Thinning and site quality influence aboveground tree carbon stocks in yellow-poplar forests of the southern Appalachians

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Abstract: Little information exists regarding the effects of intermediate stand management activities (e.g., thinning) on C storage. This lack of information has created uncertainty regarding trade-offs between the benefits observed following thinning and C storage. Using long-term growth data, this study examines the effect of thinning on C storage while controlling for the effects of site quality in yellow-poplar (*Liriodendron tulipifera* L.) forests throughout the southern Appalachian Mountains. In 1960, one hundred and eighteen 0.1 ha plots were established in yellow-poplar forests throughout the southern Appalachians and subsequently thinned to a randomly assigned residual basal area (RBA) (square metres per hectare). Carbon storage increased through time across all levels of RBA. RBA had a long-term effect on C storage with greater C storage occurring at greater RBA. On average-quality sites, thinning to 30 $m^2 \cdot ha^{-1}$ stored 84% more C than thinning to 10 $m^2 \cdot ha^{-1}$. At no time did plots with progressively lower RBA store more C than plots with progressively higher RBA. The results from this study provide information about the effects of intermediate silvicultural disturbance on C dynamics of the aboveground live tree pool in a complex landscape and may be used to inform decisions regarding trade-offs between active management and C storage.

Résumé : Il existe peu d'informations sur les effets des activités intermédiaires d'aménagement forestier (p. ex. l'éclaircie) sur l'entreposage de C. Ce manque d'informations est à la source d'incertitudes concernant les compromis entre les bénéfices observés à la suite d'une éclaircie et l'entreposage de C. À l'aide de données de croissance à long terme, cette étude évalue l'effet de l'éclaircie sur l'entreposage de C en tenant compte de l'effet de la qualité de station dans des forêts dominées par le tulipier de Virginie (*Liriodendron tulipifera* L.) dans le sud des Appalaches. En 1960, 118 parcelles de 0,1 ha ont été établies dans des forêts de tulipier du sud des Appalaches et elles ont ensuite été éclaircies en leur assignant aléatoirement une surface terrière résiduelle (STR) (mètres carrés par hectare). L'entreposage de C a augmenté avec le temps pour toutes les valeurs de STR. La STR a eu un effet à long terme sur l'entreposage de C : l'entreposage de C était plus élevé pour les plus grandes valeurs de STR. Sur les stations de qualité moyenne, une éclaircie laissant une STR de 30 $m^2 \cdot ha^{-1}$ entreposait 84 % plus de C qu'une éclaircie laissant une STR de 10 $m^2 \cdot ha^{-1}$. Les parcelles dont les valeurs de la STR étaient progressivement plus faibles n'ont jamais entreposé plus de C que les parcelles dont les valeurs de la STR étaient progressivement plus élevées. Les résultats de cette étude fournissent des informations sur les effets d'une perturbation sylvicole intermédiaire sur la dynamique du C de la partie aérienne des arbres établis dans un paysage complexe. Ces informations peuvent être utilisées pour éclairer les décisions concernant les compromis entre l'aménagement actif et l'entreposage du C.

[Traduit par la Rédaction]

Introduction

Intermediate stand management activities (e.g., thinning) are implemented to achieve numerous resource management objectives including, but not limited to, the improvement and maintenance of wildlife habitat, wildfire hazard reduction, ecosystem restoration, and timber production. Concern over mitigating climate change has created an interest in using forestland to increase the amount of C currently being stored by forests and to offset atmospheric CO_2 emissions produced from the burning of fossil fuels. Considering the C stored in wood products (Heath and Skog 2004) as well as in forested ecosystems, US forests currently sequester 200 Tg $C \cdot year^{-1}$ (Heath and Smith 2004) and have the potential to sequester up to an additional 200 Tg $C \cdot year^{-1}$ (Birdsey et al. 2006). Little information exists regarding the effects of forest management activities, in particular the effects of intermediate stand management on C storage and rates of C sequestration. Forest C stocks can be categorized into four pools: (*i*) aboveground biomass, (*ii*) belowground biomass, (*iii*) dead organic matter (deadwood and forest floor organic matter), and (*iv*) mineral soil (IPCC 2003). Past research on the effects of thinning on aboveground tree biomass has focused on traditional individual-tree or stand-level volume growth and yield. This paper examines the effects of thinning and site productivity on changes in the

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Table 1. Prethinning (1961) and postthinning (1966) stand attributes (n = 118).

Stand attribute	Mean	Minimum	Maximum	SD
Yellow-poplar SI	31.9	24.4	39.0	3.2
Basal area ($m^2 \cdot ha^{-1}$)				
Prethinning	30.9	10.9	46.7	6.9
Postthinning	19.7	9.1	34.4	6.7
Trees$\cdot ha^{-1}$				
Prethinning	570	267	1068	179
Postthinning	199	69	633	105
Stand density index (SDI) (Reineke 1933)				
Prethinning	593	257	776	107
Postthinning	334	163	582	109
Relative density (RD) (%)				
Prethinning	55	23	71	10
Postthinning	31	15	54	10
Quadratic mean diameter (cm)				
Prethinning	27.1	15.5	44.8	5.8
Postthinning	37.5	17.6	54.5	8.2
ATC ($t\ C \cdot ha^{-1}$)				
Prethinning	89.2	22.4	171.3	26.6
Postthinning	62.0	21.2	117.5	23.5
MTC ($t\ C \cdot ha^{-1}$)				
Prethinning	55.1	11.8	113.0	18.1
Postthinning	39.6	11.9	78.2	15.6

Note: RD = SDI_{obs}/SDI_{max}, SDI_{max} = 1140.

