Above-ground Carbon Storage, Down Wood, and Understory Plant Species Richness after Thinning in Western Oregon

Julia I. Burton, Adrian Ares, Sara E. Mulford, Deanna H. Olson, and Klaus J. Puettmann

Abstract

Concerns about climate change have generated worldwide interest in managing forests for the uptake and storage of carbon (C). Simultaneously, preserving and enhancing structural, functional, and species diversity in forests remains an important objective. Therefore, understanding trade-offs and synergies among C storage and sequestration and diversity in managed forests is key to achieving these multiple objectives. Using the experimental framework of the Density Management Study in western Oregon, we examined the relationships among a suite of thinning treatments, above-ground carbon stocks, and understory vascular plant species richness. Six years following treatment implementation, total above-ground C declined with residual density. Total above-ground C in the high-density thinning treatment (300 trees·ha^{-1}) did not differ statistically from the untreated control treatment (~370–775 trees·ha^{-1}), and these two treatments stored 33 percent and 61 percent more C above ground, respectively, than the moderate density (200 trees·ha^{-1}) and variable density (300, 200, 100 trees·ha^{-1}) treatments. Differences among treatments were primarily related to reductions in the live overstory pool. For all treatments, C stored in the live overstory > large down wood > snags > stumps > small down wood. Coarse down wood (CDW) comprised over 30 percent of the total above-ground C storage. Most of the C in the dead pools appears to be legacy (pre-thinning) material; 50–95 percent of snags, stumps, and large down wood were in intermediate to late stages of decomposition. Between years 6 and 11 post-treatment, the overstory C increment tended to decline with lower residual density, although this trend was not statistically significant. In contrast, understory plant species richness was greater in all thinning treatments than in untreated controls. Relationships varied slightly among treatments. Moderate- and variable-density thinning treatments resulted in a negative relationship between understory plant species richness and above-ground C, while no relationship was observed in the high-density treatment and unthinned control. Results suggest that thinning increases plant species richness, implying that there is a trade-off between management for understory plant species richness and above-ground C storage.

Keywords: Biodiversity, carbon sequestration, coarse woody debris, density management, diversity, understory vegetation.

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Introduction

Concerns about climate change have resulted in worldwide interest in managing forests to mitigate anthropogenic increases in atmospheric carbon dioxide (Gower 2003; Pacala and Socolow 2004; McKinley et al. 2011). Simultaneously, preserving and enhancing structural, functional, and biological diversity in forests remain important management objectives. However, few studies have examined effects of thinning on carbon (C) storage, as well as the trade-offs and synergies among managing for C storage and sequestration, and species diversity in managed forests.

The majority of above-ground C in temperate forests is stored in the live overstory: the ratio of understory C to overstory C is typically <0.005 (Ares et al. 2007). However, the majority of plant diversity resides in the understory. The ratio of understory species richness to overstory species richness ranges from 2 to 10, with approximately 80 percent of the plant species restricted to the understory (Gilliam 2007). Forest thinning can increase resources available for residual trees in the overstory as well as for understory plants (Gray et al. 2002), resulting in increases in tree diameter growth rates (Dodson et al. 2012) and understory plant species diversity (Fahey and Puettmann 2007; Ares et al. 2009, 2010). However, thinning may decrease C storage within forest stands initially and over time (Gower 2003), with the magnitude depending on the percentage of the stand harvested, harvesting interval, and spatial pattern of harvesting (dispersed vs. aggregated) (Harmon et al. 2009). As a result of these positive and negative effects of thinning on understory plant species richness and above-ground C, respectively, a negative relationship between above-ground C storage and understory diversity is predicted (fig. 1). Here we examine the short-term relationships among forest thinning treatments, total above-ground C (including live overstory, coarse down wood [CDW], snags, and stumps), and understory plant species richness. Because rates of soil C accumulation are generally low over the period of a single rotation, the fate of above-ground C is an important focus of mitigation efforts (Gower 2003).

