THE CARBON CONSEQUENCES OF THINNING ALLEGHENY HARDWOODS: LESSONS LEARNED FROM A STUDY DESIGNED TO INFORM SILVAH DEVELOPMENT

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Insights for Managers

- **Consider thinning methods carefully. Methods that substantially change stand structure may significantly slow stand growth or stimulate understory growth, both of which can have negative impacts on volume and carbon.**
- **Understand the factors, such as site index and elevation, which may affect the results of thinning treatments. At lower productivity sites thinning may not substantially increase stand growth or carbon storage.**
- **Carefully consider the two components of carbon sequestration: standing carbon stock and the rate of change in carbon stocks. Management objectives may determine whether one is somewhat more important than the other.**
- **The time frame is also important: the same treatment may have different short-term and long-term outcomes. The time frame of the analysis depends on management objectives. For example, stands thinned according to best practice will have a higher rate of carbon accumulation for about 10 years post-thinning, though after 30 years thinned and unthinned stands are likely to contain about the same amount of carbon.**
- **Plan at a landscape level. Young stands have a high rate of carbon accumulation but a very low standing carbon stock; older stands have a high standing stock but a very low rate (or perhaps a steady state) of carbon accumulation. Maintain a mix of age classes across the landscape to optimize the balance between the two. Maintain a mix of species across the landscape to ensure a hedge against species-specific disturbances.**
- **Carbon management objectives are generally compatible with sustainable timber production and wildlife management; all benefit from a mix of species and age classes across the landscape.**
- **Sustainable forestry practices are good carbon forestry practices.**

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INTRODUCTION

About 50 years ago, scientists and managers collaborated in an effort that would evolve into the Silviculture of Allegheny Hardwoods (SILVAH) system. Stout and Brose (2014) summarize this unusual story. SILVAH includes components that range from inventory methods to training sessions to management prescriptions, all of which were designed from the ground up and driven by the needs of managers working in Allegheny hardwood forests. Today, SILVAH has been expanded to support oak forest types.

Decision support systems often summarize expert knowledge and synthesize guidelines; scientists experimented with many of SILVAH's underlying principles, which managers tested to develop this system. A good example is the set of thinning guidelines. A multiple-block replicated thinning study was established in 1975 to determine the thinning prescription that would provide the desired results for Allegheny hardwood stands. The study examined two components:

- Thinning intensity, where plots were thinned to a range of relative density levels.
- Thinning type, where plots were thinned to the same relative density using different methods (Marquis and Ernst 1991). This study includes the 10-year results. Many blocks of the thinning study continue to be inventoried at 5-year intervals, and some have been retreated over time.

Because improved forest management is a recognized approach in the carbon credit market for increasing carbon storage in forests, Hoover and Stout (2007) used the inventory data from the block where different thinning methods altered stand structure to assess the carbon consequences of various thinning techniques. At that time, the stands had been treated twice; the most recent data inventory was conducted in 2000. They found that the thinning method applied had important effects on carbon storage and timber production. Stands that had been thinned from above contained significantly less carbon and merchantable volume than those thinned from below or left unthinned (rates of change also varied). Since then, the stands have been treated a third time. This chapter discusses the impact of the thinning methods on stand structure, merchantable volume, and carbon stocks and yields after three treatments and 37 years.

MATERIALS AND METHODS

Thinning Treatments

The study was established in 1975 on the Kane Experimental Forest in northwestern Pennsylvania. At this time, the forest was even-aged pole timber-size Allegheny hardwoods, dominated by black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), beech (*Fagus grandifolia*), and red maple (*Acer rubrum*). All stands were slightly more than 50 years old, having arisen after the nearly complete clearcutting of the existing old-growth forest in 1922-1923. Each plot is 2 acres; the interior 0.6 acres is designated as the measurement area, and the remaining 1.4 acres serve as a buffer. The entire 2-acre plot was treated. All treated plots were thinned to 60-70 percent relative density. Three thinning methods were compared for this analysis:

- Control, with no thinning (n = 2 plots).
- Thin from above: Commercial thinning by diameter, starting at the largest diameter and working down until the density target was met (n = 3 plots).

- Thin from middle: Commercial thinning; no noncommercial saplings were cut. Starting at the lowest merchantable diameter class and working upward until density target is met (n = 3 plots).
- Thin from below: Noncommercial thinning, starting at the lowest diameter class and working upward until density target is reached (n = 3 plots).