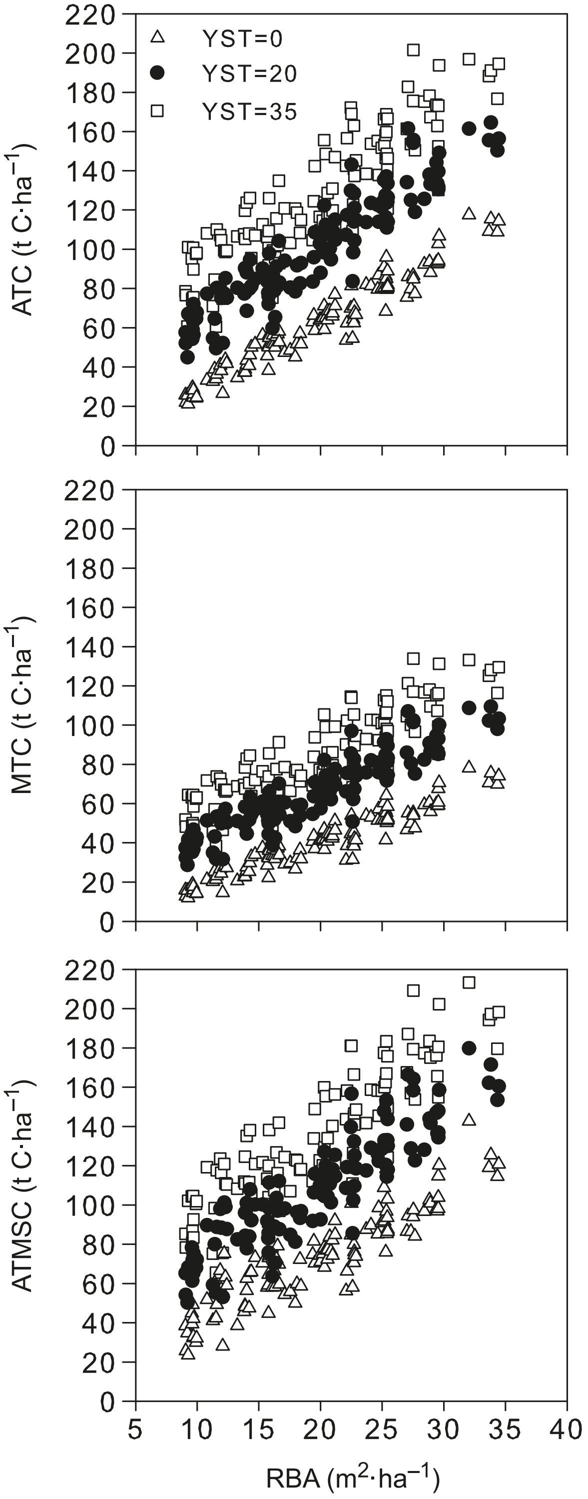
aboveground tree C pool in yellow-poplar (*Liriodendron tulipifera* L.) forests of the southern Appalachian Mountains.

Thinning is customarily used to "salvage" volume that would have been lost due to mortality during normal stand development as well as to increase and concentrate future growth on more valuable trees (Smith et al. 1997). The effects of thinning on individual-tree and stand-level growth have been intensively studied. Thinning has been shown to increase residual tree growth (Beck and Della-Bianca 1975; Seidel 1986; Marquis and Ernst 1991) as well as both merchantable volume increment and total merchantable production (Nowak 1996; Curtis et al. 1997; Smith 2003). The effects of thinning on total volume increment are less conclusive. While some studies report significant increases (Simard et al. 2004; Gilmore et al. 2005) in total volume increment, others report that thinning results in a significant decrease (Hibbs et al. 1989; Curtis et al. 1997; Smith 2003; Skovsgaard 2009) in total volume increment. Inconsistent results among various thinning studies are likely due to differences in thinning regimes (Emmingham et al. 2007; Bradford and Palik 2009), stand structure (Oliver and Murray 1983; Marquis and Ernst 1991), species composition (Nowak 1996), age (Beck and Della-Bianca 1975), and site quality (Skovsgaard 2009). Regardless of the effect on total volume increment, it is widely accepted that thinning results in a reduction in the total stand volume produced throughout a rotation relative to unthinned stands (Assman 1970).

