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Complex mountain terrain and disturbance history drive variation in forest aboveground live carbon density in the western Oregon Cascades, USA

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A B S T R A C T

Forest carbon (C) density varies tremendously across space due to the inherent heterogeneity of forest ecosystems. Variation of forest C density is especially pronounced in mountainous terrain, where environmental gradients are compressed and vary at multiple spatial scales. Additionally, the influence of environmental gradients may vary with forest age and developmental stage, an important consideration as forest landscapes often have a diversity of stand ages from past management and other disturbance agents. Quantifying forest C density and its underlying environmental determinants in mountain terrain has remained challenging because many available data sources lack the spatial grain and ecological resolution needed at both stand and landscape scales. The objective of this study was to determine if environmental factors influencing aboveground live carbon (ALC) density differed between young versus old forests. We integrated aerial light detection and ranging (lidar) data with 702 field plots to map forest ALC density at a grain of 25 m across the H.J. Andrews Experimental Forest, a 6369 ha watershed in the Cascade Mountains of Oregon, USA. We used linear regressions, random forest ensemble learning (RF) and sequential autoregressive modeling (SAR) to reveal how mapped forest ALC density was related to climate, topography, soils, and past disturbance history (timber harvesting and wildfires). ALC increased with stand age in young managed forests, with much greater variation of ALC in relation to years since wildfire in old unmanaged forests. Timber harvesting was the most important driver of ALC across the entire watershed, despite occurring on only 23% of the landscape. More variation in forest ALC density was explained in models of young managed forests than in models of old unmanaged forests. Besides stand age, ALC density in young managed forests was driven by factors influencing site productivity, whereas variation in ALC density in old unmanaged forests was also affected by finer scale topographic conditions associated with sheltered sites. Past wildfires only had a small influence on current ALC density, which may be a result of long times since fire and/or prevalence of non-stand replacing fire. Our results indicate that forest ALC density depends on a suite of multi-scale environmental drivers mediated by complex mountain topography, and that these relationships are dependent on stand age. The high and context-dependent spatial variability of forest ALC density has implications for quantifying forest carbon stores, establishing upper bounds of potential carbon sequestration, and scaling field data to landscape and regional scales.

1. Introduction

Forests play a critical role as a carbon (C) sink of atmospheric CO_2, partially offsetting anthropogenic greenhouse gas emissions and thereby mitigating their effect on climate change (Goodale et al., 2002; Woodbury et al., 2007; Pan et al., 2011). Forest C density (C stored per unit land area) varies tremendously at stand, regional, and global spatial scales (Smithwick et al., 2002;

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Bradford et al., 2010; Pan et al., 2011; Gray and Whittier, 2014). Given the importance of forests in the global C cycle, understanding the patterns and sources of variability of forest C density across scales is critical for inventory and monitoring of forest C in support of ecosystem management for climate change mitigation. For example, estimates of forest C pools and fluxes are one component of national and international reporting obligations on greenhouse gas emissions (UNFCCC, 2009; US EPA, 2015). Furthermore, quantifying the patterns and sources of variability of forest C is important for parameterization of simulation models used to understand how different management strategies, disturbance agents, and climate change may influence forest C sequestration and emissions (Kindermann et al., 2013; Seidl et al., 2014a,b).

Many factors are known to influence forest C density, including climate (Chen et al., 2003; Baccini et al., 2004), soil conditions (Oren et al., 2001), forest age (Pregitzer and Euskirchen, 2004), disturbance history and land management (Houghton et al., 1999; Goodale et al., 2002; Kashian et al., 2006; Kurz et al., 2008), species diversity (Bunker et al., 2005; Bradford, 2011), and vegetation structural complexity (Hardiman et al., 2011; Fahey et al., 2015). Variation of forest C density may be especially pronounced in mountainous regions, which contain approximately one quarter of the world's forests (FAO, 2011). Steep gradients of elevation and physiography that characterize mountainous terrain strongly influence climate (Daly et al., 1994, 2010; Lundquist and Cayan, 2007; Dobrowski et al., 2009), soil characteristics (Tromp-van Meerveld and McDonnell, 2006; Griffiths et al., 2009; Pelletier and Rasmussen, 2009), and disturbance regimes (Heyerdahl et al., 2001; Taylor and Skinner, 2003). Furthermore, in complex mountainous terrain individual environmental factors often have interactive, hierarchical, and multi-scale relationships with forest composition and structure (Urban et al., 2000; Seidl et al., 2012).