All plots were tallied before treatment (all stems 1 inch diameter at breast height and higher); following the first thinning, the plots were reinventoried and all stems larger than 1 inch diameter at breast height were marked with a numbered tag for subsequent measurements. Plots were tallied approximately every 5 years. A second round of treatments was applied in 1990 and a third in 2011. The most recent inventory was taken in 2012. For additional details on the implementation of the treatments, see Marquis and Ernst (1991).

DATA ANALYSIS

We used SILVAH 7 (Thomasma and Stout 2017) to process inventory and to calculate basal area (BA), trees per acre (TPA), median merchantable diameter, and net board foot volume (BF; International ¼ inch Rule). We used the species and diameter data from the inventory records to calculate aboveground and belowground biomass according to Jenkins et al. (2003). Live tree biomass remained in the live tree carbon pool. Biomass in trees recorded as dead was transferred to the dead wood pool, and a fixed decomposition rate was applied; similarly, when a treatment was applied the biomass in the tops of the trees was allocated to the slash category and a decomposition coefficient was applied (following Birdsey 1996). We used the coefficients from Smith et al. (2006) to include the biomass in the cut stems in the wood products pool; this pool is the sum of carbon in products in use and discarded in landfills. The carbon in harvested wood products changes over time as more products become discarded and decompose, and only a proportion of harvested carbon initially is included in products, because waste occurs during processing and may be burned or discarded. For all pools, carbon is calculated as 50 percent of dry biomass weight. Differences were tested by one-way analysis of variance after checking assumptions of normality and equal variance; multiple pairwise comparisons were conducted using the Holm-Sidak test.

RESULTS

Stand Characteristics

Before treatment, all plots had similar BA, TPA, medial merchantable diameter, and net volume (Table 1). By 2000, 10 years after the second thinning treatment, BA, merchantable diameter, and net volume were lowest in the thin from above treatment (81 ft^2/acre, 8.1 inches, and 161 BF/acre, respectively). In contrast, the thin from below treatment had the highest values for these variables (103 ft^2/acre, 16.4 inches, and 9319 BF/acre), although values were similar for the control plots. At the most recent measurement, 2 years after the third treatment, the number of trees does not differ significantly between treatments, although BA, merchantable diameter, and net volume are significantly lower in the plots thinned from above than in any other treatment or the control plots. Almost no merchantable volume remains in the plots thinned from above, and merchantable diameter is less than half that in the other treatments (Table 1).

Table 1.—Mean and standard error (in parentheses) of selected stand attributes. In 2000, stands were 10 years post-treatment after the second thinning. In 2012, the most recent measurement, stands were 2 years post-treatment after the third thinning.

	Basal area ($feet^2$/acre)	Trees/acre	Merch. dia.[a] (inches)	Net BF/acre[b]
Pretreatment				
Below	131 (6.1)	908 (34.3)	11.5 (0.31)	4065 (609)
Middle	148 (4.9)	929 (42.9)	11.0 (0.55)	4373 (577)
Above	131 (6.1)	770 (42.9)	10.9 (0.31)	3634 (735)
Control	128 (8.4)	824 (64.1)	10.6 (0.05)	3314 (135)
After Cut 1975				
Below	96 (1.7)	1840 (165.7)	11.9 (0.38)	3791 (571)
Middle	80 (7.4)	1279 (172.1)	11.3 (0.41)	2145 (422)
Above	65 (3.1)	1704 (91.5)	8.5 (0.56)	393 (273)
Control	122 (7.0)	1009 (119)	10.7 (0.05)	2985 (18)
2000				
Below	130 (9.2)	1271 (115.8)	16.4 (0.27)	9319 (1273)
Middle	107 (7.4)	812 (145.4)	14.8 (0.17)	5802 (1115)
Above	81 (1.4)	1081 (80.5)	8.1 (0.32)	161 (122)
Control	120 (11.5)	494 (57.5)	14.9 (0.00)	7045 (1280)
After Cut 2012				
Below	129 (8.1)	363 (64.1)	18.0 (0.67)	11281 (1646)
Middle	106 (10.0)	522 (40.9)	17.2 (0.27)	7185 (1234)
Above	67 (6.7)	576 (58.2)	7.5 (0.33)	24 (24)
Control	120 (0.05)	529 (36.0)	15.8 (0.35)	6897 (549)