Similar to total volume production, C stored in the aboveground biomass pool in managed forests is often maximized by reducing disturbance (e.g., silvicultural activities) frequency (Harmon and Marks 2002; Harmon et al. 2009; Hudiburg et al. 2009). Along a 500-year chronosequence of unmanaged Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) – western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests in Washington, Janisch and Harmon (2002) reported that C stored in tree boles was maximized at ~200 years following stand-replacing disturbance with no decrease in C stores observed up through 500 years postdisturbance. Similarly, Law et al. (2003) report that the proportion of C in aboveground live wood mass increases rapidly in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands in central Oregon up through age 200 but does not decline in older (up to 316 years) stands.

Relatively few studies have examined the effects of intermediate stand management on C storage. Law et al. (2003) commented that thinning ponderosa pine for fuel treatments and to accelerate late successional habitat may moderately reduce C storage in aboveground biomass. Some recent studies support this statement and show that thinning from below for hazardous fuel reduction in western conifer forests (Finkral and Evans 2008; Campbell et al. 2009) as well as eastern deciduous forests (Chiang et al. 2008) decreases aboveground live tree C stocks relative to unthinned stands, at least in the short term. Although these studies suggest that C storage decreases with thinning, a recent study by Hoover and Stout (2007) suggests that the impact of thinning on C storage is significantly influenced by the type of thinning conducted. For example, Hoover and Stout (2007) report that although total C storage (C stored in live biomass, deadwood, logging residue, and products) in black cherry (*Prunus serotina* Ehrh.) – sugar maple (*Acer saccharum* Marsh.) stands thinned from below stored similar amounts of C and had similar C sequestration rates compared with unthinned controls, stands commercially thinned from the middle as well as thinned from above experienced significant decreases in C stocks and C sequestration rates, suggesting that stand structure and thinning interact to influence C storage.

Fig. 1. Observed C storage in the ATC, MTC, and ATMSC biomass pools over 0, 20, and 35 years since thinning (YST) (0 = 1966).



Many factors can influence stand-level growth and consequently C storage and C sequestration rates. Past forest production research has suggested that differences in site productivity in past studies have limited the ability to detect the magnitude of impact that various management actions, including thinning, can have on stand-level growth. Skovsgaard (2009), for example, found that the effect of thinning on stand volume growth was strongly site dependent for Sitka spruce (*Picea sitchensis* (Bong.) Carr.), emphasizing the need to account for differences in site quality when interpreting results from thinning studies. This objective of this study was to determine the effect of thinning on long-term C storage and C sequestration rates across a broad range of site qualities in yellow-poplar forests throughout the southern Appalachian Mountains.

Table 2. Model statistics associated with the fitting of eq. 1 to ATC, MTC, and ATMSC.

Measure	Formula	ATC	MTC	ATMSC
Accuracy	$\frac{\sum(y_{ij}-\widehat{y}_{ij})}{n}$	–0.46	–0.29	–0.26
Bias	$\sqrt{\frac{\sum(y_{ij}-\widehat{y}_{ij})^2}{n}}$	10.2	7.3	11.9

Methods

Data

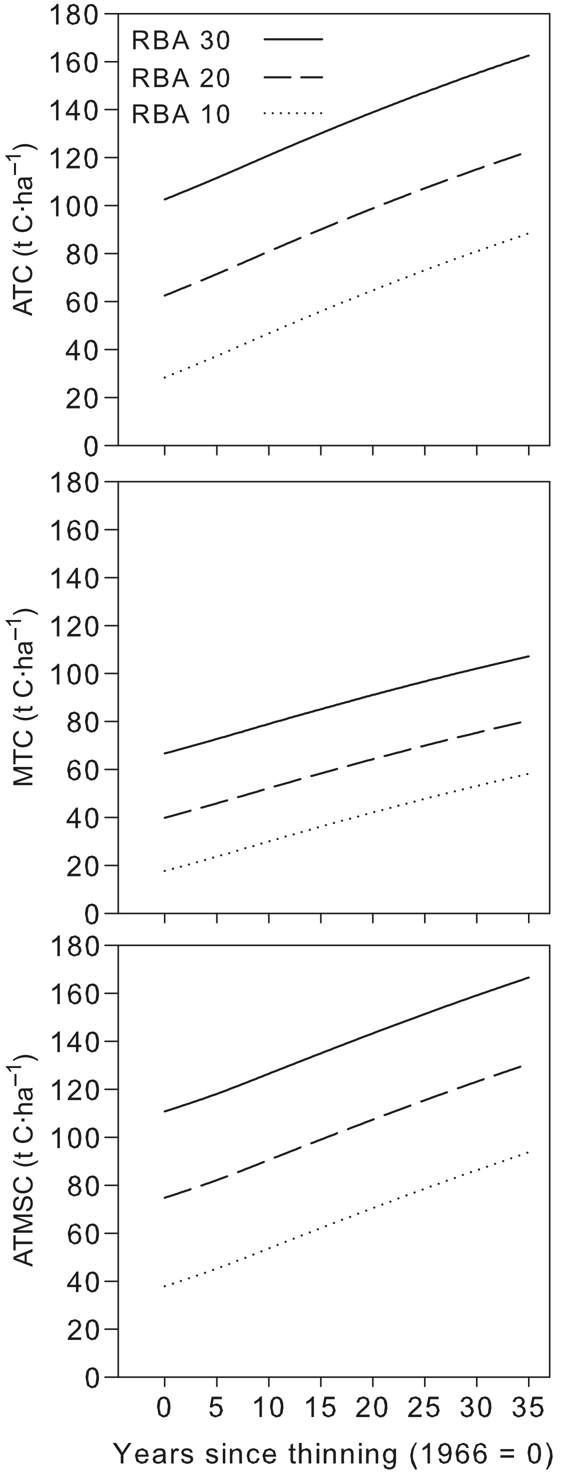
This study uses data collected as part of a long-term study examining the growth and yield of yellow-poplar throughout the southern Appalachians as it relates to site index (SI) and thinning intensity. Between 1960 and 1964, a total of one hundred and forty-one 0.1 ha growth and yield plots were established in yellow-poplar stands throughout the Blue Ridge and northern Ridge and Valley provinces of the southern Appalachian Mountains. Plots were located in northern Georgia, western North Carolina, eastern Tennessee, and southern Virginia. All plots were established in even-aged stands dominated by yellow-poplar (>80% of the overstory basal area (BA)) with no recent evidence of past disturbance or harvesting.

