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Carbon storage implications of active management in mature *Pseudotsuga menziesii* forests of western Oregon

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ABSTRACT

Mature stands, mid-successional communities in which large live trees are the dominant structural feature, are a major component of forested landscapes across North America. Despite this prominence at regional scales, mature stands have rarely been the focus of research on forest carbon dynamics. We utilized an observational study design to (i) examine the medium-term impact of active management on carbon storage in live and dead vegetation in mature Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)–dominated stands in western Oregon, and (ii) provide baseline estimates of total non-soil carbon storage during the mature phase of stand development for this forest type. Stands aged 106–193 years at the time of sampling were selected to represent a gradient in harvest intensity, from passive (reserve-based) management, to low-intensity (commercial thinning) and high-intensity (regeneration harvest with structural retention) active management. Active management treatments were implemented following the onset of maturity in stands with no prior management history, and sampling was conducted an average of 38 years and 22 years following treatment (mean for thinned and retention harvest conditions, respectively). Total non-soil carbon storage was significantly greater in stands managed using a reserve-based approach (mean of 575 Mg C ha^{-1}) than those subject to retention harvest (mean 257 Mg C ha^{-1}) 17 to –34 years previously, but was not different from stands managed over extended rotations with commercial thinning (mean 546 Mg C ha^{-1}). A similar trend was evident for carbon storage in live overstory trees, which were also the dominant component of total non-soil carbon in all management conditions. Dead wood pools varied greatly among stands, but estimates did not indicate any systematic differences in carbon storage in dead wood between management conditions. Our results suggest that shifting from passive management to a high-intensity harvest regime in mature Douglas-fir stands will entail substantial reductions in carbon storage. By contrast, managing stands over extended rotations with light thinning may enable the provision of wood products while maintaining relatively high carbon storage in the forest ecosystem. In absolute terms, mean carbon storage across our full sample of unmanaged, low-intensity and high-intensity harvest conditions exceeded previously reported values from inventories of mature plots across a similarly broad range of site conditions, but remains below the potential upper bounds to carbon storage in Douglas-fir-dominated forests. However, total aboveground carbon stocks in excess of 700 Mg ha^{-1} in individual mature stands in our dataset implies that, under certain conditions, forest biomass approaches its maximum by the close of the mature phase of stand development in Douglas-fir-dominated forests.

1. Introduction

Regeneration of temperate forests in North America following past disturbance has provided an important carbon sink at regional, national and global scales over the past half century (Pan et al., 2011; Skog et al., 2014; Urbano and Keeton, 2017). A legacy of this regrowth is extensive tracts of secondary forest now in the mature phase of stand development (Oswalt et al., 2014; Davis et al., 2015). Although concerns exist about future carbon sequestration potential as these forests transition to the later stages of succession, their absolute carbon stores are now material to national carbon dynamics, with implications for policy-making in an era of heightened awareness over climate change and related disturbance risks (Albani et al., 2006; Pacala et al., 2007; USDA Forest Service, 2012). On public lands, existing forest policy in many regions encourages passive, reserve-based management in mature stands (e.g. Thomas et al., 2006), a strategy that is consistent with maximizing the carbon balance of the forestry sector (McKinley et al., 2011). Active management approaches involving partial overstory

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harvest are another option that may be used to address a broader range of management goals. While harvesting temporarily reduces in-situ forest carbon stocks (Finkral and Evans, 2008; Harmon et al., 2009), overstory density reduction may extend the phase of active carbon sequestration (Powers et al., 2012), and improve the resiliency of forests to a variety of climate change-induced stressors (Chmura et al., 2011; Bradford and Bell, 2016), in addition to supplying traditional forest products (Curtis et al., 1998) or modifying wildlife habitat characteristics (Hagar, 2011). Evaluating the extent to which these advantages of active management compensate for any associated reduction in absolute carbon storage requires a detailed understanding of carbon stocks in mature stands managed under alternative active and passive treatment regimes.

Although mature stands are a major component of many temperate forest landscapes, the carbon dynamics of this phase of stand development have rarely been considered in isolation. Present understanding of the impacts of active management on carbon storage in mature stands is particularly limited, and overly reliant on regional or global chronosequences (e.g. Pregitzer and Euskirchen, 2004; Hudiburg et al., 2009; Goulden et al., 2011), and the results of a small number of long-term silvicultural experiments (e.g. Powers et al., 2011; Puhlick et al., 2016). Only the latter provide a useful guide to stand-scale management responses, as many existing chronosequences combine records from managed and unmanaged plots, are coarse-grained in geographical extent, and apply identical age-related definitions of 'maturity' across multiple forest types. Datasets from silvicultural experiments do not suffer these limitations, but the predominance of research from a small number of forest types hampers the development of generalized theories on carbon storage responses to management in mature stands. Observational studies can help overcome the shortage of long-term experimental data by assessing the extent to which previous findings are broadly applicable in different regional settings.