[a] Medial merchantable diameter
[b] Net board feet (BF), International ¼ inch Rule

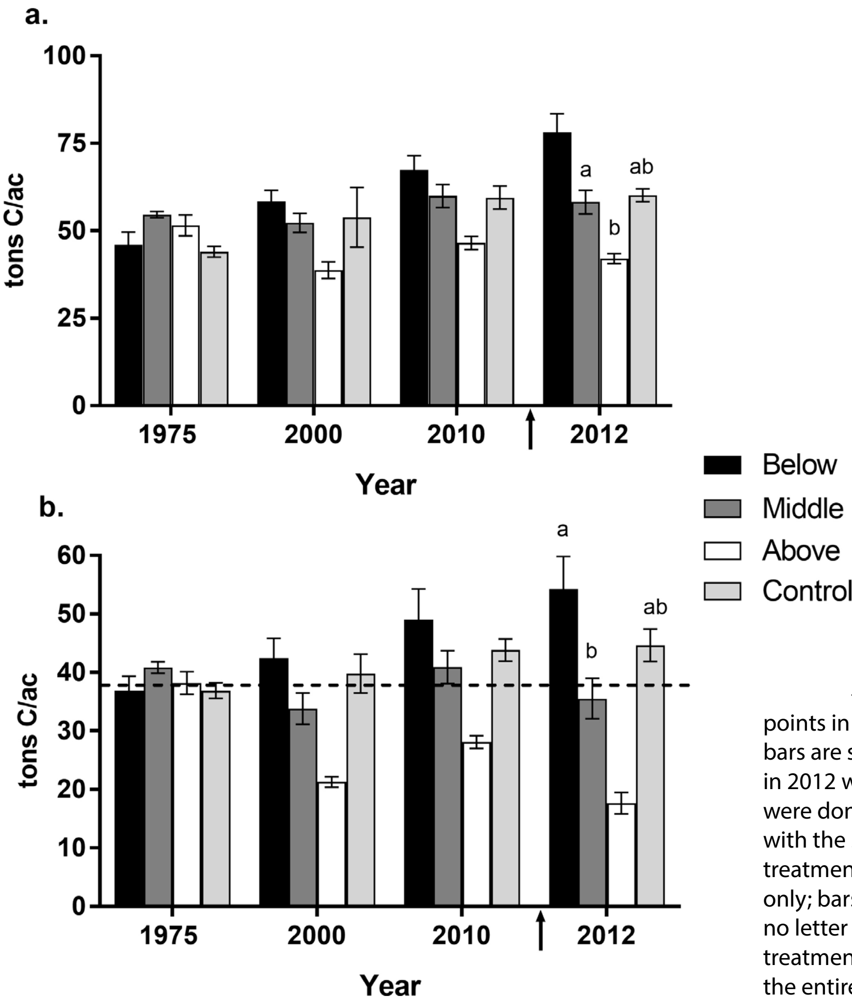
Table 2.—Mean carbon stocks (tons C/acre) by pool for each treatment in 2012, after three thinnings. Values in parenthesis indicate stock before first treatment in 1975.

	Below	Middle	Above	Control
Live tree [a]	54.2 (37)	35.5 (41)	17.7 (38)	44.6 (37)
Live root	10.2	6.8	3.4	8.5
Dead wood	7.2	5.9	8.9	7.0
Slash	3.6	4.6	4.3	0
Products	2.9	5.4	7.8	0
Total	78.1	58.2	42.0	60.1

[a] Aboveground
Does not include shrubs

Carbon Stocks and Stock Changes

Before the stands were thinned, all plots had similar amounts of carbon in live aboveground tree biomass (range: 37-41 tons/acre). By 2012, both the amount of carbon and the distribution among pools varied by treatment (Table 2); the lowest amount of live tree carbon and the largest amount of carbon in wood products appeared in the thin from above treatment. Conversely, average live tree carbon stocks are highest in the plots thinned from below. The non-live carbon pools are similar across treatments (except for slash and products carbon in the control plots, which have zero values).



