The Carbon Consequences of Thinning Techniques: Stand Structure Makes a Difference

Coeli Hoover and Susan Stout

ABSTRACT

Using results from a 25-year study of thinning in a northwestern Pennsylvania Allegheny hardwood stand, we assess whether and how thinning method affected carbon sequestration and merchantable volume production. Plots were thinned to similar residual relative density by removing trees from different portions of the diameter distribution. Plots that were thinned from below had greater volume production and carbon sequestration rates than plots that were thinned from the middle or thinned from above. Control plots, which were not thinned, also had higher carbon sequestration rates than plots thinned from the middle and higher merchantable volume production and carbon sequestration rates than plots thinned from above. In this forest type, changing stand structure by thinning can affect carbon sequestration and stand growth either positively or negatively. Those effects can be significant, with long-term implications for the growth of the stand. In general, structures that favored volume production also favor carbon sequestration.

Keywords: carbon sequestration; thinning; forest carbon

On Dec. 12, 2003, trading in carbon credits began at the Chicago Climate Exchange (CCX) is the world's first and North America's only legally binding rules-based greenhouse gas emissions allowance trading system. At that time, the 14 member companies, including three forest products companies, committed to annual reductions in their collective greenhouse gas emissions equivalent to 1% per year for the next 4 years using their average annual emissions from 1998 through 2001 as a baseline. Since the opening of the exchange, the number of full members has increased to over 50 and initial emission reduction goals have been met or exceeded. Current US carbon credit trading programs are voluntary; increased interest in credit trading is evidenced by the fact that the price of credits on the CCX has increased from \$1.70 to \$4 per metric ton of CO_2 equivalent over the past year.

An increasing number of US states are forming regional climate partnerships and are beginning to examine possible mitigation options; the mayors of over 130 US cities have agreed to abide by the targets set in the Kyoto Protocol, and US companies that do business in Kyoto nations must comply with the emissions caps in the Protocol. These developments suggest that the market for carbon credits in the United States is likely to continue growing, leading to a sustained increase in the value of credits. Carbon sequestered through forestry activities may be counted toward emissions reductions under the Protocol, and forestry offset projects are part of the CCX; therefore, the growing market for carbon credits could provide income opportunities for forest landowners and managers. Monitoring and verification of carbon storage are an important part of any carbon trading or offset program, and multiple third-party certification and offset firms have been formed to provide these services. In addition, "carbon aggregators" bundle acres and projects into portfolios, which can provide an opportunity for smaller landowners to engage in this emerging market; a number of such aggregators are members of the Exchange.

In an earlier article (Hoover et al. 2000) we described a method for forest landowners to estimate carbon storage at the management unit scale, an essential first step in participating in this emerging market. In this article, we investigate the carbon storage

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consequences of partial cutting practices in mixed hardwood stands of the Allegheny Plateau. Will management for carbon sequestration be compatible with management for wood products?

Methodology

We assessed the carbon consequences of thinning-induced changes in stand structure by analyzing inventory data from an ongoing thinning study that was established in 1975. The study was initiated to examine how thinning Allegheny hardwoods (cherry-maple) to the same relative density while altering stand structure affected growth, yield, and stand value. The study stand is located on the Kane Experimental Forest in northwestern Pennsylvania and at the beginning of the experiment was a pole sized even-aged cherry-maple stand that originated after the initial old-growth stand was clearcut in 1922–1923. Before the start of the study, the stand was fully stocked and dominated by sugar maple (*Acer saccharum*) and beech (*Fagus grandifolia*) in the smaller diameter and crown classes, black cherry (*Prunus serotina*) in the larger diameter and crown classes, and red maple (*Acer rubrum*) in the intermediate classes (Marquis and Ernst 1991). The Kane Experimental Forest is dominated by Allegheny hardwoods; these cherry-maple stands are a subtype of the northern hardwood beech-birch-maple forest. Soils are unglaciated stony and sandy loams derived from acid sandstones and shales. The forest is about 1,900 ft above sea level, and climate is humid–temperate with an average annual rainfall of 44.9 in. and an average temperature of 43°F.