At the time of plot establishment and prior to the thinning treatment, all live trees >11.4 cm diameter at breast height (DBH) (1.37 m above the ground line) within each plot were tagged and stem-mapped. For all tagged trees, species, DBH, and total height were recorded. One increment core at stump height was obtained from five dominant/codominant yellow-poplar trees per plot. Age at stump height was obtained from the increment cores in the laboratory under magnification. Using the age and height data, an estimate of SI (base age 50) was calculated using yellow-poplar SI equations developed by Beck (1962) for each of the five trees per plot. Plot-level SI was calculated as the average SI of the five sample trees.

Following plot establishment and the prethinning inventory, plots were thinned from below (i.e., low thinning; Smith et al. 1997, pg. 99) to a randomly assigned residual basal area (RBA). Unlike an operational low thinning, all trees and woody shrub species <11.4 cm DBH were removed to ground level. Species other than yellow-poplar were targeted for removal to obtain the specified RBA. After the second inventory cycle (1966–1969) was completed, 128 of the 141 permanent plots were thinned from below for a second time to the originally assigned RBA. No subsequent thinnings followed.

Remeasurement of all plots occurred during the dormant season every 5 years following plot establishment beginning

Fig. 2. Carbon storage in the ATC, MTC, and ATMSC biomass pools as modeled by eq. 1. Values presented are based on an intermediate quality site with a SI value of 30 m.



in 1960 up through 2001 for a total of nine inventory cycles including the prethinning inventory in 1960. During each inventory cycle, the status of all tagged trees was assessed (e.g., live, dead, or harvested) and DBH was recorded on all live trees. Beginning during inventory cycle 8 (years 1996–1999), ingrowth (trees >11.4 cm DBH) was tagged and species and DBH were recorded. When tagged trees were recorded as "dead" during a given inventory cycle, individual tree data including DBH were not recorded in the current or any subsequent inventory cycles.

Estimation of C

Because C stored in woody tissue is proportional to biomass, aboveground biomass of individual trees during each inventory cycle was used as a measure of both plot-level total aboveground live tree C (ATC) and merchantable (from a 30.5 cm stump height up to a 10.2 cm diameter top) aboveground live tree C (MTC). To minimize variability in biomass predictions due to geographic differences in tree allometries in the southern Appalachian Mountains (e.g., Martin et al. 1998), generalized biomass equations based on DBH and appropriate for use across broad geographic areas (Jenkins et al. 2003) were used to compute the biomass (kilograms) of all live trees recorded during each inventory cycle. The whole-tree biomass equations produced by Jenkins et al. (2003) include biomass contained in coarse roots (>6.4 cm in diameter). Therefore, whole-tree biomass estimates for individual tree data used in this study includes that of coarse roots. Because size and status of mortality (i.e., standing versus dead and down) were not recorded during the inventories, mortality was not included in the ATC, MTC, and ATMSC biomass pools. Little mortality was observed on the plots throughout the 35-year sampling period. Much of the mortality observed over the 35-year sampling period was recorded as windthrow, broken tops, and (or) lightening damage as opposed to being recorded as standing dead with no apparent cause of death.

To estimate total C (metric tons (t)) for each plot, biomass estimates were multiplied by 0.5 (Penman et al. 2003) and scaled to a per hectare basis. The C submodel (Reinhardt et al. 2007) within the Fire and Fuels Extension (Reinhardt and Crookston 2003) to the Forest Vegetation Simulator (FFE-FVS) (version 6.21, revision date 19 September 2008) (Crookston and Dixon 2005,) was used to facilitate the calculation of both biomass, ATC, and MTC using the individual tree data collected during each inventory cycle. In addition, FFE-FVS was also used to calculate the biomass and C of harvested (i.e., biomass removed in the thinnings) merchantable material stored in landfills and products (PRODUCT). The fate of harvested C through time was based on regional relationships outlined by Smith et al. (2006) as modeled in FFE-FVS. The sum of ATC and PRODUCT during any given year represents the amount of C stored in aboveground live biomass and merchantable C stored in PRODUCT through time (ATMSC).