—Carbon stock, in tons/acre, by thinning treatment at selected points in time. Arrow indicates time of most recent treatment. Error bars are standard error of the mean. Differences between carbon stocks in 2012 were compared with analysis of variance (no comparisons were done for other years). Figure 1a: All carbon pools included; bars with the same letter do not differ significantly at p = 0.05; otherwise, treatments differ significantly. Figure 1b: Aboveground live tree carbon only; bars with the same letter do not differ significantly at p = 0.05. If no letter is present, that treatment differs significantly from the other treatments. Dashed line indicates average live tree carbon stock over the entire study before the first thinning treatment.

For overall carbon stocks examined at points through time, the pattern remains similar (Fig. 1a): the differences that were apparent in 2000, 10 years after the second treatment, remain in 2012, 2 years after the third thinning. Average carbon stocks (for all estimated pools) are significantly higher in the plots thinned from below, and plots thinned from the middle contain significantly more carbon than those thinned from above. However, the total carbon stocks in the stands thinned from above and from the middle do not differ from those in unthinned control plots (n = 3 for the treated plots; n = 2 for controls). An upward trend in total standing carbon stocks is apparent over time in all but the plots thinned from above, which stored less carbon in 2012 than in 1975. Looking at just the carbon stored in the aboveground portion of living trees, the differences between thinning approaches become even more apparent (Fig. 1b); the dashed line indicates the experiment-wide pretreatment average live tree carbon stock. By 2012 the stands thinned from above have far less carbon in live biomass than at the beginning of the study; significantly less than the other treatments or the unthinned controls. More live tree carbon is present in the thin from below treatment, this difference is significant compared to the thin from the middle, though not from the untreated controls.

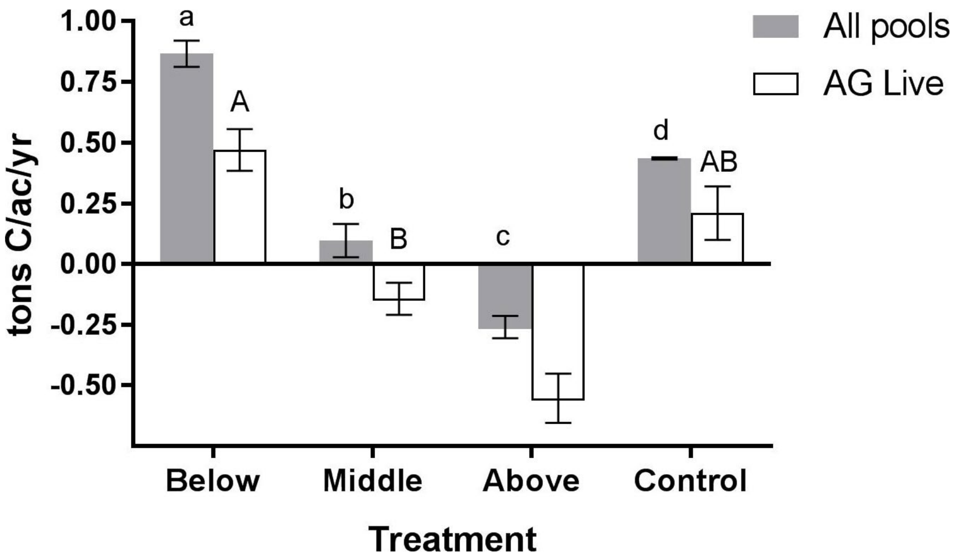


Figure 2.—Average annual change in carbon stock (tons/acre/year) for the study period 1975-2012. Shaded bar: all carbon pools, white bar: aboveground live tree carbon only. Error bars are standard error of the mean. Statistical comparisons are indicated by uppercase letters for live tree pool. Treatments with the same letter are not significantly different; otherwise, treatments are significantly different (including when no letter is present). For the rate of average annual change in total carbon stock all treatments are significantly different from each other and no letters are present.