The following thinning treatments were applied in 1976 and again in 1990:

1. Control. No thinning ($n = 2$ plots).
2. Thin from below. Noncommercial thinning, starting with the smallest diameter trees and working upward through diameter classes until the specified relative density [1] was achieved ($n = 3$ plots).
3. Thin from middle. Commercial thinning in the merchantable-size classes, but no thinning of noncommercial saplings (dbh is less than 5.49 in.). Removals of merchantable stems continued until the target relative density was reached ($n = 3$ plots).
4. Thin from above. Commercial thinning in merchantable-size classes, removing the largest diameter stems first and working downward through diameter classes until the desired relative density was achieved ($n = 3$ plots).

In all cases except the control plots, the desired relative density was 60–70%. Plots are 2 ac with a central 0.6-ac measurement area surrounded by a 1.4-ac buffer that received the same thinning treatment. Treatments were randomly assigned to plots within a contiguous block of land. A 100% inventory of all stems of 1 in. dbh and greater in the measurement area was conducted every 5 years and immediately before and after the stands were thinned. For additional study details and results, see Marquis and Ernst (1991) and Nowak (1996).

For the carbon analysis, the biomass of all stems of 1 in. dbh or greater was computed using species group biomass equations (Jenkins et al. 2003) with stand inventory data taken at the beginning of the study, before and after the first and second thinnings (1974, 1975, 1989, and 1990), and in 2000. These estimates include all aboveground live biomass and live coarse roots (more than 2.5 in.). The inventory records indicate the fate of each individual stem, including which stems were harvested or died, and ingrowth was recorded also. Any stems reaching 1 in. dbh during the study period were included in the analysis. Products were estimated as the stem portion of the harvested trees and were allocated to carbon pools according to the HARVCARB model of Row and Phelps (1991). HARVCARB allocates harvested biomass into pools including products in use, products in landfills, and emissions; proportions of harvested carbon in each pool vary for hardwood and softwood sawtimber and pulpwood. When stands were thinned, harvest residue was calculated as the difference between the total aboveground biomass and the harvested (stem) biomass, and slash decomposition was calculated as described by Birdsey (1996). Stems recorded as dead were transferred to the deadwood pool in that inventory year and decomposed accordingly. Biomass estimates were converted to carbon estimates using the factor of 50% carbon. Statistical testing of differences among changes in carbon stocks was accomplished using a single-factor analysis of variance (ANOVA) after tests for heterogeneity of variances.

Changes in Carbon Stocks

Figure 1 gives the average stock of carbon for each thinning type in 1975, before the first thinning, and in 2000, after two thinning cycles. Although a metric ton of carbon per acre (mtC/ac) is a nonstandard unit, it is becoming more commonly used in the United States where area often is not reported in hectares. In this case, the unit facilitates comparison with board foot volumes, which are reported on a per acre basis and for which there is no comparable metric unit. In the pretreatment case, the carbon stocks include merchantable and nonmerchantable biomass, as well as live coarse roots. Carbon stocks reported for 2000 include those pools as well as carbon in harvest residue and dead trees (no data on dead stems were taken in the pretreatment inventory). Before treatment all plots were fully stocked and contained similar amounts of carbon, with no significant differences across planned treatments (ANOVA on ranks, $P = 0.383$). Twenty-five years after the start of the experiment, the average amount of carbon contained in the live biomass pool had increased in the control plots and plots thinned from below but had declined in plots thinned from the middle or from above (Table 1).

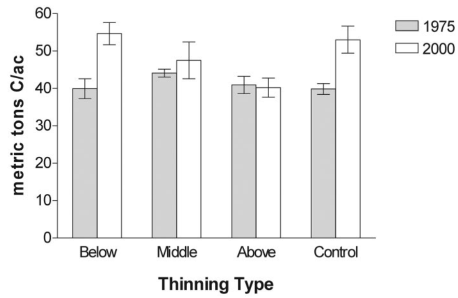

Figure 1. Carbon stocks, in metric tons per acre, before treatment and in 2000 after two thinnings. Carbon pools include live biomass (including coarse roots) for the pretreatment case, and live biomass, deadwood, logging residue, and products for the posttreatment case. Error bars are standard error of the mean.

Since plots differ in their initial carbon stocks, straightforward comparisons among treatments are most easily made using average annual change. This is simply the difference between the final stock and the initial stock, divided by the number of years between the measurements. Average annual change in carbon stocks for each treatment over the 25-year period of the study varied from −0.04 mtC/ac per year in the thin from above treatment to 0.59 mtC/ac per year for plots thinned from below; control plots averaged 0.53 mtC/ac per year (Figure 2). Among-treatment differences in the av-

Table 1. Carbon stocks by pool in 2000, after 25 yr and two thinnings.