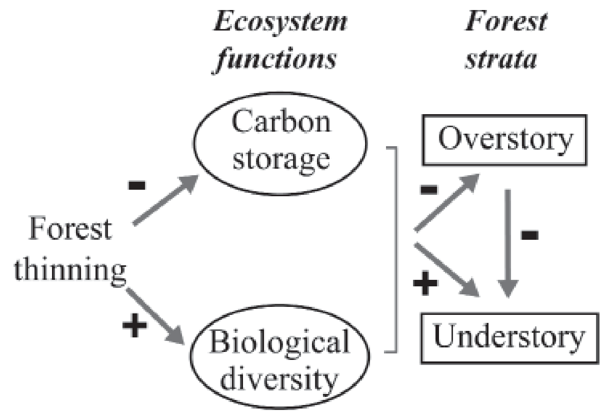

Figure 1—Conceptual diagram illustrating the contrasting effects of thinning on carbon storage (-) and biodiversity (measured as understory plant species richness) (+). Here we hypothesize that a trade-off emerges as a result of the negative effects of thinning on carbon storage in the overstory and positive effects of thinning on plant diversity in the understory.

Methods

Experimental Design

Using the experimental framework of the Density Management Study (Cissel et al. 2006), we analyzed the effects of a suite of thinning treatments on above-ground C stocks and understory plant species richness. The thinning treatments, replicated seven times across the Coast Range and northern Cascade Range of western Oregon, included three levels of residual density: 1) a high-density treatment with 300 trees·ha^{-1} (HD); 2) a moderate-density treatment with 200 trees·ha^{-1} (MD); and 3) a variable-density treatment with 300 trees·ha^{-1}, 200 trees·ha^{-1} and 100 trees·ha^{-1} (VD). In addition to an even distribution of residual trees (i.e., dispersed retention), 3 to 11 percent of the treatment unit was left unthinned in circular leave-island reserves (patches of undisturbed forest trees) in the HD and MD treatments, and 3 to 10 percent of the treatment unit was cut in circular gap openings in the MD treatment. In the VD treatment, 8.2 to 10.3 percent of the area was preserved in leave islands, and 8 to 17 percent of the area was left in circular gap openings. Gap openings and leave islands were 0.1, 0.2, and 0.4 ha in size. In addition to comparisons among the three thinning treatments, the effects of thinning were compared with unthinned control areas (CON; approximately 600 trees·ha^{-1}). Each of the seven study sites consisted of large forested stands (94 to 131 ha, with controls on 16 to 24 ha and each thinning treatment implemented on 14- and 69-ha parcels) to allow for operational application of treatments and thus avoid the need to scale-up the experimental results (fig. 2).

Field sampling

Seventy-seven permanent 0.1-ha circular plots were installed in each site to sample overstory trees. Plot centers were located randomly within treatment units (n = 21 in HD, MD and VD, n = 14 in controls) using a random point generator (Cissel et al. 2006). Plot boundaries were constrained to be ≥50 m from treatment unit boundaries and non-overlapping. Within each overstory plot, four 0.002-ha circular understory vegetation subplots were installed 9 m from plot centers in each cardinal direction. Overstory and understory vegetation measurements were taken during the summer 6 and 11 years after thinning. In each overstory plot, all trees ≥5.1 cm dbh (diameter at 1.37 m above ground) were numbered, identified by species, and measured for dbh using a diameter tape. We also measured height of 16 trees per plot (10 conifers and 6 hardwoods) using a laser hypsometer (Laser Technology, Centennial, CO, USA). In the understory subplots, we visually estimated total cover of each vascular plant species present using cover classes: 1 percent, 5 percent, and then in 10 percent increments. Overstory trees and shrubs >6 m in height were excluded from cover estimates. Species richness was calculated as the number of vascular plant species recorded in the four understory subplots (a total area of 80 m^2). Detailed vegetation measurement protocols and data analyses have been reported previously (Cissel et al. 2006; Ares et al. 2009, 2010).