We can also assess the effects of the treatments over time by considering average annual change for the duration of the study; stocks and stock changes each provide insight on the carbon consequences of a management practice, and depending on management objectives, one quantity may be more useful than the other. The time frame of the analysis strongly affects the rate of average annual change; rates may vary dramatically according to a particular management treatment over shorter and longer time frames. Here we consider the rates for the time span for which measurements are available: 1975-2012. The change of carbon stocks show significantly different rates in all treatments (Fig. 2; gray bar), ranging from 0.87 tons C/acre/year for the thin from below treatment to -0.26 tons C/acre/year in the thin from above treatment; the control mean is 0.43 tons C/acre/year. As with the standing carbon stocks, we can also calculate the rate of change in aboveground live tree carbon (Figure 2; white bar), and the thin from above treatment shows a change of -0.55 tons C/acre/year, significantly lower than the other treatments. This contrasts sharply with the average increase of 0.47 tons C/acre/year in live tree carbon in the plots thinned from below (unthinned controls added an average of 0.21 tons/acre/year).

DISCUSSION

When the Hoover and Stout study was published in 2007, few studies had investigated the carbon consequences of thinning or other silvicultural treatments. Since that time a growing body of literature, both international and domestic, has examined this topic. In many cases the same approach is used; analyzing data from past or ongoing silviculture studies to glean insight on the possible effects of management practices on forest carbon storage. These studies may report carbon stocks, rates of change in stock, or both. Hoover and Stout (2007) found that the way a stand was thinned could have a significant impact on both the carbon stored in the stand and the rate of carbon accumulation. They advised caution when employing thinning techniques that could substantially alter stand structure. Recent studies report varied results. Zhou et al. (2013) conducted a meta-analysis that included data from 81 studies (from a range of forest types around the world) that addressed the effects of partial cutting on carbon storage, forest structure, or both; levels of cutting intensity and time since cutting varied across the studies. Results were grouped into light (<34 percent), moderate (34-67 percent, and heavy (≥67 percent) cutting; outcomes were also analyzed with all results in a single pool. Zhou et al. (2013) also reported that overall, carbon stored in aboveground live trees declined by an average of 43.4 percent (rates were not reported) relative to uncut control plots. In the light intensity group, the average decrease was 28.2 percent, and the moderate and heavy cutting groups showed similar declines with 42.2 and 49.2 percent, respectively. Stand BA and volume were also lower in cut plots, and diameter growth was greater. A significant increase in understory carbon stock was also reported for all cutting intensity groups.

Other investigators have found varying results, depending on forest type and thinning method. D'Amato et al. (2011) analyzed results from several red pine (*Pinus resinosa*) and northern hardwood thinning studies initiated between 1949 and 1957 in the Upper Great Lakes region. Studies focused on stocking level, thinning method, cutting cycle length, or a combination of factors. They considered both carbon stock and accumulation rate and assessed only aboveground biomass in live trees. The results from the stocking level studies were similar and reflect typical stand dynamics: carbon stocks fluctuated in response to thinning treatments but were related to stocking level and stand age. Carbon accumulation rates were also generally related to stand age and declined over time. In the red pine thinning method study, the rate of carbon accumulation declined over time, and in contrast to Hoover and Stout (2007) was highest in the stands thinned from above compared to those thinned from below or with a proportional approach. Carbon stocks were also related to stand age and thinning method; the lowest stock was found in the stands that were thinned from above compared to the other approaches. A separate red pine cutting methods and stocking level study was also considered by D'Amato et al. (2011). Results were similar and revealed that stocks and rates were affected by stand age, stocking level, and thinning method as well as interactions among those factors. In general, they report that the rate of carbon accumulation decreased with stand age, and that differences in rates within a thinning method were attributable to lower rates at the 74-square-foot stocking level. Carbon accumulation rates were lowest in the stands thinned from below; the thin from above and proportional treatments did not differ. Carbon stocks increased with stand age and stocking level; thinning method had an effect only at the lowest level of stocking, where both the thin from above and thin from below treatments had lower carbon stocks than stands that were thinned proportionally. Schaedel et al. (2017) investigated the effects of early precommercial thinning in western larch (*Larix occidentalis*, again, using a historical study) in Montana; stands were thinned from below to range of density levels (target levels 200, 360, and 680 TPA). The number of entries also varied. At each targeted density, plots received one, two, or four entries; the target density was reached at the last entry. Unthinned control plots had the highest carbon stocks, but this difference was not significant; live aboveground carbon stocks were not affected by the thinning treatments, and the number of entries had no effect at any density level. Understory carbon did differ between treatments, with higher understory stocks occurring at lower overstory densities, similar to the findings of Zhou et al (2013).

