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Early forest thinning changes aboveground carbon distribution among pools, but not total amount

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ABSTRACT

Mounting concerns about global climate change have increased interest in the potential to use common forest management practices, such as forest density management with thinning, in climate change mitigation and adaptation efforts. Long-term effects of forest density management on total aboveground C are not well understood, especially for precommercial thinning (PCT) implemented very early in stand development. To assess the climate change mitigation potential of PCT, as well as tradeoffs with climate change adaptation, we examined total aboveground C stores in a 54-year-old western larch (*Larix occidentalis* Nutt.) precommercial thinning experiment to determine how different PCT treatments affect long-term aboveground C storage and distribution among pools. Four aboveground C pools (live overstory, live understory/mid-story, woody detritus, and forest floor) were measured and separated into C accumulated prior to initiation of the current stand (legacy C) and C accumulated by the current stand (non-legacy C). PCT had no influence on the total non-legacy aboveground C stores 54 years after treatment. Live tree C was nearly identical across densities due to much larger trees in low density treatments. Low density stands had more understory and mid-story C while unthinned plots had significantly more non-legacy woody detritus C than thinned stands. Legacy pools did not vary significantly with density, but made up a substantial proportion of aboveground C stores. We found that: (1) fifty-four years after PCT total aboveground C is similar across treatments, due primarily to the increase in mean tree C of trees grown at lower stand densities; (2) deadwood legacies from the pre-disturbance forest still play an important role in long-term C storage 62 years after current stand initiation, accounting for approximately 20–25% of aboveground C stores; and (3) given enough time since early thinning, there is no trade-off between managing stands to promote individual tree growth and development of understory vegetation, and maximizing stand level accumulation of aboveground C over the long term. We infer that early PCT can be used to simultaneously achieve climate change mitigation and adaptation objectives, provided treatments are implemented early in stand development before canopy closure and the onset of intense intertree competition.

1. Introduction

Mounting concerns about anthropogenic climate change have increased interest in enhancing forests' capacity to capture and store atmospheric carbon dioxide (CO_2). Forests in the United States store an estimated 22 Tg of carbon (C) year^{-1} (Heath and Smith, 2004; Birdsey et al., 2006), and increasing attention is being directed towards understanding how to mitigate climate change effects by maintaining or increasing C storage in forest ecosystems through management actions (Pregitzer and Euskirchen, 2004; Birdsey et al., 2006; Millar et al., 2007; McKinley et al., 2011). Even global political leaders are beginning to recognize the important role of forest ecosystems in a global C management strategy, evidenced by the inclusion of forest C specific management strategies in the 2015 Paris Climate Agreement, (UNFCCC, 2015). Despite increasing policy interest and recent research, there remains uncertainty over long-term effects of common forest management practices, such as density management with thinning, on C storage.

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Carbon accumulates in the form of woody biomass and foliage in trees and, at the stand level, generally increases with time as mean tree size increases (Pregitzer and Euskirchen, 2004; Peichl and Arain, 2006). Any management actions that increase tree growth also have the potential to increase forest C accumulation and storage; conversely, management actions that reduce the number of trees on a site may potentially reduce forest C accumulation and storage.

Thinning is a common management activity used to manipulate the growth rate, size, and form of individual trees, as well as the structure and yield of forest stands (Sjolte-Jorgensen, 1967; Smith et al., 1997; Tappeiner et al., 2007). Thinning involves the selective removal of some trees such that more resources and growing space are allocated to the residual trees, thereby increasing their growth rates. Thinning in second growth forests is often suggested as a climate change adaptation strategy (Bradford and D'Amato, 2012; Churchill et al., 2013), because thinning can be used to promote the development of complex stand structures resilient to disturbances and drought. However, these climate change adaptation outcomes attainable with thinning generally require a tradeoff with climate change mitigation objectives: most studies have shown decreased forest C storage in thinned stands (Bradford and D'Amato, 2012).

Different methods of thinning—i.e., different methods of tree selection for removal and retention during thinning treatments—can have strong, differential effects on long-term forest C storage (Hoover and Stout, 2007). Thinning from above (preferential removal of the largest trees) or across the tree size distribution decreases aboveground C storage both immediately and over the long-term (Hoover and Stout, 2007; Harmon et al., 2009; Chatterjee et al., 2009; D'Amato et al., 2011; Zhou et al., 2013). However, studies of thinning from below (selective removal of the smallest trees) implemented early in stand development, a practice also termed precommercial thinning (PCT) when the thinned trees have no commercial value, show inconsistent results. Some PCT studies of this type found that decreasing stand density decreased total forest C stores (Skovsgaard et al., 2006; Jiménez et al., 2011), while others noted that the increased growth rate of trees grown at lower densities can maintain or increase live tree C (Hoover and Stout, 2007; Dwyer et al., 2010), especially in the case of longer-term responses to thinning (Horner et al., 2010). Short-term studies of PCT effects on aboveground C have shown consistent decreases in aboveground C (Campbell et al., 2009; De las Heras et al., 2013; Jiménez et al., 2011; Dwyer et al., 2010), indicating that low densities of small trees do not fully occupy the site (Turner et al., 2016). Given these conflicting results, it is still unclear whether PCT is compatible with the climate change mitigation goal of forest C storage (Jiménez et al., 2011).