Because this study lacked unthinned controls and there is no available information on C storage in unmanaged yellow-poplar stands across the geographic and SI range sampled in this study, FVS, a distance-independent, individual-tree growth and yield model, was used to model potential C storage in the ATC biomass pool without thinning between 1961 and 2001. The pre-1961 thinning individual-tree inventory data (species, DBH, and total height) along with plot-level variables used in the growth model (e.g., SI, slope, physiographic location, etc.) were input into FVS and grown through time using species-specific growth and mortality relations inherent to the Southern Variant of FVS (FVS-Sn). Carbon storage values from the unthinned FVS growth sim-

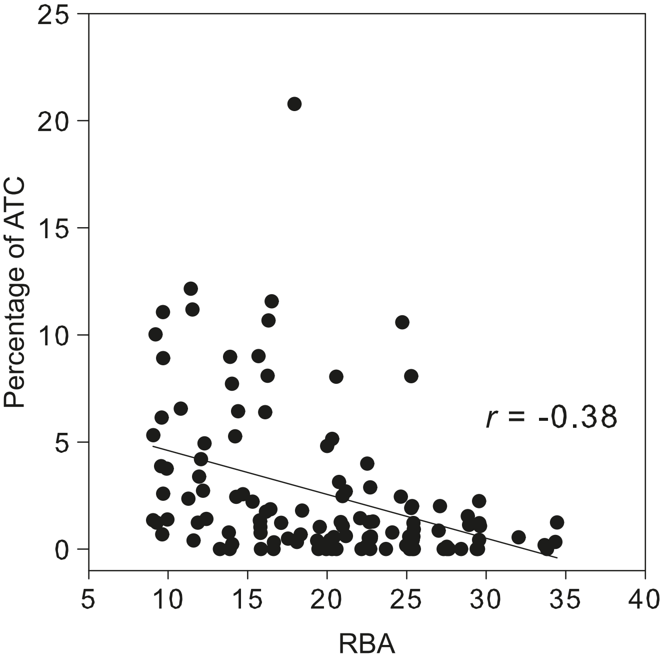
Table 3. Estimated parameters (SE) and associated −2 log likelihood (−2LL) and Akaike information criterion values for ATC, MTC, and ATMSC fitted using eq. 1.

Variable	b_0	b_1	b_2	b_3	b_4	−2LL	Akaike information criterion
ATC	2.5346 (0.1814)	0.0294 (0.0075)	168.82 (17.13)	−0.134 (0.0021)	32.6940 (0.8666)	5484.1	5498.1
MTC	1.5314 (0.1312)	0.0230 (0.0054)	120.83 (12.59)	−0.0130 (0.0020)	32.5538 (0.8257)	4736.4	4750.4
ATMSC	3.8348 (0.2201)	−0.0048 (0.0089)*	177.02 (21.08)	−0.0131 (0.0022)	34.6174 (0.9865)	5536.6	5550.6

Note: *P* values for all parameters were <0.0001 except where noted.

*Parameter estimate not significant at $\alpha = 0.05$.

Fig. 3. Percentage of ATC due to ingrowth at the end of the 35-year analysis period.



ulations are provided for reference only and were not included in any statistical analyses.

Data analysis

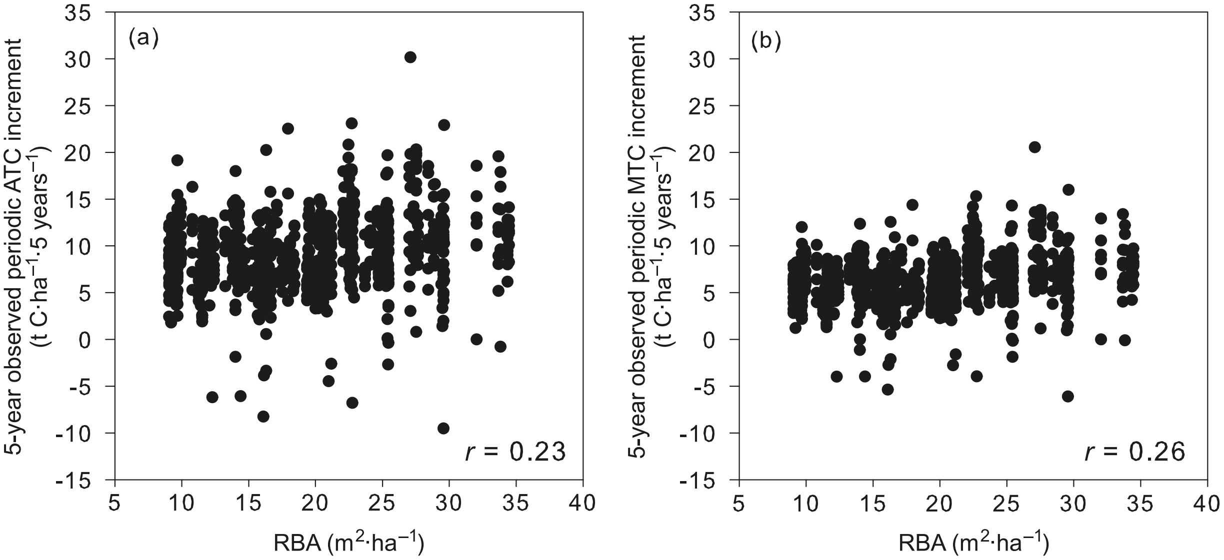
The 13 plots that did not receive a second thinning were demonstrated by Knoebel et al. (1986) to possess significantly different growth patterns than twice-thinned plots. Therefore, these 13 plots were removed from the current analysis. An additional 10 plots were removed from analysis due to the harvesting and incomplete data, making 118 of the original 141 plots available for use in the current study.

