Forest Ecology and Management 363 (2016) 31–38

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Canopy gaps affect the shape of Douglas-fir crowns in the western Cascades, Oregon

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ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form 14 December 2015
Accepted 17 December 2015
Available online 24 December 2015

Keywords:
Terrestrial laser scanning
Tree crown
Forest management
Complexity

ABSTRACT

Silvicultural regimes that aim at an increased stand structural diversity typically promote small-scale heterogeneity in horizontal and vertical structures, e.g. through the creation of gaps. We used terrestrial laser scanning (TLS) to investigate impacts of altered growing conditions on trees adjacent to artificial gaps as compared to responses of trees in a regularly spaced, thinned forest interior. Based on the TLS-based point clouds we calculated a number of structural tree crown properties that were hypothesized to be sensitive to spatial variability in growing conditions. We found several significant differences between structural properties of trees in the two growing conditions. Compared to trees in regular spacing, border trees near gaps had a lower crown base height (CBH) and a lower height of maximum crown projection. Crown surface area and crown volume of border trees were significantly larger than those of trees growing in a regular spacing. Also, the asymmetry of entire tree crowns of border trees, and in particular of the lower third of crowns, was directed towards the gap center, reflecting the increased light level in the gap. Our results raise concerns that the economic value of border trees is negatively affected by gap creation. These trees had shorter branch free boles and additionally, due to horizontal branch elongation, larger knots. Conversely, the overall increase in structural variability contributed by the border trees in stands with artificial gaps is likely to positively affect several ecosystem functions as well as biodiversity.

1. Introduction

Over the last several decades, plantations managed for timber production have replaced natural forests in many regions of the United States (Williams, 1989) and other parts of the world (e.g. Wagner et al., 2006). Such monocultures often have lower levels of variety or are lacking key attributes, such as standing deadwood. These key attributes can be of great importance for ecosystem services and functions, such as habitat diversity, aesthetics for recreation purposes or ecosystem resilience and stability (e.g. Haynes et al., 1996; Bauhus et al., 2009, 2010). Increasing knowledge about the ecological consequences of large scale conversions has been a key development leading to the rethinking of traditional silviculture (Kohm and Franklin, 1997; Bauhus et al., 2010; Kuuluvainen, 2009). Today, silviculture on many ownerships worldwide is undergoing a management paradigm shift which includes a new focus on providing a wider range of ecosystem services while ensuring ecosystem resilience and adaptability at the same time (e.g. Puettmann et al., 2013).

New silvicultural approaches have been proposed to accelerate the development of old-growth like composition and structures in planted forests (e.g. Bauhus et al., 2009) and better prepare these forests for an uncertain future (Messier et al., 2013). One of the key features of these approaches includes increasing the horizontal and vertical heterogeneity within stands. Typically, this goal is modelled after conditions in old-growth forests, such as irregular tree distributions and multiple canopy layers (Franklin and van Pelt, 2004). Bauhus and colleagues (2009) collected a number of structural attributes typically associated with "old-growth conditions" and suggested silvicultural operations that could result in the development of desired attributes. They highlight the creation of gaps in even-aged monocultures to simulate natural disturbances such as small-scale mortality through diseases or tree falls (Lutz and Halpern, 2006; Wilson et al., 2009; Schliemann and Bockheim, 2011). Interestingly, simulation studies suggested that stand productivity may not necessarily be negatively affected by gap creation when compared to standard plantation management (Barbour et al., 1997; Busing and Garman, 2002), even though

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http://dx.doi.org/10.1016/j.foreco.2015.12.024
0378-1127/

management costs are higher. Even for mixed-aged, mixed-species forests the creation of canopy gaps was found to reduce the forest growth rates considerably less than gap area indicates (Pedersen and Howard, 2004).

Increased heterogeneity in horizontal and vertical structures through gap creation implies changing growing conditions for trees and other vegetation. It is well documented that gaps have a strong influence on growing conditions for trees in their vicinity due to changed light conditions and belowground resource levels (e.g. Ammer and Wagner, 2002; Harper and Macdonald, 2002; Harper et al., 2005; Gray et al., 2012). Creation of man-made gaps in even-aged stands also results in significantly changed belowground resource availability (e.g. Thiel and Perakis, 2009). In the past, research has addressed the response of understory vegetation (e.g. Fahey and Puettmann, 2007, 2008), seedling growth (York et al., 2007; York and Battles, 2008) and growth of surrounding canopy trees (e.g. Dodson et al., 2012) to gap formation. Gap closure rates were derived from a combination of height growth of trees, in-growth in gaps, and lateral branch extension of trees adjacent to gaps (e.g. Runkle, 1981, 1998; Schliemann and Bockheim, 2011). Mean turn-over rates of canopy trees and gap formation rates are a key factor in understanding forest stand dynamics and have been derived for forests all over the world (Pickett and White, 1985; Oliver and Larson, 1996; Henbo et al., 2004).