	Metric tons C/acre			
Carbon Pool	Below	Middle	Above	Control
Live biomass	46 (40)	33 (44)	23 (41)	43 (40)
Deadwood	4.4	2.9	5.1	10
Slash	1.6	3.8	3.4	0
Products	2.8	8.2	8.5	0
Total	55	47	40	53

Data are metric tons of C per acre, and are an average of the plots in that treatment. Numbers in parentheses are carbon stocks at the beginning of the study, prior to thinning.

erage annual change of carbon stocks were statistically significant ($P = 0.007$). Of the total variance in average annual change in carbon stocks among treatments, 68% is explained by the thinning treatment, following the statistical methods of Gotelli and Ellison (2004). Pairwise comparisons conducted using the Student-Newman-Keuls (SNK) method indicate that average annual carbon storage did not differ between the control plots and the plots thinned from below; annual carbon storage rates for plots thinned from the middle and from above also were not significantly different. All other comparisons were statistically significant.

Because of the emerging carbon credit trading market, carbon stocks and carbon sequestration rates are becoming more important to forest managers and landowners. Those practitioners interested in participating in carbon credit trading need to know how common forest management practices affect carbon storage rates. It is unlikely that landowners will manage their forests exclusively for carbon sequestration; thus, it is important to understand how carbon sequestration compares with other forest management objectives. Our results indicated that changes in stand structure can affect carbon storage (remembering that the stands were all thinned to 60–70% of relative density), with the thin from below treatments storing the most carbon and the thin from above treatment storing the least. How do these results compare with the changes in board feet (bd ft) volume?

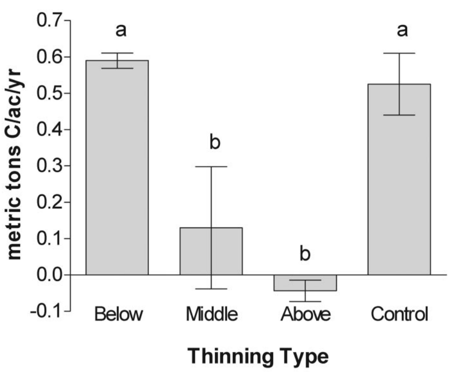

Figure 2. Average annual change in carbon stocks for the period 1975–2000, in metric tons of carbon per acre per year. Pools included are live biomass, deadwood, logging residue, and products. Error bars are standard error of the mean. Bars with the same lower case letter above the bar are not significantly different.

Changes in Merchantable Volume

The SILVAH computer program can provide stand information using different output variables, including bd ft volume (¼ in. international rule) defined as the merchantable volume of all stems that are 10.5 in. dbh and higher. Before the start of the experiment, the research plots contained, on average, between 3,300 and 4,400 bd ft/ac. After 25 years and two thinnings, average standing bd ft volume ranged from 148 bd ft/ac in the thin from above treatment to 9,270 bd ft/ac in stands thinned from below; unthinned control plots had an average merchantable volume of 6,700 bd ft/ac (Figure 3). Just as we compared the rates of change in carbon stocks, we also can look at the average annual change in merchantable volume across treatments. Plots that were thinned from below had the highest rate of increase in bd ft volume at 208 bd ft/ac per year, and plots that had been thinned from above had a decline in merchantable volume of 139 bd ft/ac per year. Unthinned plots added merchantable volume at a rate of 142 bd ft/ac per year, and the thin from the middle treatment increased at a rate of 57 bd ft/ac per year (Figure 4). The differences in average annual merchantable volume increment among thinning treatments were statistically significant ($P < 0.001$). Multiple comparison results are similar to those for differences in the average annual change of carbon storage: there was no significant difference between the control and thin from below treatment and also no statistically significant difference between the thin from the middle and the control plots; all other pairwise comparisons were statistically significant.

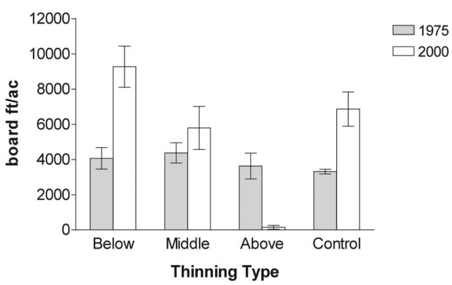

Figure 3. Merchantable volume, in bd ft per acre, before treatment and in 2000 after two thinnings. Error bars are standard error of the mean.