Six years after thinning, all standing dead trees (snags) and three types of above-ground

Figure 2—Example of a treatment layout at one site, Bottomline. The high-density treatment retained 300 trees·ha^{-1}, the moderate-density treatment retained 200 trees·ha^{-1}, and the variable-density retained variable densities of trees: 300 trees·ha^{-1}, 200·trees·ha^{-1} and 100 trees·ha^{-1}. The density of untreated control plots was approximately 600 trees·ha^{-1}. Leave islands were maintained in all thinning treatments, canopy gaps were also created as part of the moderate- and variable-density treatments.

coarse down wood (CDW) were sampled: stumps, large CDW (≥25.4 cm in diameter and ≥0.3 m length), and small CDW (<25.4 cm in diameter and <0.3 m length). All stumps (≤1.37 m in height measured on the uphill side) within the northeast quarter-section of the overstory plot were measured for diameter and height. We measured large CDW along four 12.9-m transects connecting the centers of the understory subplots. Down wood that crossed transects multiple times (e.g., forked logs or long logs that spanned two transects) was counted as separate pieces (Harmon and Sexton 1996). Elevated dead wood at an angle >45° above the ground was not considered CDW, but was counted as a snag. For each piece of down wood, we measured the diameter at the point where it intercepted the transect line. Small CDW was measured within the understory subplots. Only pieces with their large ends inside the subplots were included in the measurement. Diameter at both ends and total length of each piece (including any part extending outside the subplot) were measured. Diameter measurements of large and small down wood pieces were taken with calipers, length was measured using a measuring tape. Decay stage was characterized using a five-class scale from 1 (least decayed) to 5 (most decayed) as per Maser et al. (1979). All snags ≥1.37 m tall and ≥5.1 cm dbh in the overstory plots were identified as such and measured for dbh.

Calculations of Above-ground C Storage

We derived above-ground C storage from biomass using the specific gravity and C-concentration values reported by Ares et al. (2007). A carbon content of 0.5 kg C·kg^{-1} was used for tree species not listed in Ares et al. (2007). Live tree biomass (bole, bark, live and dead branches, and foliage components) was estimated using measurements of dbh and height in allometric equations using BIOPAK version 2.50 (Means et al. 1994). Volumes of snags, stumps, and large and small down wood were calculated and converted to biomass and C stores by decay class using the specific gravity (mass per unit volume) and C-concentration values reported by Ares et al. (2007).

Statistical Analysis

A mixed-effects model was used to examine thinning treatment effects on above-ground C, differences in live C in the overstory between year six and year eleven post-treatment, vascular plant species richness six years after thinning, and differences in understory plant species richness between year six and year eleven post-treatment. Analyses were performed on the averages of all plots (subsamples) within a treatment unit. Thinning treatment was modeled as a fixed effect and site was modeled as a random effect in order to control for underlying differences among sites (Littell et al. 1996). Post-hoc pairwise comparisons of treatment means used orthogonal contrasts with one degree of freedom, and Tukey's HSD was used to correct p-values for multiple comparisons.

Additionally, we examined the relationship among understory plant species richness, experimental thinning treatments (HD, MD, VD, and CON), and above-ground C stocks at the plot scale using a mixed effects model (Littell et al. 1996) of fixed effects (treatments and above-ground C) and random effects (site, treatment x site). Plots were nested within a treatment unit and site. We examined main effects of thinning treatment, above-ground C, and the interaction between richness and above-ground C. In the case of a significant interaction, we tested the null hypothesis of no relationship between understory plant species richness and above-ground C for each treatment (CON, HD, MD, and VD) and then compared treatment slopes to test the null hypothesis of equal slopes between treatments (n = 6 comparisons). P-values were not corrected for multiple comparisons. We used the mixed procedure in SAS 9.2 for all statistical analyses reported here (SAS Institute 2004).

Results

Carbon Stocks Year 6 Post-treatment

By the sixth growing season following thinning, above-ground carbon (C) decreased with decreased residual density (table 1). Moderate- and variable-density treatments had lower levels of C storage than untreated control and the high-density retention treatment (difference = 78.2 ± 13.0 $Mg \cdot ha^{-1}$, T = -6.01, $p < 0.001$). Among the above-ground stocks, the majority of C was stored in the live overstory (~68 percent) relative to dead pools: coarse down wood, snags, and stumps (~32 percent cumulatively). Within the live overstory, the majority of C was stored in the bole wood (~72 percent of the live overstory C), although nearly 30 percent of the live overstory C was found in bark, branches, and foliage. Among the dead pools, the largest stock of C was in CDW with diameters ≥25.4 cm (large CDW) and in later stages of decomposition (classes 3–5).

