [46]. Simulations for each elevation band (low, medium, high) were run for each of three SIs. The SI range for each elevation group was: low elevation (60, 65 and 70); medium elevation (55, 60 and 65); and high elevation (55, 60 and 65).

2.4. Silvicultural Scenarios

We used the 2003 data as the starting point for each of the silvicultural scenarios and ran 100-year simulations (2003–2103). For each scenario the CarbCalc keyword was used to set C accounting parameters. Parameters selected included the base FVS biomass equations, default decay rates, and model output in Mg ha^{-1}. The CarbRept keyword was used to generate a C report every 5 years for 100 years while the CarbCut keyword was used to generate a harvested C report every 5 years, and finally the SiteCode keyword was used to vary the SI above for each elevation group.

In the no-action scenario, stands were able to develop without the effect of management activities. Stand density index (SDI) maximum was constrained at 460. All calculations of SDI were done within FVS, which uses a summation method [42]. Standing dead trees fell and decayed according to default model parameters. Although in this scenario the measured understory data from the 2003 inventory were included during the 2003 time step, no additional understory trees were added during the simulation period. Theoretically, fully stocked stands would not promote the establishment of understory trees, or allow their ascension to the canopy [47]. While in actuality some regeneration is likely to occur over a 100-yr scenario, we made the simplifying assumption that no disturbance or gaps promoting establishment would occur over the scenario in lieu of arbitrarily adding regeneration.

Under the even-aged scenario we sought to control stand density so as to maintain "full-site occupancy" and avoid substantial density-related mortality [13]. Plot level SDI was maintained between 45% (207) and 60% (276) of maximum SDI through simulated harvesting using a conditional statement in the ThinSDI keyword. Although in this scenario we included the measured understory data from the 2003 inventory during the 2003 time step, we did not add any additional understory during the simulation period. This scenario simulates a series of commercial thinning, which should not typically result in establishment of understory trees, or allow their ascension to the canopy [47].

For the uneven-aged scenario, we relaxed the constraint to maximize stand growth, while simultaneously seeking to build the structural attributes of an uneven-aged or late successional spruce-fir forest exhibiting gap-phase dynamics. In this scenario, the Uneven-aged Management Action option in FVS was used to implement an individual tree selection system that constrained SDI between 45% and

60% of maximum SDI (207–276). Residual stocking was distributed, expressed as SDI, relatively evenly across the DBH classes. Simply thinning within each DBH class to the desired SDI may excessively reduce stocking over time because some DBH classes may be initially deficit. The Uneven-aged Management Action adjusts for this by detecting deficit size classes and allowing additional trees to remain in the adjacent lower DBH classes in order to achieve the target SDI for the plot. A Liocourt or diminution coefficient (q) of 1.3 between each of the 8–12.7 cm DBH classes was used to push the stand DBH distribution toward a negative exponential or reverse J-shape over time. Our initial estimates of understory stocking were input into FVS on a 5-year cycle.

2.5. Carbon Accounting

Carbon pools were estimated from the Stand Carbon Report and the Harvested Carbon Report generated by FFE. These two reports include C pools consistent with the Intergovernmental Panel on Climate Change Good Practice Guidance [48] for national greenhouse gas inventories [26]. FFE C estimates are produced by multiplying standard FVS dry weight biomass estimates for all pools by 0.5 (assumed 50% C) except for the forest floor pool which is converted using 0.37 [22,26]. Soil C is not accounted for in FFE. TC was calculated as the sum of all reported forest carbon from the Stand Carbon Report. This includes dynamic predictions for the following C pools: total aboveground live, merchantable aboveground, standing dead, belowground live, belowground dead, down dead, duff, litter herbs and shrubs using methods described in Reinhardt *et al.* [25]. Calculation methods for C pools were held constant across all scenarios in order to more fairly test the effects of silvicultural manipulation on C sequestration. Any C removed during thinning is reported in the Harvested Carbon Report including the following C pools: forest products in use, products in landfills, and C emitted from combustion with and without energy capture. These pools were accounted for following the decay fates for harvested products in Smith *et al.* [22]. Although protocols exist to explicitly monitor the products and their inefficiencies (e.g., the CO_2Fix model [49]) the FFE accounting system is built-in to the FVS framework, follows international C sequestration protocols [25] and is most likely to be used by forest managers.