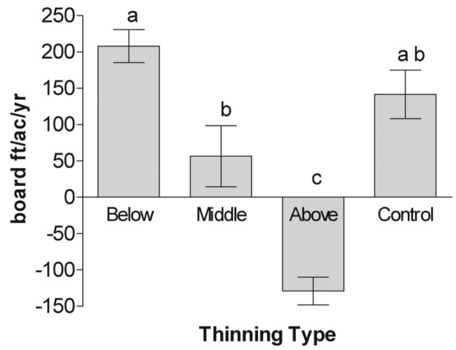

Figure 4. Average annual change in merchantable volume for the period 1975–2000, in bd ft per acre per year. Error bars are standard error of the mean. Bars with the same lower case letter above the bar are not significantly different.

The effect of changes in stand structure is clearly evident in the changes seen in the timber size class distributions (Table 2). After two treatments the plots that were thinned from above have little merchantable volume remaining and no trees above the small sawtimber class, whereas the other thinning treatments increased the amount of medium and large sawtimber in the stand. In addition, average stand diameter increased by 4.8, 2.8, and 4.6 in. in the below, middle, and control plots, respectively, but decreased by 3.2 in. in the thin from above treatment.

Points to Consider

When evaluating the carbon consequences of forest management practices, a few important distinctions need to be con-

Table 2. Standing merchantable volume in 2000, by size class, after 25 yr and two thinnings.

Size Class	Below	Middle	Above	Control
Poletimber	119 (−62)	53 (−364)	32 (−224)	104 (−154)
Small sawtimber	3,662 (881)	2,442 (−936)	116 (−2,119)	2,440 (343)
Medium sawtimber	4,250 (3,147)	2,731 (2,152)	0 (−1,443)	3,345 (2,385)
Large sawtimber	1,239 (1,239)	561 (561)	0 (0)	974 (974)
Total	9,270 (5,205)	5,786 (1,413)	148 (−3,487)	6,863 (3,549)

Data are board feet per acre and are the average for the plots in that treatment. Numbers in parentheses give the change since the beginning of the study.

sidered. The first is the difference between stocks and changes. In this example, we have reported both carbon and timber stocks and stock changes. Although stock estimates are useful, measures such as net change or average annual change are better suited for comparisons among treatments, because initial conditions or site conditions often differ somewhat among stands or plots. Another factor that should be taken into account is the difference between short-term and long-term change or yield. A practice may produce a high rate of carbon storage or volume production initially but over the long term may produce lower rates of production or storage than other treatments with lower initial gains (or vice versa). When assessing the carbon consequences of a management practice, it is important to choose the relevant interval for the analysis. Currently, it is envisioned that contracts for forest carbon sequestration will be of variable length, as negotiated by the buyer and the seller. The appropriate time frame for evaluation will depend on the length of the proposed contract, the objectives and future needs of the landowner, and other factors such as the acceptable level of risk or the likelihood of a catastrophic event.

Carbon Consequences of Thinning Practices

Thinning a stand to concentrate growth on selected stems is a long-standing forest management practice. Although much research has been conducted to develop guidelines for thinning to produce optimal stand growth in different forest types, until recently, there was no reason to study the carbon implications of thinning. The majority of thinning studies are focused on finding the optimal residual stand density; the experiment on which this article is based differs in that stands were cut to the same residual density, while stand structure was altered by concentrating the cut in different diameter classes. Can the choice of thinning methods be a tool used to increase carbon sequestration?

Our results indicate that the choice of thinning method has the potential to alter the stand's ability to sequester carbon. Plots thinned from below had the highest carbon sequestration rate, although this rate was not statistically different from the control plots. Plots that were thinned from the middle had significantly lower carbon storage rates than control plots or plots thinned from below. Although the mechanism for these differences is beyond the scope of this article, it appears that leaving abundant trees that have already shown evidence of fast growth, as in the control and thin from below treatment, is important for sustaining high levels of carbon sequestration. The thin from above treatment displayed negative carbon sequestration rates, storing significantly less carbon than the thin from below or control treatments. The thin from above treatment, as applied here, can be considered a severe case of the commonly used practice of diameter-limit cutting. Thinning from above was the only treatment to have a negative change in carbon storage even when products, logging debris, and deadwood were included. The larger diameter trees removed in the first thinning in this treatment produced wood from which longer lived products are derived (such as furniture and structural lumber), but this difference was not enough to compensate for the fact that the smaller suppressed trees were generally unable to respond to release, slowing stand growth. At the time of the last inventory (2000), live biomass carbon was 56% of the pretreatment value in these plots, and live biomass carbon in the thin from below treatment was 115% of its initial value.