Estimates of forest C storage and its variability are often made at regional to global scales (Smithwick et al., 2002; Hudiburg et al., 2009; Pan et al., 2011). There is a rich history of ecological research investigating landscape and regional environmental controls on forest productivity and biomass in mountains (Assmann and Franz, 1963; Whittaker, 1966; Whittaker et al., 1974; Whittaker and Niering, 1975; Bormann and Likens, 2012; Nabuurs et al., 2008; Pretzsch et al., 2014). However, we still lack a understanding of the relative importance of environmental factors driving forest C density in mountain forest landscapes that are a mixture of managed and unmanaged stands (although see Baraloto et al., 2011; Seidl et al., 2012). Often, quantification of forest C and its environmental controls has been focused on the importance of old-growth forests and the upper bounds of forest C (Smithwick et al., 2002; Hudiburg et al., 2009). Younger managed forests have received less attention, in part due to their lower C stores, yet they can occupy large areas and are the location of much of the potential future additions to C stores in most landscapes. Furthermore, conservation of old-growth forests suggests future management activities will be increasingly concentrated in younger forests. Relatively few studies have compared environmental influences on forest C between young and old forests (although see Berenguer et al., 2014). The lack of knowledge as to how environmental factors drive forest C density in old versus young forests limits development of forest carbon management strategies and limits our ability to scale up results for landscapes that are a mosaic of managed and unmanaged forests.

This knowledge gap may in part be due to methodological limitations of measuring forest C and its spatial variability. Empirical estimates of forest C pools and fluxes are generally made using plot-based measurements (Smithwick et al., 2002), micrometeorological towers (Baldocchi et al., 2001), or optical satellite imagery (Turner et al., 2003). These data types often occur at different spatial and temporal scales, and each have specific limitations for quantifying the fine-grained spatial variability of forest C density and its underlying controls across landscapes. Plot-based measurements of forest C use biometric methods that are accurate, but they are labor intensive and sample intensities in traditional plot-based forest inventories may be inadequate in heterogeneous landscapes (Bradford et al., 2010). Using flux towers to quantity forest C in heterogeneous landscapes is also problematic, because their spatial resolution can extend hundreds or thousands of meters in tall forests (Baldocchi, 1997), and flux towers measure short-term C flux rather than C stores (i.e., the long-term integral of forest C sequestration). Finally, imagery from Landsat and other satellite passive optical sensors have known sensitivity and saturation limitations when estimating C density in forest types with high leaf area indices, high aboveground live biomass, and complex vertical canopy structure (Turner et al., 1999; Lu, 2006; Duncanson et al., 2010). In contrast to passive remote sensing, light detection and ranging (lidar) is well suited to fine-grained quantification of forest C density and its environmental determinants across landscapes. Lidar can characterize vegetation structure and underlying topography at fine resolutions (Lefsky et al., 2002a), and provide highly accurate estimates of aboveground biomass and carbon (Lefsky et al., 2002b; Li et al., 2008; Asner and Mascaro, 2014). In combination with ancillary data sources, lidar can provide novel insights into the spatial variation of forest C and its underlying controls (Asner et al., 2010).

In this study we coupled lidar data with fine-scale forest inventory data to map and analyze aboveground live carbon (ALC) density of the H.J. Andrews Experimental Forest (HJA), a mountainous forested watershed in the western Cascade Mountains of Oregon, USA. The Pacific Northwest Region of North America has some of the highest forest C densities in the world (Smithwick et al., 2002; Keith et al., 2009). We analyzed patterns of mapped ALC density in relation to climate, topography, and disturbance history. Seidl et al. (2012) previously examined the spatial drivers of forest C density in the old-growth portion of the HJA using correlation analyses and a 500 year landscape simulation model experiment that was validated with lidar-derived estimates of forest C density. Their analyses showed that only about 55% of the variation in C stocks could be explained by environmental drivers, and much of the remaining variation in ALC was attributable to differences in forest composition and structure. Yet, the role of management and disturbance history and its potential interaction with environmental drivers of ALC density was left unexplored by this previous analysis. Here, our primary objectives were thus to quantify how environmental factors influence ALC density, and determine if these factors and their relative importance vary between young managed and old unmanaged portions of the landscape. We hypothesize that environmental drivers should explain more variation of ALC in younger forests, because young forests have less accumulated history of mortality from density dependent and density independent processes (e.g., wind, disease, fire) (Franklin et al., 2002), and both their growth rates and structural development are primarily driven by site productivity (Klinka and Carter, 1990; Larson et al., 2008). In contrast, old forests in the region are characterized by centuries of disturbances ranging from individual tree and small-scale gap formation (Spies and Franklin, 1988; Spies et al., 1990) to larger wildfires of variable severity (Teensma, 1987; Morrison and Swanson, 1990; Tepley et al., 2013). Furthermore, older forests are characterized by more complex patterns and processes of stand development, including significant establishment and growth of shade tolerant trees, and changes in canopy structure and development in older trees compared to young forests (Franklin et al., 2002). As a result of these differences in growth and mortality between young and old forests, we hypothesized that drivers of ALC density vary with age.