To compare TC between silvicultural scenarios we added total standing carbon to harvested carbon in wood products for each plot and each 5-year time step before averaging over plots in each elevation and SI group. By only including the harvested carbon in wood products we effectively remove C that is only stored short-term or is released as emissions due to the decay of forest products and energy required to transport the C out of the forest. Average annual change in C sequestration (AAC) was calculated as the 5-year difference in total C (calculated above) for the 100-year simulation [26]. Results for TC and AAC were plotted over time to compare potential C sequestration by management scenario. To account for additionality (e.g., [50]), we compared the AAC for the two management scenarios relative to the no-action scenario. This gives an indication of the patterns of relative increases (positive) or decreases (negative) in potential C sequestration when deviating from the no-action, or "business-as-usual" scenario.

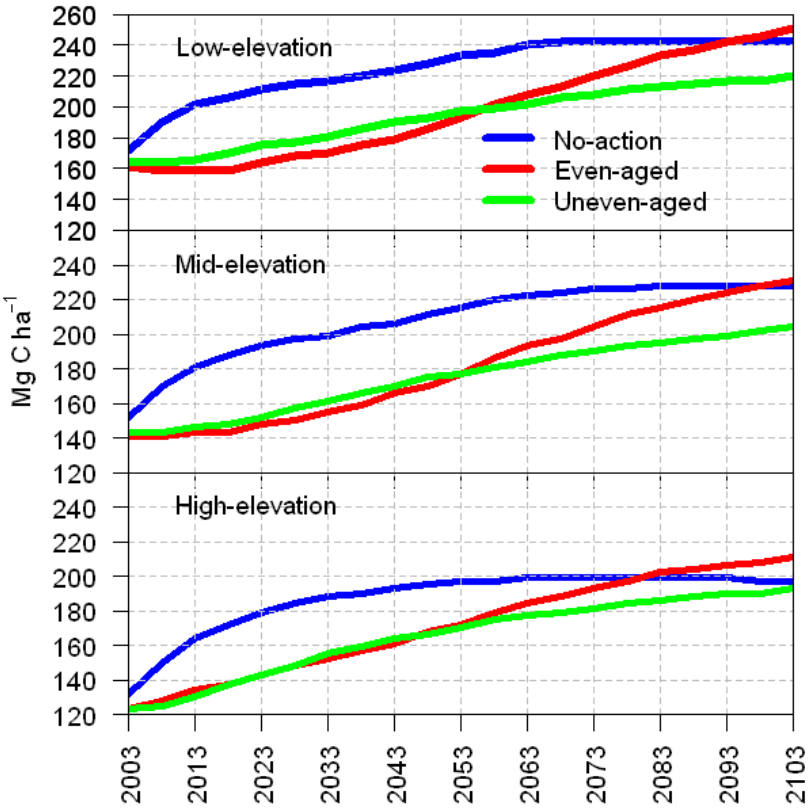
3. Results

3.1. Total Carbon Sequestration

Although we modeled a range of SIs within each elevation group to test the influence of site quality on C sequestration, the effect was minimal (coefficient of variation = 12.9–17% by the end of the 100-year simulation) and the variation occurred in an expected manner. That is, between elevation bands productivity increased with decreasing elevation, and within each elevation band, productivity increased with increasing SI, as expected. Therefore, results are only presented for the middle SI value in each elevation group.

TC in the no-action scenario increased rapidly during the first part of the simulation period for each elevation group before leveling off towards the end of the simulation (Figure 2). This value increased from 174, 152 and 132 Mg ha^{-1} in the low, medium and high elevation band, respectively, and approached a maximum in 2103 of 242, 227 and 198 Mg ha^{-1} in the low, medium and high elevation band, respectively.