Regression analysis was used to determine the effects of thinning intensity as defined by RBA, years since thinning, and SI on the ATC, MTC, and ATMSC biomass pools. Plot-level growth over time follows a sigmoid-shaped pattern; consequently, the Chapman–Richards function (Richards 1959) with modifications to allow for variable postthinning RBA and variable growth rates based on SI (e.g., Knoebel et al. 1986) was used as a basis for the analysis of C storage over time and was defined as follows:

$$[1] \qquad y_{ij} = b_0\mathrm{RBA}_{i0} + b_1\mathrm{RBA}_{i0}^2 + b_2\left(1 - \mathrm{e}^{b_3(t_{ij})}\right)^{b_4/\mathrm{SI}} + \varepsilon_{ij}$$

where y_{ij} is C (metric tons per hectare) on plot i (i = 1, 2, 3, ...,118) at time j (j = 0, 5, 10, 15, 20, 25, 30, and 35 years postthinning), RBA is residual basal area (square metres per hectare) following the second thinning in 1966 of plot i at time j = 0, t_{ij} is the years since thinning of plot i at time j, SI is site index of yellow-poplar (metres) measured at the time of plot establishment, b_0, b_1, b_2, b_3, and b_4 are the estimated model parameters, and ε_{ij} is the normally distributed error term associated with plot i at time j. The parameter b_2 is the maximum (asymptotic) C (metric tons per hectare), b_3 is the growth constant parameter, and b_4 is the shape parameter.

Fig. 4. Observed 5-year periodic C increment for the (*a*) ATC and (*b*) MTC biomass pools.



This model was developed as an analysis tool rather than a predictive model of C storage over time. The nonlinear model 1 was fitted to ATC, MTC, and ATMSC data using the SAS %NLINMIX macro described by Littell et al. (2006) and available from www.sas.com. This macro uses both PROC NLIN and PROC MIXED to fit nonlinear models and has the ability to account for the autocorrelation among repeated measurements that occurred on each independent plot. A first-order autoregressive covariance structure was chosen because the measurements were made on equally spaced time intervals (i.e., every 5 years). For ATC, MTC, and ATMSC, weighted nonlinear regression was utilized to fulfill the assumption of homoscedasticity. The form of the weighting function used was $(\mathrm{RBA})^{-0.5}$ for the ATC and MTC variables and $(\mathrm{RBA})^{-0.25}$ for the ATMSC variable. Weights were chosen based on the model resulting in the lowest Akaike information criterion values with weights starting at a value of –0.25 and decreasing at intervals of –0.25.

Results

Prior to the 1961 thinning and at the time of plot establishment, BA, density, and quadratic mean diameter of the 118 plots ranged from 10.9 to 47.6 $\mathrm{m^2{\cdot}ha^{-1}}$, from 267 to 1068 $\mathrm{trees{\cdot}ha^{-1}}$, and from 15.5 to 44.8 cm, respectively (Table 1). All plots were located on productive sites with SI ranging from 24.4 to 39.0 m. The C stocks prior to thinning were variable, ranging from 22.4 to 171.3 $\mathrm{t\ C{\cdot}ha^{-1}}$ for ATC and from 11.8 to 113.0 $\mathrm{t\ C{\cdot}ha^{-1}}$ for MTC. After the second thinning in 1966, BA and density ranged from 9.1 to 34.4 $\mathrm{m^2{\cdot}ha^{-1}}$ and from 69 to 633 $\mathrm{trees{\cdot}ha^{-1}}$, respectively. Because low thinning was used, quadratic mean diameter increased in all plots and ranged from 17.6 to 54.5 cm immediately postthinning in 1966. The combination of the first thinning in 1961 and the second thinning in 1966 removed a substantial amount of C from the plots. Total ATC was reduced from prethinning averages by 31%, while MTC was reduced by 28% immediately following the 1966 thinning.