Overstory C was greater in year eleven than in year six in all treatments ($p < 0.05$). Increments ranged from 12.6 to 19.1 $Mg \cdot ha^{-1}$, amounting to an increase of 10 to 15 percent. The difference in overstory C between year eleven and year six post-treatment increased with increases in residual density (i.e., CON > HD > MD > VD); however, while this trend was apparent, there was no evidence for significant differences among treatments statistically speaking.

Plant Species Richness Six years after Thinning

In contrast to C, understory plant species richness was higher ($p < 0.001$) in all thinning treatments than the untreated controls during the sixth growing season following treatment (table 1). Plant species richness, however, did not differ among high-, moderate- and variable-density thinning treatments ($p > 0.9$). Thinned treatments (HD, MD, and VD) contained 11.9 ± 1.4 species more than untreated controls on average (T = 8.62, $p < 0.001$). Understory plant species richness decreased from year six to year eleven in the moderate- and variable density thinning treatments, while significant changes in richness were not observed in the CON and HD treatments (table 1). On average, understory plant species declined by 4.4 ± 0.6 more species between years 6 and 11 in MD and VD relative to CON and HD treatments (T = -7.29, $p < 0.001$).

Carbon – Understory Plant Species Richness Trade-off

In year six post-treatment, species richness was related to above-ground C and thinning treatment; evidence for an interaction between treatment and above-ground C was weak ($p = 0.07$). This weak interaction resulted from the lack of a relationship between above-ground C

Table 1—Treatment averages for carbon (C) and diversity: above-ground (C) in year 6 post-treatment, differences and live overstory C between years 6 and 11 post-treatment, understory plant species richness in year six post-treatment, and differences in understory plant species richness between years 6 and 11 post-treatment. Thinning treatments = HD = high-density retention, MD = moderate-density retention, and VD = variable-density; untreated control (CON).

	Thinning treatment			
	CON	HD	MD	VD
Carbon				
†Above-ground C	269.2 ^{a}	223.7^{a}	168.0^{b}	168.5^{b}
Difference in live overstory C (Yr. 11 – Yr. 6)	19.1	18.2	17.1	12.6
Diversity				
†Understory plant species richness	15.9^{a}	27.3^{b}	28.2^{b}	27.9^{b}
†Difference in richness (Yr. 11 – Yr. 6)	1.6^{a}	-0.5^{a}	-4.1^{b}	-3.7^{b}

†Different superscripts indicate evidence for significant differences between treatments ($p < 0.05$).

and understory plant species richness in both the untreated control (estimate = -0.01, T = -1.1, p = 0.27) and HD treatment (estimate < -0.01, T = -0.01, p = 0.99). In contrast, in the MD (estimate = -0.02, T = -2.5, p = 0.013) and VD (estimate = -0.03, T = -3.3, p = 0.001) thinning treatments, the negative relationships between understory plant species richness and C suggest a trade-off between diversity and C at fine spatial scales in MD and VD treatments (fig. 3). There was evidence for different relationships between understory plant species richness and above-ground C in between HD and MD (albeit weak, estimate = 0.02, T = 0.96, p = 0.051) and between VD and HD (estimate = 0.03, T = 2.46, p = 0.014). In contrast, there was no evidence that the slope of the relationship differed between HD and CON (estimate = -0.001, T = -0.87, p = 0.382).