Figure 2. Total aboveground C sequestered (Mg ha^{-1}) for three elevation groups as a result of no-action, even-aged management and uneven-aged management in a southern Appalachian forest.



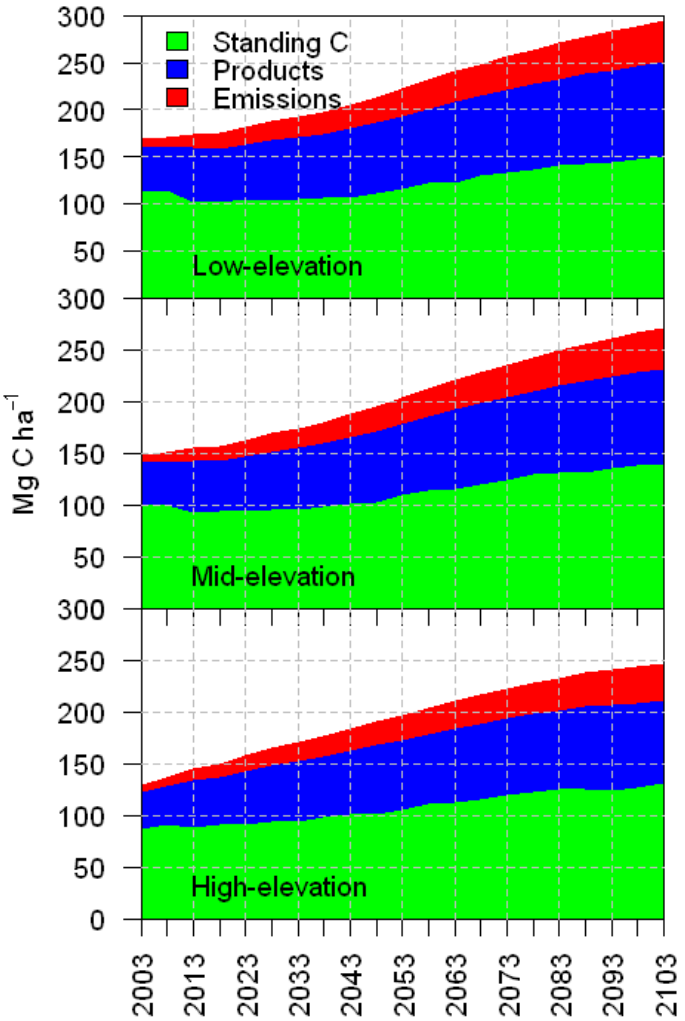
In the even-aged scenario, initial TC (total C sequestered in biomass and forest products) was slightly lower than the no-action scenario due to the effects of harvesting at the beginning of the simulation. This value increased from 161, 141 and 123 Mg ha^{-1} in the low, medium and high elevation bands, respectively, and continued with a positive slope throughout the simulation period,

reaching a value of 250, 231 and 211 Mg ha^{-1} in the low, medium and high elevation bands, respectively, by the end of the simulation period (2103).

In the uneven-aged scenario, TC similarly began slightly lower than the no-action scenario due to the effects of harvesting at the beginning of the simulation. Sequestration increased from 163, 143 and 124 Mg ha^{-1} in the low, medium and high elevation band, respectively, through the simulation period with 220, 204 and 193 Mg C ha^{-1} sequestered by the end of the simulation period in 2103. These values were well below those obtained in the even-aged scenario, which resulted in highest TC values by the end of the simulation period.

Results from the even-aged scenario were further broken down into 3 major categories in order to demonstrate the fate of various C components in our accounting (Figure 3). The standing C category represented the C stored in the forest. The forest products category represented additional C stored in forest products produced from material removed from the forest over time. These two components together comprised the TC sequestration of the scenario. In addition, a cumulative emissions category represented C lost as emissions from the decomposition of the forest products category. Across the three elevation bands, standing C, products, and emissions accounted for approximately 51%, 34% and 15%, respectively, of the C accounted for over the simulation period.