The average predicted ATC storage in the FVS-modeled unthinned plots ranged from 162 $\mathrm{t\ C{\cdot}ha^{-1}}$ on lower quality sites (SI < 30.5 m) to 185 $\mathrm{t\ C{\cdot}ha^{-1}}$ on higher quality sites (SI > 36.6 m) 40 years after the initial thinning was conducted in 1961. These average predicted values were slightly lower than the maximum observed ATC values at the same point in time (Fig. 1). The FVS-Sn is not capable of automatically inputting and modeling ingrowth (i.e., it is not a full establishment model). Consequently, these modeled ATC values do not include any additional C storage resulting from ingrowth that may have occurred in these stands during stand development and, therefore, may underestimate potential C storage in these modeled unthinned yellow-poplar plots.

On average, eq. 1 resulted in a slight overestimation of C storage for all three biomass pools examined (Table 2). As expected, C storage increased through time across all levels of RBA and SI. The level of RBA following the 1966 thinning, however, had a significant and long-term effect on C storage in the ATC, MTC, and ATMSC pools (Fig. 2). The positive value of the parameter associated with RBA (i.e., b_0) suggests that C storage is greatest at higher levels of RBA for all three C pools examined in this study (Table 3). Results from the fitting of eq. 1 to data suggest that for a site of average quality (e.g., SI = 30 m), a plot thinned to 30 $\mathrm{m^2{\cdot}ha^{-1}}$ possessed 33% more ATC than a plot thinned to 20 $\mathrm{m^2{\cdot}ha^{-1}}$ and 84% more ATC than a plot thinned to 10 $\mathrm{m^2{\cdot}ha^{-1}}$. The effects of RBA were greatest in the ATMSC pool and lowest in the MTC pool as evidenced by the magnitude of the b_0 parameter estimate. The greater value of the b_0 parameter for ATMSC resulted from the fact that ATMSC was a combination of merchantable material removed during the thinning and stored in PRODUCT over time and ATC with a lower RBA (i.e., heavier thinning) coinciding with greater amounts of C being stored long-term in PRODUCT. Including C stored in PRODUCT somewhat diminished the discrepancy between C storage compared with the ATC and MTC biomass pools. For a site of average quality, a plot thinned to 30 $\mathrm{m^2{\cdot}ha^{-1}}$ possessed 28% more ATC than a plot thinned to 20 $\mathrm{m^2{\cdot}ha^{-1}}$ and 78% more ATC than a plot thinned to 10 $m^2 \cdot ha^{-1}$. The amount of merchantable C stored in PRODUCT as a result of the thinning, however, diminished through time. Immediately after the second thinning in 1966, C stored in PRODUCT accounted for 15% of the observed C in the ATMSC pool. By 2001, due to the decay and loss of C, only 5% of the observed C in the ATMSC pool was in stored in PRODUCT. At no time during the 35 years did more heavily thinned plots (i.e., lower RBA) store more C than less heavily thinned (i.e., higher RBA) plots even when taking into account C harvested at the time of thinning and stored in PRODUCT (Fig. 2). At the end of 35 years, the percentage of ATC due to ingrowth was significantly and negatively correlated (r = –0.38) with RBA but varied widely, ranging from 0% to as much as 25% (Fig. 3).

Not surprisingly, C storage following thinning varied by SI with higher SI values resulting in greater C storage over time for the ATC, MTC, and ATMSC pools. The effects of SI were noticeably greater at lower levels of RBA. For example, a plot thinned to 10 $m^2 \cdot ha^{-1}$ of RBA with a SI of 36 was predicted to have 22% more C after 35 years than a plot thinned to 10 $m^2 \cdot ha^{-1}$ of RBA with a SI of 26, whereas a plot thinned to 30 $m^2 \cdot ha^{-1}$ with a SI of 34 was predicted to have only 12% greater C storage than a plot thinned to the same level with a SI of 26. Similar but slightly more pronounced trends in C storage associated with SI were observed for MTC.

The 5-year observed periodic ATC increment (calculated as $(y_{i(j+5)} - y_{ij})$) ranged from –9.5 to 22.9 t $C \cdot ha^{-1} \cdot 5$ $years^{-1}$ (Fig. 4*a*). Variation in the observed 5-year periodic MTC increment was less, ranging from –6.1 to 16.0 t $C \cdot ha^{-1} \cdot 5$ $years^{-1}$ (Fig. 4*b*). Negative ATC and MTC increment values were the result of plot-level tree mortality due to windthrow, lightening, etc., that occurred in a relatively small proportion of plots over time. A significant but weak correlation between 5-year periodic ATC (r = 0.23) and MTC (r = 0.26) increment and RBA was observed.