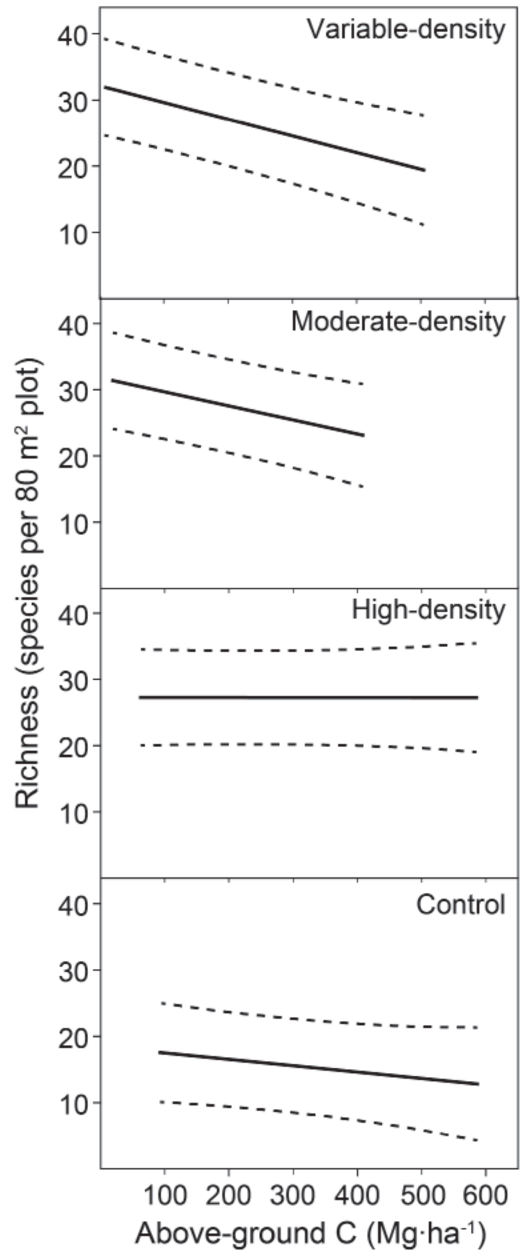

Figure 3—Relationship between understory plant species richness and above-ground carbon by thinning treatment (VD = variable-density, MD = moderate-density, HD = high-density, and CON = untreated control) 6 years post-treatment. Richness is expressed for each plot as the aggregate number of species in four subplots (80 m^2). Solid lines show model-predicted relationship; dashed lines show 95 percent confidence intervals. The random effect, site, is not shown.

Discussion

In addition to maintaining or restoring diversity and ecosystem function, forest managers are now tasked with managing forests to mitigate anthropogenic carbon dioxide in the atmosphere. Tree boles removed during timber harvesting can significantly reduce C storage within forest ecosystems (Harmon et al. 2009). Such patterns are associated with both C extraction and with transient declines in above-ground net primary productivity following harvesting (e.g., Dyer et al. 2010).

Although the live overstory comprises the largest stock of C above ground, nearly one-third of the total above-ground C at our study sites is stored as snags and coarse down wood. These proportions are likely associated with legacy material that resulted from the previous clearcutting operation, as the majority of CDW is in the large size classes (≥25.4 cm diameter) and later stages of decay. The relative importance of this portion of the CDW stock of C will decline as the legacy wood continues to decompose. Further, it appears that natural mortality rates following thinning are not sufficient to augment the size of the CDW stock (Dodson et al. 2013). CDW volumes are typically lower in harvested relative to unharvested stands (e.g., Burton et al. 2009). Therefore, management activities such as creation of down wood may be warranted to achieve C storage as well as structural goals articulated in the initial study plan (Cissel et al. 2006). Creation of down wood or snags would prevent future C deficits in CDW in late stages of decay as well as below ground in the soil.

Although not addressed here, the spatial distribution of C from large CDW was variable and not related to thinning treatments or topographic position (Julia Burton, unpublished data). Thus, managers may consider establishing a spatially heterogeneous, patchy distribution of fresh CDW. Alternative designs for down wood placement include augmenting wildlife habitat and dispersal corridors, for example orienting wood toward streams and over headwater ridgelines to increase connectivity and the dispersal of animals among riparian buffers (Olson and Burnett 2013).