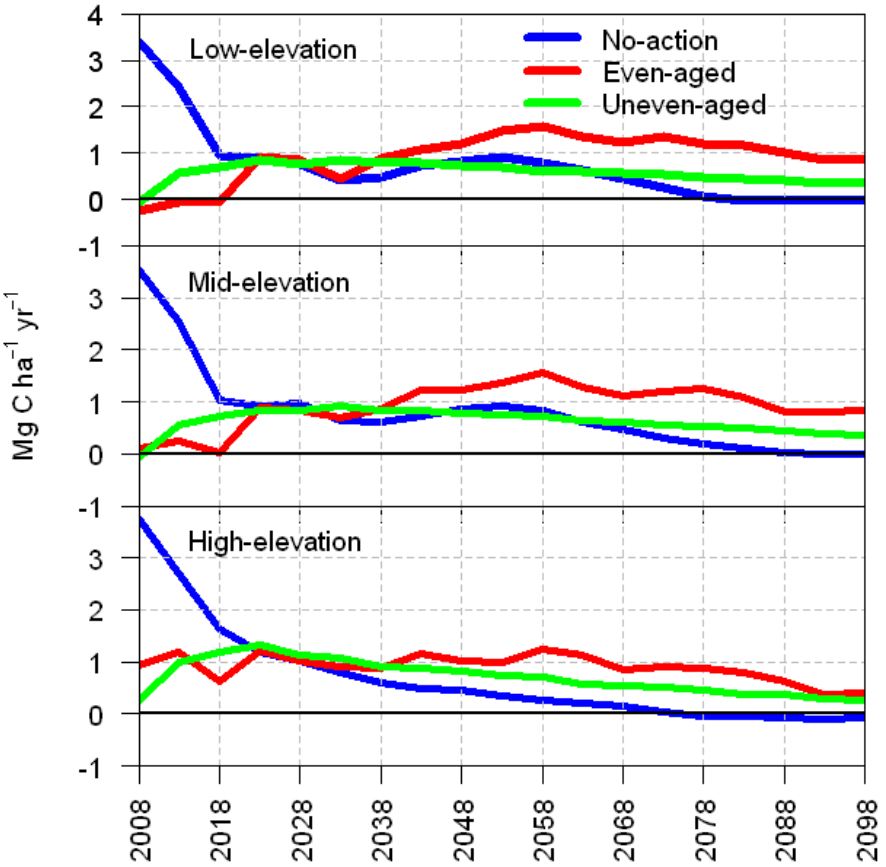
Figure 3. Cumulative aboveground live C, C stored in forest products and C released as emissions (Mg ha^{-1}) for three elevation groups under the even-aged management scenario.



3.2. Average Annual Change in Carbon

The AAC (average annual change in C sequestered in biomass and forest products) during the no-action scenario immediately decreased from 3.4, 3.5 and 3.7 Mg ha^{-1} yr^{-1}, approaching zero in all elevation bands (Figure 4). In the even-aged scenario, AAC began low (0–1 Mg ha^{-1} yr^{-1}) due to the effect of reduced stocking, and reached a maximum at 1.6, 1.6, and 1.2 Mg ha^{-1} yr^{-1} in the 2053–2058 time period, before they stabilized towards the end of the simulation at 0.8, 0.7 and 0.6 Mg ha^{-1} yr^{-1} at the low, medium and high elevation bands, respectively. In the uneven-aged scenario, AAC also began low (−0.1 to 0.3 Mg ha^{-1} yr^{-1}) due to the effect of reduced stocking, reached a plateau at 0.9, 0.9 and 1.3 Mg ha^{-1} yr^{-1} in the 2018–2033 time period, and stabilized at 0.4, 0.5 and 0.4 Mg ha^{-1} yr^{-1} at the low, medium and high elevation band, respectively.