Discussion

Although this study did not contain unthinned controls, the positive parameter estimate associated with RBA suggests that more intense thinning operations in yellow-poplar stands cause a reduction in plot-level ATC, MTC, and ATMSC relative to less intense thinning, even after 35 years of postthinning growth (Fig. 2). This is consistent with thinning operations designed to reduce hazardous fuels in other eastern (Chiang et al. 2008) and western (Campbell et al. 2009) US forest types. In contrast, Hoover and Stout (2007) documented that black cherry – sugar maple plots in northwestern Pennsylvania thinned from below to a relative density of 60%–70% experienced a slight “crossover” effect in the aboveground live C pool, meaning that thinned plots contained greater C storage in the aboveground live biomass pool than unthinned plots (114 versus 106 t $C \cdot ha^{-1}$). Similarly, the authors reported that total C storage (i.e., C stored in live biomass, deadwood, and PRODUCT) was similar in unthinned plots and plots thinned from below after 25 years. Due to the lack of unthinned controls in this study, examination of a potential crossover effect in yellow-poplar was not directly possible. A future analysis including inventory data from unthinned and undisturbed yellow-poplar stands across the geographic range and SI values sampled in this study would be required to assess potential crossover effects following thinning. This study does, however, show that yellow-poplar plots that received progressively heavier thinnings did not store more C in the aboveground biomass pool, even when taking into consideration the amount of C stored long-term in PRODUCT. This lack of compensation by PRODUCT for loss of stand-level C storage following harvesting is consistent with other studies examining the effects of both complete (Harmon and Marks 2002) and partial (Harmon et al. 2009) harvesting systems.

It should be noted that it is uncommon during commercial thinning operations to remove all woody biomass <11.4 cm DBH as occurred in this study. The effects of the unconventional thinning on C stocks cannot be assessed with this data set. However, little to no shrub layer was present in the plots either prior to the thinnings or during the postthinning inventories (David Loftis, personal communication). Therefore, any change in C storage in the shrub layer was likely minimal, regardless of RBA. The removal of smaller diameter trees may have simply delayed ingrowth in sites with lower RBAs and may have limited ingrowth observed in plots at higher RBAs (Fig. 3), as dense stands likely limited new seedling establishment and recruitment into measurable size classes. Regardless, it is unlikely that the thinning prescription performed in this study modified the relative differences in C storage observed across the broad range of RBA and SI values assessed in this study.

Most studies have shown thinning to have minimal impact on net annual wood production (Campbell et al. 2009), net annual wood plus net annual foliage production (Chiang et al. 2008), and average C increment (Hoover and Stout 2007). Although observed 5-year periodic C increments for ATC and MTC pools in this study were positively correlated with RBA, the relationship was weak, and average annual ATC and MTC at low levels of RBA was often similar to that observed at higher levels of RBA (Fig. 4). Relatively similar C increment or sequestration rates across variable levels of RBA in this study suggest that individual-tree growth, which has been documented to increase with thinning intensity (e.g., Beck and Della-Bianca 1975), although does not completely compensate for the loss of stand-level production that often occurs subsequent to the removal of biomass during thinning operations, does offset a substantial proportion of stand-level C loss.

The implications from this study suggest that there are numerous management options for C storage in yellow-poplar stands in the southern Appalachians. Although this study did not contain unthinned controls, results showing greater C storage at progressively greater RBA values coupled with existing studies of C dynamics following both stand-replacing (e.g., Janisch and Harmon 2002; Law et al. 2003; Taylor et al. 2007) and partial disturbance (e.g., Chiang et al. 2008; Finkral and Evans 2008; Campbell et al. 2009) would suggest eliminating silvicultural disturbance if the primary management objective was to maximize C storage in yellow-poplar stands. However, if managing for multiple objectives including creating or restoring wildlife habitat quality (e.g., Beck 1983), timber production and products, restoration efforts, etc., along with C storage, this study suggests that thinning to the highest RBA possible while still achieving management objectives associated with thinning will maximize C storage in the context of a low thinning silvicultural prescription. The weak correlation between C sequestration rates and RBA (Fig. 4) suggests that other factors such as annual variations in climatic variables (e.g., Beck 1985) may be more of a driver of stand-level growth and C sequestration over the long term than stand structure in yellow-poplar forests.

The significant effect of SI on C storage in this study emphasizes the need to account for the effects of site quality on C dynamics following various management actions. In an area where site quality changes dramatically with topography, elevation, and soil type, ignoring site quality could significantly impact long-term projections of C storage for a given site over time. As the need for accurate C accounting increases, it will become increasingly important to identify the C dynamics following various management actions across the gradient of site qualities that can exist across a highly complex landscape.

Conclusions

This study used a long-term data set to examine the effects of thinning and site quality on C storage in the aboveground biomass pool of yellow-poplar stands in the southern Appalachian Mountains. A more complete and detailed picture of the effects of C dynamics following thinning could be assessed by obtaining a complete inventory of all ecosystem C components including small (<11.4 cm DBH) trees, shrubs, standing dead trees, dead and down coarse woody debris, forest floor (e.g., litter and duff), and mineral soil. However, as reported in Bolstad and Vose (2005), in the southern Appalachians, the greatest proportion of total ecosystem C is found in the aboveground live biomass pool and mineral soil. Therefore, this study, although limited with regard to assessing the effects of thinning on total ecosystem C, does provide valuable information about the effects of partial or intermediate silvicultural disturbance on C dynamics on one of the largest C pools in this complex and variable landscape.

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