The spatial variability in growing conditions after gap creation causes trees directly adjacent to the opening's "edges" (i.e., border trees) to respond with higher diameter growth than trees in the interior of homogenously spaced even-aged stands (Dodson et al., 2012). This response is partially due to the changes in structural development of tree crowns. For example, crown asymmetry increased towards gaps (e.g. Young and Hubbell, 1991; Muth and Bazzaz, 2002) and the increased number of epicormic branches due to increased radiation reaching the bark (Franklin and van Pelt, 2004). Even in small gaps, diameters of the largest branches (larger), height of the lowest living branch (lower), taper (higher), and other branch and stem characteristics of Norway spruce (*Picea abies* (L.) H. Karst) edge trees showed significant trends compared to trees growing in evenly spaced conditions (Pfister et al., 2008). Besides their impact on tree growth, crown characteristics are an important ecological indicator for wildlife and other aspects of diversity (e.g. Muir et al., 2002). We study these phenomena in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) because this species is especially flexible in terms of crown shape (Ishii and Wilson, 2001; Ishii and McDowell, 2002) and managing for variability in crowns shapes, such as those typically found in old-growth trees is of great interest in the region (Cissel et al., 2006; Kohm and Franklin, 1997).

Qualitative and quantitative assessments of tree and crown shape responses to gaps have been difficult in the past. Accurate measurements were difficult to obtain due to methodical constraints of measuring the three-dimensional structure of tree canopies surrounding gaps (Seidel et al., 2011a) or even the gap dimensions itself (Seidel et al., 2015a). For this reason, past research on indirect methods has focused mainly on modelling approaches that relate thinning regimes to wood properties as affected by crown dynamics (Barbour et al., 1997; Busing and Garman, 2002). Recent advances in measurement technologies, such as terrestrial laser scanning (TLS) provide an opportunity to investigate morphological aspects of crown response to forest management practices, including gaps. A number of laser scans from different perspectives can be combined into a single point cloud offering comprehensive 3D- geometry of the scanned trees and forest structure (e.g. Watt et al., 2003).

In our study, we used terrestrial laser scanning to investigate the effects of a change in growing conditions on trees adjacent to artificially created gaps as compared to the response of trees in the regularly spaced, thinned forest interior. Understanding the changes in tree and crown shapes can provide new insights into effects of silvicultural practices on tree stability, timber quality, and habitat suitability for a variety of species.

2. Methods

2.1. Study sites

Our study area was located in the Willamette National Forest on the western slopes of the Cascade mountain range in Oregon, USA (Fig. 1). This area experiences a Mediterranean climate with cool, wet winters and warm, dry summers. The site, Christy Flats, receives an average 1680 mm of precipitation falling primarily as rain from November to May and was part of the Young Stand Thinning and Diversity Study (YSTDS). In this larger silvicultural experiment options for accelerating the development of late-seral conditions in young forests are investigated (for more detail about the study, see Davis et al., 2007). The site is 122 ha, mostly flat, and at an elevation of about 898 m. Although the exact history is unknown, the site was clear-cut sometime in the 1950s, broadcast-burned and planted to Douglas-fir. The plantation was pre-commercially thinned to 4 m spacing about 10–15 years after planting. Consequently, Douglas-fir was the dominant overstory tree species with only minor components of western hemlock (*Tsuga heterophylla* Raf.) and hardwoods, such as bigleaf maple (*Acer macrophyllum* Pursh.).

In 1997, the stand was fairly homogeneous in terms of the structural properties of trees in the study area (Davis et al., 2007). Before treatments it was dominated by 35–45 year-old Douglas-fir with an average density of 855–871 trees per ha and a basal area of 39.5 m^2 per ha. For our study we examined trees in the 'light thinning' and trees adjacent to the gaps in the 'light thinning with gaps' treatment. The light thinning treatment (32 ha) involved the removal of smaller diameter trees (low thinning) to achieve a target density of 275 trees per ha with fairly regular spacing. The thinned with gaps treatment (39 ha) was thinned using the same prescription as the light-thin treatment, but in addition 20 percent of the area was cut into 0.2 ha fairly circular gaps. In these gaps all trees were removed except a few hardwoods that were left to encourage species diversity. Treatments were completed in 1997 with harvester-forwarders. After harvest, the gaps were planted at a density of 500 seedlings per ha with a mix of conifer species. Some of the seedlings reached heights of up to 7 m at the time of our measurements (height measurements taken from the scan data from 2015) but the gap area was still easily distinguishable from the surrounding forest.

2.2. Study trees and terrestrial laser scanning

2.2.1. Trees adjacent to a gap

Within the light thinning with gaps treatment we identified 18 Douglas-fir trees growing directly adjacent to gaps. The selected trees (from here on named 'border trees') had no other tree (or any portion of another tree's crown) between the stem and the gap center in a cone with an angle of 45° (Fig. 2). Trees were only selected if they were vigorous codominant trees, at least 30 m in height, and greater than 40 cm in diameter at breast height (DBH; measured at 1.3 m above ground). We only selected healthy looking individuals with abundant foliage in good color and fairly straight stems (i.e., without crooks or forks).

In early April 2015 we used a Faro Focus 3D 120 terrestrial laser scanner (Faro Technologies Inc., Lake Marry, USA) to scan all border trees from six to ten different perspectives and with varying distances to the stem (10–20 m). These perspectives, or scanner positions, were chosen in the field to ensure a good visibility of the