Figure 4. Average annual change in aboveground C (AAC; Mg ha^{-1} yr^{-1}) for three elevation groups as a result of no-action, even-aged management and uneven-aged management in a southern Appalachian forest.



4. Discussion

Using a forest growth and yield model (FVS) we have demonstrated that silvicultural manipulation can yield improvement in C sequestration over the no-action (*i.e.*, business-as-usual) scenario. By controlling stand density and stand development, it should be possible to increase C sequestration. The amount of predicted C sequestered varied by silvicultural scenario (*i.e.*, even-aged or uneven-aged). It is especially noteworthy that whether a silvicultural scenario actually was predicted to have met the

additionality objective (*i.e.*, an improvement over no-action) over the mandatory 100-year planning horizon depended primarily on how additional C sequestration was assessed. For example, if just considering TC, *i.e.*, C pool size, dense, older stands would likely be considered the largest C pools. On the other hand, if the focus was on AAC, *i.e.*, the rate of C accumulation, young, rapidly growing stands are likely to accumulate C faster, even if their TC is lower [51]. Furthermore, accounting for the fate of harvested material (*i.e.*, percent in long-term storage) will influence the assessment of managed and no-action scenarios with respect to long-term C sequestration.

In this study the even-aged scenario marginally outperformed the no-action scenario in TC sequestration over the 100-year time period for all three elevation bands. This demonstrated that silvicultural manipulation including commercial harvest can be an effective tool for sequestering C over time when wood harvested for long-term products is included in the analysis. Although the increased TC of this scenario over the no-action was manifest after nearly 100 years, it emphasizes the importance of timely implementation in order to achieve future results. The uneven-aged scenario did not outperform the no-action scenario during the simulation period in terms of TC sequestration. It did, however, come close, and would likely surpass the no-action scenario over a longer time period.

In terms of AAC, both the even-aged and uneven-aged scenarios outperformed the no-action scenario within 20–30 years and continued to outperform the no-action scenario for most of the simulation period. While decay fates of forest products will likely determine how long AAC will remain positive, the end-of-rotation harvest in the even-aged scenario would temporarily create a carbon source [51]. Unlike comparisons of TC, calculating AAC takes into account the fact that the silviculture scenarios include periodic reductions in stand stocking due to thinning schedules. In contrast with TC, comparisons of AAC between the no-action and the silvicultural scenarios highlight the potential benefits of management. The somewhat modest gains in TC, which did not occur until well into the 100-year simulation, mask what were actually important management-induced changes in sequestration (wood products) and growth rate (increased subsequent growth due to density regulation) that translated into much higher AAC for the managed stands. In other words, by calculating AAC, we accounted for the fact that the no-action scenario, although starting with higher TC, had a relatively slow rate of C increase over time in comparison to managed stands.

That we found potential increases in C sequestration as a result of silvicultural intervention is especially noteworthy, as the spruce-fir forest type is likely not the ideal candidate for C sequestration. For example, the large amounts of decaying organic matter created as a result of the BWA has been documented for this spruce-fir forest [37] and could lead to the release of CO_2 into the atmosphere. Therefore, if incorporated into the analysis, forest response to a disturbance like BWA could potentially affect C sequestration trajectories when compared to an undisturbed spruce-fir ecosystem. Therefore, other forest types with lower amounts of decaying organic matter might exhibit a stronger C sequestration effect in response to silvicultural activities. In general, decadent forests with high levels of standing C but little net C accumulation may provide the greatest potential for C sequestration through silvicultural intervention [29,52]; however, implementing management in older forests of all types may be difficult given their potential old-growth status. Converting decadent stands to younger and more vigorous stands (*i.e.*, below the zone of imminent density-dependent mortality, [53]), could potentially provide an increase in sequestered C, in the form of both forest products and increased growth, from many currently unmanaged forests. In addition, Keyser [10] determined that higher

quality sites (high SIs) may sequester more C over time, which is consistent with our results. Therefore, potential C sequestration could be further maximized by focusing on higher quality sites; in this case high SIs and lower elevation sites (Figure 4).