While thinning resulted in reductions in C storage, it increased understory plant species richness. Furthermore, the negative relationship between species richness and above-ground C suggests that thinning results in a trade-off between plant diversity and C. As a result of the recent logging history, the majority of forests in the Coast Range are younger and in earlier, even-aged stages of structural development and have been managed at high densities to facilitate wood production. Because spatial and temporal variability in stand structure is associated with patterns of biodiversity within forests (Ares et al. 2009), recent management efforts have focused on using thinning to accelerate the development of structural heterogeneity and restore patterns of diversity within younger stands (Bauhus et al. 2009). Trade-offs between plant species richness and C therefore suggest that forest management for maximum C storage may be at odds with management for biodiversity if thinning removes C stored in live tree boles.

A number of mechanisms may contribute to the negative relationship between above-ground C and plant species richness. First, removal of live overstory C during thinning creates gaps in the canopy that function to alter the microclimate and increase resource availability above and below ground (Gray et al. 2002; Burton 2011). Such changes in the local abiotic environment interact with the traits of the individual plant species in the understory to drive changes in rates of colonization and competitive exclusion to affect the composition and structure of the plant communities (Roberts and Gilliam 1995; Burton 2011). Specifically, increases in resource availability coupled with physical disturbance of the forest floor may explain the increased levels of plant species richness (Fahey and Puettmann 2007) and coexistence of early- and late-seral species six years after treatments (Ares et al. 2009, 2010). Declines in richness overtime may be associated with increased rates of competitive exclusion of late-seral species by competitive early-seral species (Ares et al. 2010). Harvesting can facilitate the invasion of non-native or weedy plant species (Scheller et al. 2002; Aubin et al. 2007), and our previous studies have reported that introduced species richness and cover was greater in the thinning treatment units relative to the untreated controls. However, non-native species comprised a small proportion of the response of richness and cover (Ares et al. 2009). Relationships between understory plant species richness and C stored as CDW are likely more variable and complex relative to C stored in the overstory. Relationships between C and understory species richness may vary in strength and direction (positive or negative) among different pools of CDW (small vs. large pieces, early vs. late stages of decay, snags and stumps). For instance, the recruitment of fresh down wood may decrease plant species richness through its direct effects on plant survival and indirect effects on the local environment (e.g., increased shading and interference). Over time, as wood decays, such relationships may become positive as interference decreases and resource availability increases (e.g., moisture and nutrients released from decaying wood) (Campbell and Gower 2000; Spears et al. 2003). Such effects may be mediated by C storage in the overstory. For instance, CDW shading may have a negative effect on understory plant species richness in a shady understory where overstory C is high, but a positive effect in an opening (low overstory C) where it may mediate environmental extremes such as temperature. Apparent trade-offs between above-ground C and understory plant species richness reflect the net result of many complex relationships among forest structure, resource availability and the characteristics of the plants in the regional species pool (Burton et al., in press).

Finally, if forests are to be managed to mitigate global climate change by reducing atmospheric carbon dioxide, simply looking at the effects of timber harvesting on C storage and sequestration within a given stand is not the whole story, and may not reflect the net effects of thinning in mitigating the global C balance (Gower 2003; McKinley et al. 2011). As we demonstrate here, thinning can reduce above-ground C storage in the short term by removing woody biomass, reducing the input of CDW, and leading to reductions in the size of the CDW C stock. Such activities can also lead to reductions in below-ground C stocks in the organic horizon and soil (Gower 2003). However, over the life cycle of the wood (from establishment to decomposition, be it in the forest or in a forest product), thinning effects on C storage depend on whether forest products are long-lived, and on carbon-emissions during harvesting operations and processing (Gower 2003; McKinley et al. 2011).

Conclusion

Linkages between carbon (C) storage and understory plant diversity may arise from a variety of processes and mechanisms operating over different temporal and spatial scales. Our work suggests that the net effect of these interactions is a trade-off between understory plant species richness and C storage (see also Burton et al., in press). Thus, forest management aimed to increase above-ground C storage by maintaining high-density forests may negatively affect aspects of restoration and maintenance of biodiversity within stands, and vice versa. Integrating C storage goals into a larger conservation-oriented management scheme may require accepting some losses and managing trade-offs by maintaining early seral habitat within dense C-rich stands or retaining live and detrital C in regenerating early-seral stands. Alternatively, plans could separate these goals across temporal or spatial scales.

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