To be of broad practical relevance, conclusions on the response of mature stands to active management must be underpinned by a structure-based definition of maturity, rather than one based solely on age or time since disturbance. The mature phase of stand development is a period of re-organization. Stands entering maturity are thought to have relatively high biomass and rates of production, but relatively low structural diversity (Bormann and Likens, 1979; Spies and Franklin, 1991). Over subsequent decades, changes in canopy architecture associated with foliage attrition from mechanical abrasion, and increasing disturbance-induced mortality of large overstory trees, lead to a gradual reallocation of growing space from overstory trees to understory vegetation, including emerging mid-canopy trees. Disturbance events also increase stocks of large diameter dead wood (Spies et al., 1988). These changes diversify stand structure, and should dramatically influence future rates of carbon accumulation, and its distribution between components of the forest ecosystem.

In actively managed mature stands, timber harvesting influences the structural development process, with repercussions for carbon storage and future rates of primary production. In common with natural disturbance-induced overstory mortality, harvesting periodically reduces leaf area, temporarily depressing stand-scale production (Long et al., 2004). By contrast, mortality from natural disturbances is typically redistributed to the dead wood pools (with relatively little immediate change in total ecosystem stores) (e.g. Palik and Robl, 1999; Campbell et al., 2007; Meigs and Keeton, 2018), whereas harvesting generally removes a substantial fraction of the biomass of affected trees, thereby reducing in-situ carbon stocks for a period of time (e.g. Franklin et al., 2007; Zhou et al., 2013). Simulation models in temperate forests suggest that both effects should lead to reduced mean annual carbon storage over multiple rotations in stands managed using partial overstory harvesting compared to unmanaged stands (Harmon et al., 2009; Nunery and Keeton, 2010). Empirical research is complementary to these model-based evaluations, and particularly effective in demonstrating the carbon storage implications of silvicultural actions in individual stands at specific points in time post-treatment. To date, such empirical studies have focussed on younger stands from a wide range of forest types (Nilsen and Strand, 2008; Vargas et al., 2009; Burton et al., 2013), with the impact of overstory density reduction in previously unmanaged mature stands receiving little attention. However, responses to overstory density reduction may differ with overstory age and stand structure at the time of treatment (D'Amato et al., 2011; Schaedel et al., 2017), suggesting that previous observations from younger stands are, in isolation, insufficient as a guide to the consequences of stand density reduction following the onset of maturity.

Closer examination of mature forest carbon dynamics is timely given renewed interest in management activities that retain full or partial cover of overstory trees to advanced ages. In even-aged systems, the use of extended rotations with thinning has been proposed as a means of maximizing wood volume production and providing habitat for species associated with older forests (e.g. Curtis, 1995; D'Amato et al., 2010; Newton and Cole, 2015). Irregular shelterwood and retention harvesting approaches may also incorporate mature overstory structures, and are being trialled by federal agencies in efforts to satisfy biodiversity and social objectives alongside timber production (Raymond et al., 2009; Gustafsson et al., 2012; Franklin et al., 2018). Thinning treatments and structural retention harvests are inherently flexible, but typically result in different levels of overstory retention. Whereas thinning operations usually represent a low- to moderate-intensity harvest practice, retention harvest is a higher intensity treatment. Harvest intensity is an important determinant of carbon storage in forests of various ages and types (Zhou et al., 2013). For example, carbon storage in unmanaged stands commonly exceeds that in stands managed for timber production (Ruiz-Peinado et al., 2013, 2016), and may decline as harvest intensity increases (e.g. Skovsgaard et al., 2006; D'Amato et al., 2011; Ford and Keeton, 2018). However, relationships between harvest intensity and forest carbon storage show considerable variability according to site and treatment design (Ruiz-Peinado et al., 2017); in some settings total forest carbon storage in stands managed using light thinning may be comparable to that in unmanaged stands (Hoover and Stout, 2007; Coletta et al., 2016). In other situations, forest carbon storage in actively managed stands is lower than in unmanaged stands, but relatively constant across a range of treatment intensities (Powers et al., 2011; Bravo-Oviedo et al., 2015). Such variability in the relationship between harvest intensity and forest carbon storage further cautions against generalizing previous findings to new forest types, or management regimes, without additional empirical research.

In this study, we evaluated differences in stand-scale carbon storage across a gradient of management intensity in mature, low-moderate elevation Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests of western Oregon, United States. Mature stands are a major component of the total forested area in this study region (Davis et al., 2015), and unmanaged forests have an extremely high carbon storage capacity, thereby increasing the potential for major changes in carbon stocks when shifting between alternate forest management regimes (Smithwick et al., 2002; Smithwick et al., 2007). Present understanding of these carbon storage trajectories is largely derived from simulation studies (e.g. Harmon and Marks, 2002). To help fill this gap, we sampled mature stands representing high intensity harvesting, low intensity harvesting, and passive/reserve-based treatment alternatives. Our primary objective was to assess the medium-term impact of active management, with varying levels of overstory retention, on forest ecosystem carbon stores. An important secondary aim was the development of detailed stand-scale estimates of carbon storage during the mature phase of stand development, an interval that is presently under-represented in the literature on temperate forest carbon dynamics.