This Allegheny hardwood example demonstrates that the choice of thinning method affects the amount of carbon sequestered. Although the per acre differences may seem small, they can add up quickly. Using the rates of average annual change in Figure 2, over a 5-year period a 100-ac wood treated with a thin from below would sequester 295 tons of carbon, the thin from the middle would sequester 65 tons, and unthinned areas would store 263 tons of carbon. If thinned from above, the stand would release 22 tons of carbon. Carbon sequestration is just one value of forestland; it will most likely be considered in addition to management objectives that are more traditional. How do the carbon outcomes of these thinning practices compare with the changes in stand volume that occur as a result of the thinning treatments?

Comparison of Carbon Sequestration and Merchantable Volume Production

Optimizing merchantable volume often is a key management objective. Table 2 shows the merchantable volume at the last inventory by size class, as well as the change in bd ft over the 25-year study period. Looking at the net change in merchantable volume over time, we can see that the treatments rank as follows: thin from below > no thinning > thin from the middle ≫ thin from above. All treatments except the thin from above increased merchantable volume and resulted in increases in the medium and large sawtimber size classes; the thin from below and control plots also showed increases in the amount of small sawtimber. As discussed in the previous section, the thin from above treatment is a severe example of a diameter-limit cut, and those plots generally suffered from reduced growth after the main crown canopy opened. The plots that were thinned from the middle did not increase in sawtimber volume as much as the untreated plots; in the Allegheny hardwood forest type, noncommercial saplings such as striped maple often will occupy the opened space if they are not removed during thinning, slowing the overall growth of the stand by concentrating too much growth on slow-growing stems. Comparing Figures 2 and 4 shows that although the magnitude of the response is different, the results for average annual change in carbon and average annual change in merchantable volume look quite similar across treatments.

Silviculture as practiced in Allegheny hardwoods generally is even-aged, with a rotation length of about 80 years. This leads to the question of the carbon impacts of final stand harvest and how those removals would affect any existing carbon contracts. Even when considering carbon sequestered in products, there is a loss of carbon when a stand is harvested. A landowner practicing sustainable forest management would harvest a small proportion of their total land base annually, and if the remaining lands are managed using appropriate thinning practices, short-term losses that occur during final harvest and stand replacement could be absorbed by the remaining acreage. Landowners with small acreages could achieve this outcome by working cooperatively with others managing similar forests.

Sustainable Forestry, Carbon Sequestration, and Carbon Credit Trading

Forest carbon sequestration projects can take many forms, from planting trees on abandoned agricultural or reclaimed mine lands, to preserving tracts of forest, to improving forest management. Participation in a carbon sequestration project does not mean that a landowner can not harvest timber. Because the goal of sustainable forest management is to produce a supply of wood products without compromising future stand growth, it seems logical that sustainable forestry practices would be compatible with forest carbon sequestration. A carbon credit market and trading system is evolving in the United States and around the globe; credits are traded experimentally in the United States and operationally by the nations that have ratified the Kyoto Protocol. It often is assumed that the choice is to leave the carbon in the woods to earn credits (forgoing harvest income) or to remove the wood for income (forgoing the opportunity to sell credits); this is true for short time frames or a small land base. However, the example presented here uses empirical data to show that it is possible to achieve carbon sequestration *while* producing sawtimber, without compromising the future growth of the stand. As an additional value of forested lands, carbon sequestration may provide the opportunity for landowners who practice sustainable forestry to receive additional income from carbon contracts while producing quality timber and maintaining a healthy forest ecosystem.

Conclusion

In a twice-thinned Allegheny hardwood stand, choice of thinning method affected carbon sequestration and merchantable volume production. Plots that were thinned from below had greater volume production and carbon sequestration rates than plots that were thinned from the middle or thinned from above. Control plots, which were not thinned, also had higher carbon sequestration rates than plots thinned from the middle and higher merchantable volume production and carbon sequestration rates than plots thinned from above. In this forest type, changing stand structure can affect carbon sequestration and stand growth either positively or negatively, and those effects can be significant, with long-term implications for the future growth of the stand.

Endnote

[1] For an explanation of the relative density measure, see Roach (1977) and Stout and Nyland (1986).

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