In southern Appalachian spruce-fir forests, management which aims to reduce the occurrence or severity of disturbance can help moderate the fluctuation of C losses over time. For example, the probability for recurrence of the non-native BWA might be minimized by maintaining lower stocking levels of suitable host (Fraser fir) thereby lowering insect risk. Although the no-action scenario appears desirable in terms of TC, this comes with the increased probability of future BWA mortality and the associated C release that would ultimately threaten the long-term effectiveness of the no-action strategy for sequestering C. The same reasoning has been applied to southwestern forests threatened by wildfire. Hurteau *et al.* [27] suggested maintaining low ponderosa pine (*Pinus ponderosa* Dougl.) stand densities via thinning and prescribed fire to reduce the risk of wildfire and subsequent release of large amounts of C into the atmosphere. Indeed, large-scale disturbances, although they occur at longer intervals, have the potential to drastically change C dynamics in forested systems. In particular, the effect of climate change-induced shifts in forest stand dynamics or disturbance processes on Appalachian spruce-fir C dynamics is a topic for future study.

Historically, spruce-fir forests may have been C neutral or near-neutral as forest growth, mortality, and soil respiration fluctuated over time. Using *in situ* C estimates, van Miegroet *et al.* [37] found the NDW spruce-fir forest exhibited near-neutral ecosystem C over a 10-year period (1993–2003). The discrepancy between C neutrality observed by van Miegroet *et al.* [37] and these results, which suggest C is accumulating, is likely a result of precluding soil C dynamics in our modeling. Changes in soil C are very difficult to estimate and there are few studies that document soil C dynamics even though it is a large forest C pool [37,54], which might explain why soil C models such as Yasso [55] are not yet supported in FVS. Van Miegroet *et al.* [37] found soil C comprised >50% of ecosystem C in our study area. Changes in soil C dynamics due to management actions (e.g., thinning) might alter interpretations of C sequestration potential, especially considering possible differences between active harvesting and no-action scenarios [56]. However, based on reviews of various disturbance regimes, including forest management strategies, soils were found to be generally less responsive to disturbance compared to the forest floor [56,57]. In general, soil C changes tend to be large near the surface and diminish with depth depending on management-related disturbances to the soil [56]. With minimal soil disturbance both the no-action and uneven-aged scenario would reduce soil C loss over time compared to the even-aged scenario, which necessitates a regeneration harvest at the end-of-rotation. However, labile soil C after regeneration harvest under the even-aged scenario is likely to return to pre-harvest conditions in a relatively short time period [56].

5. Management Implications

To mitigate the effects of climate change a diverse set of strategies will have to be implemented. One very important and effective strategy is silvicultural intervention that enhances the rate of forest C sequestration by actively managing forest stands. We have shown that silviculture can increase C sequestration rates in a southern Appalachian spruce-fir forest, and suggest similar outcomes could be achieved in other forest types, particularly more productive types. In general, results from our

simulations are consistent with Hoover and Heath [8], who proposed that stocking management could considerably increase C sequestration on a regional basis (northeast US). Our analysis further demonstrated the tools and carbon accounting protocol that any silviculturist could use to model the effect of silvicultural activities on aboveground C sequestration. FVS is easily accessible, readily available to land managers and is part of a nationally supported framework. We suggest that FVS-FFE could be used in a variety of applications to evaluate whether active management may be a better strategy than passive management for aboveground C sequestration. Finally, we have demonstrated that whether the objective of additionality can be met is potentially influenced by: (1) the C accounting method (*i.e.*, TC *versus* AAC); (2) the carbon-community dictated planning horizon of 100 years; (3) whether or not long-term storage (*i.e.*, solid wood products) is considered. Therefore, silviculturists wishing to evaluate C sequestration potential would do well to take into consideration these factors before evaluating the efficacy of their treatments.

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Conflict of Interest

The authors declare no conflict of interest.

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