The age at which a forest is thinned has a strong effect on aboveground C storage. Evidence from the few PCT studies that considered timing of thinning shows that total stem volume, which is a large component of the aboveground C (Harmon et al., 2004), is greater in stands thinned early as compared to stands thinned later (Varmola and Salminen, 2004). This is consistent with stand dynamics theory, which suggests that wood volume growth rates recover more quickly from early thinnings than from late thinnings (Oliver and Larson, 1996; Long et al., 2004; Varmola and Salminen, 2004).

Understory vegetation, woody detritus, and forest floor material are also important pools of aboveground C. Understory vegetation—composed of shrubs, subcanopy trees, forbs, and grasses—can be a major C pool, especially early in stand development or at lower stand densities (Campbell et al., 2009). Woody detritus, including snags, coarse woody debris (CWD; diameter ⩾7.62 cm), and fine woody debris (FWD; diameter <7.62 cm), can store large amounts of C, especially in temperate forests where trees may attain large sizes and decompose slowly (Harmon and Hua, 1991). Forest floor C is composed of litter, duff, and soil wood. Forest floor components can store significant amounts of C especially as large logs decay and become part of the forest floor in old-growth forests (Page-Dumroese and Jurgensen, 2006).

Other pools can store large amounts of C, but are not strongly affected by density management. Substantial C is stored in mineral soil (Johnson and Curtis, 2001; Page-Dumroese and Jurgensen, 2006; Bisbing et al., 2010), however evidence suggests that these soil C stocks are not as sensitive to density management as aboveground C pools, and often show little change following thinning (Johnson and Curtis, 2001; Nave et al., 2010; Zhou et al., 2013; Hoover and Heath, 2015). In second growth forests, where large woody structures from the previous stand were left onsite, both the woody debris and forest floor pools can be largely composed of biomass produced by the pre-disturbance, old-growth stand (Franklin et al., 2002). These C stores, referred to as legacy C, can make up a substantial proportion of the C stored in a second growth forest (Spies et al., 1988; Sturtevant et al., 1997; Franklin et al., 2002), however we would not expect these C stores to be strongly affected by early density management with PCT.

Questions remain about how early thinning affects long-term total aboveground C because many studies, (1) focused on controlling the "level of growing stock" with repeated thinning entries throughout the duration of the study (e.g. Skovsgaard et al., 2006, D'Amato 2011); (2) involved treatments applied relatively later in stand development (⩾30 years after stand initiation), after tree canopy closure and the onset of intense competition and crown recession, a scenario in which we would only expect a negative C impact from thinning (e.g. Finkral and Evans, 2008; North et al., 2009; D'Amato et al., 2011); (3) collapsed many different types of thinning treatments into one catch-all category (e.g., Powers et al., 2012); (4) only examined a short-term post-treatment response (e.g. Campbell et al., 2009; De las Heras et al., 2013; Jiménez et al., 2011; Dwyer et al., 2010); or (5) did not measure all aboveground pools (Skovsgaard et al., 2006; Horner et al., 2010; D'Amato et al., 2011; De las Heras et al., 2013; Zhou et al., 2013).

We overcame these constraints by measuring all aboveground C pools in a replicated, long-term (54-year-old) western larch (*Larix occidentalis* Nutt.) precommercial thinning experiment. Our objectives were to determine how different PCT treatments affect total aboveground C storage, and C distribution among different aboveground pools. We tested four predictions for the effect of tree density management with PCT on aboveground C pools.

(1) *Live overstory conifer C will increase with stand density.* Forest structural development theory suggests that overstory tree C increases with increasing density (Turner et al., 2004, 2016; Kashian et al., 2013); at high densities mean C per tree is smaller but the greater number of trees compensates for the small mean tree size.
(2) *Live non-conifer C (understory and subcanopy trees, shrubs, forbs, and grasses) will decrease with increasing stand density.* Forest structural development theory predicts that as canopies close and light becomes limited below the main canopy, understory plants and subcanopy trees will be competitively excluded (Long and Turner, 1975; Peet and Christensen, 1987; Oliver and Larson, 1996; Franklin et al., 2002). This occurs earlier and more completely at high stand densities, resulting in less mass of understory vegetation (Campbell et al., 2009).
(3) *Non-legacy deadwood C—dead woody material produced since initiation of the current stand—will increase with stand density.* Self-thinning theory predicts that as a stand nears a maximum size-density relationship, mortality will increase