Keyser (2010) used data from 118 plots in yellow-poplar (*Liriodendron tulipifera*) forests in the southern Appalachians to explore the effects of thinning on carbon storage, taking site quality into account. Plots were thinned from below to a residual BA ranging from 40 to 150 square feet per acre; most of the plots were thinned a second time to the same target approximately 6 years after the first treatment (the analysis excluded plots that received a single thinning). Keyser (2010) reported that on an average quality site, plots thinned to 130 square feet per acre stored 28 percent more carbon in live aboveground tree biomass than plots thinned to 85 square feet per acre and 78 percent more than those thinned to 40 square feet per acre (the original study design did not include unthinned controls).

Keyser also calculated carbon in harvested wood products. When this was factored in, the more heavily thinned plots still stored less carbon than the more lightly thinned plots throughout the study. Site quality also affected carbon storage; more carbon was stored in plots with a higher site index. The effect of site quality was more pronounced at lower density levels. For example, at a site index of 36 plots thinned to 40 square feet per acre stored 22 percent more carbon than plots with a site index of 26, and at the 130-square foot density level a plot of site index 34 had a predicted carbon storage of just 12 percent more than a plot with a site index of 26.

Moore et al. (2012) took another approach. They used data from inventory plots in the Great Smoky Mountains National Park with the Forest Vegetation Simulator to examine the effects of various management scenarios in a forest dominated by red spruce (*Picea rubens*) and Fraser fir (*Abies fraseri*) over a 100-year time frame. They simulated no-management, uneven-age management, and even-age management scenarios and assessed the effects of elevation and site index. Within each elevation band, site index had a minimal effect. Elevation was an important factor; growth increased with decreasing elevation. In every elevation group, the uneven-age scenario stored less carbon than the even-age or no-action scenarios; both regimes maintained a positive slope throughout the simulation period. In contrast, the no-action scenario always had the highest carbon stocks for the first half of the simulation, then slowly leveled off. Differences were more pronounced in the low- and mid-elevation bands, where the even-aged and no-action options had similar carbon stocks at the end of the simulation period, and the uneven-aged scenario showed clearly lower stocks; differences were smaller in the high-elevation band.

CONCLUSIONS

Precommercial thinning and partial harvesting have led to varying outcomes on carbon storage, but a few key themes emerge. In some cases, partial harvesting has led to a decrease in stand carbon storage that has persisted for several decades; in others, thinning has either had no effect on carbon stocks or has led to an increase in carbon stock, the rate of carbon accumulation, or both. Site quality, stand age, and elevation may all affect the outcome of a thinning treatment, with interactions between the factors, and should be taken into account when planning management actions, because thinning to a given density level on a high-quality site is likely to produce a different result than on a low-quality site. Stand structure also needs to be considered; in several studies cited here, thinned stands showed a decrease in overstory carbon accompanied by a significant increase in understory carbon, which could compromise management objectives.

In the Kane Experimental Forest example, the treatments were applied specifically to gather data to inform the development of SILVAH, and as such do not represent the manner in which thinning treatments are applied as part of a management plan. For example, tree species and quality were not considered when selecting stems for removal. That said, the nature of the treatments illustrates some important lessons about the importance of stand structure that are useful to managers who are considering the carbon consequences of silvicultural prescriptions. For example, the extreme thin from above treatment resulted in a situation where the suppressed stems could not respond well to release, and over the course of the 35-year study period these stands showed a significant decrease in aboveground live tree carbon, net volume, and BA and had lower merchantable medial diameters than the other treatments or the unthinned stands. The thin from below treatment, however, showed higher rates of carbon accumulation and greater carbon stocks, as well as net volume, diameter, and BA. D'Amato et al. (2011) also reported that the type of thinning applied affected carbon stocks and rates, with results varying across studies. An important outcome of that study is that the type of thinning often had an effect at only the lowest density level.

In summary, thinning does remove carbon from a stand; however, such treatments may lead to an increase in carbon stocks or rates of accumulation, or both. Density level, site index, elevation, stand structure, and management objectives must be carefully considered when planning a thinning treatment aimed at increasing forest carbon storage. Care should be taken not to compromise long-term stand growth with treatments that result in understory capture of growing space or the release of stems not capable of responding. With proper planning, thinning can be an important tool for advancing not only sustainable timber management objectives, but also enhancing forest carbon storage.

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