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Long-term responses of tree and stand growth of young lodgepole pine to pre-commercial thinning and repeated fertilization

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ABSTRACT

This study was designed to test the hypothesis that application of a range of pre-commercial thinning (PCT) intensities and repeated fertilization would enhance 15-year growth increments of lodgepole pine (*Pinus contorta* var. *latifolia*) crop trees at both tree and stand levels. Study areas were located near Summerland and Kelowna in south-central British Columbia, Canada. Each study area had nine treatments: four pairs of stands thinned to densities of ~250 (very low), ~500 (low), ~1000 (medium), and ~2000 (high) stems/ha with one stand of each pair fertilized five times at 2-year intervals, and an unthinned stand. Neither density nor fertilization treatments had any significant effect on 15-year increments of height growth. Mean diameter at breast height (17% increase), basal area (BA) (28% increase), and volume (27% increase) growth increments per tree were significantly enhanced by fertilization, but were not affected by density. Repeated fertilization enhanced both BA (20% increase) and volume (18% increase)/ha at the stand level. Despite the significant decrease in crop tree stand density resulting from PCT, 15-year BA and volume increments were statistically similar across density treatments. Contributions of non-crop trees to total stand productivity appeared to be substantial, particularly within the heavily thinned stands. Because trees provide the majority of all aboveground terrestrial carbon, they are an important sink for atmospheric CO_2. Enhancing stand productivity may provide adaptive advantages for carbon sequestration to help limit greenhouse gases as well as resiliency of forests subjected to changing growing conditions due to climate change.

1. Introduction

With very few exceptions, Canada's forest industry has been based on extensive silviculture practices that have been able to take advantage of large tracts of unmanaged, old forests, often with little or no investment in silviculture treatments beyond stand establishment. Intensive silviculture has been clearly demonstrated as an economically beneficial strategy within pine (*Pinus* spp.) plantations throughout the southern United States (US) with growth rates more than doubled and rotation lengths cut by more than 50% (Fox et al., 2007). However, the benefits of intensive silviculture remain largely unrealized throughout northern latitudes, and within boreal and sub-boreal forests in particular (Lautenschlager, 2000; Park and Wilson, 2007). There is an ever-increasing global demand for timber production and forest cover to produce conventional wood products, biofuels production, and sequester carbon in response to climate change (Sedjo, 1999; Raunikar et al., 2010). This demand is concurrent with conservation strategies that endeavor to increase the size of protected areas and conserve biodiversity (Hunter and Schmiegelow, 2011), while balancing the unpredictable large-scale loss of existing timber to natural disturbances (e.g., losses to wildfire and insect epidemics; Agee, 1993; Walton et al., 2009). Clearly, enhanced wood production will become increasingly necessary to mitigate current and future wood supply shortfalls (Brooks, 1997; Sutton, 1999).

Intensive silvicultural practices such as pre-commercial thinning (PCT), commercial thinning (CT), and fertilization have the potential to sustain wood and biomass production while creating a diversity of forest habitat conditions to meet the goals of biodiversity conservation (Moore and Allen, 1999; Hartley, 2002; Sullivan et al., 2009). These silvicultural treatments have been used successfully around the world to increase biomass production in existing even-aged forests (Allen et al., 1990; Oliver and Larson, 1996), across northern Europe (Nabuurs et al., 2007; Bergh et al., 2008), the southeastern US (Albaugh et al., 2004; Jokela et al., 2004), and inland lodgepolepine (*Pinus contorta* var. *latifolia*) forests of the Pacific Northwest (PNW) of North America (NA) (Sullivan et al., 2006; Lindgren et al., 2007).

Early- to mid-seral (1–40 years old) lodgepole pine is the dominant coniferous tree species across a vast area of the inland PNW of NA (Koch, 1996; Sullivan et al., 2001). This species likely has the greatest potential to respond favorably to silvicultural treatments designed to enhance the growth of crop trees within stands

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(Johnstone, 1985; Brockley, 2005). Lodgepole pine often regenerates over-abundantly, after wildfire or clearcut harvesting, with excessive stand densities that reduce tree growth and stand productivity. PCT and CT concentrate growth on a smaller number of stems and provide some control over the rotation, yield, and value of the future crop (Johnstone, 1985; Cole and Koch, 1996). Because they originated from repeated fire disturbance, lodgepole pine forests usually occupy sites of low-N status (Brockley et al., 1992), and hence respond well to conventional, single applications of nitrogen, as well as in combination with other elements (Weetman, 1988; Brockley, 1996). Sustained growth responses to fertilization with optimum nutrition formulations have been demonstrated in field experiments with lodgepole pine (Brockley, 2005; Lindgren et al., 2007) and other *Pinus* species (Malkonen and Kukkola, 1991; Tamm et al., 1999; Fox et al., 2007).

Operational scale nutrition experiments apply nutrients infrequently, usually in a larger amount. Thinning and repeated fertilization treatments are applied over an entire ecosystem, and hence they have the potential to significantly increase stand-level wood production and structural diversity. Small-scale studies have demonstrated the concept of "steady-state" nutrition, whereby small, balanced supplies of nutrients are provided at optimum rates consistent with estimated demand (Linder, 1987; Raison and Myers, 1992; Brockley, 2005). Stand production and structural diversity may be enhanced by maintaining steady state nutrition with repeated optimum nutrient applications. With respect to stand structure and biodiversity, we have barely begun to explore the possibilities (Sullivan et al., in press).

This study was designed to test the hypothesis that, among managed stands, application of a range of PCT intensities and repeated fertilization with optimum nutrition formulations would enhance the 15-year growth increments of lodgepole pine crop trees at both tree and stand levels.

2. Methods

2.1. Study areas

Three study areas each containing several lodgepole pine stands were originally established in 1993. The Summerland study area is located in the Bald Range, 25 km west of Summerland in south-central British Columbia (BC), Canada (49°40′N; 119°53′W). The Kelowna study area is located 37 km northwest of Kelowna, BC (50°04′N; 119°34′W). Both areas are in the Montane Spruce (MS_{dm}; d,m = dry precipitation regime, mild temperature regime) biogeoclimatic zone (Meidinger and Pojar, 1991). A third study area near Williams Lake, BC, reported in Lindgren et al. (2007), was decimated by mountain pine beetle (MPB) (*Dendroctonus ponderosae*) in 2005, and therefore excluded from this analysis. Descriptions of these study areas are provided in Lindgren et al. (2007).

At the start of the study (1993), mean DBH (diameter at breast height, 1.3 m above the forest floor) at Summerland ranged from 2.2 ± 0.1 cm (mean ± S.E.) to 4.1 ± 0.1 cm with a mean age of 12–14 years. Tree height ranged from 2.3 ± 0.1 m to 3.4 ± 0.1 m (Fig. 1). Stand areas ranged from 4.4 to 11.3 ha (Table 1). In 1993 at Kelowna, the mean tree diameter and height ranged from 3.1 ± 0.1 cm to 4.7 ± 0.1 cm and 3.0 ± 0.1 m to 4.1 ± 0.1 m, respectively (Fig. 2), with a mean stand age of 12–13 years. Stand areas ranged from 9.5 to 12.6 ha (Table 1).

2.2. Experimental design

The two study areas were replicates (blocks). Within each replicate, there were five experimental lodgepole pine stands PCT in the following randomized block design: very low density (target 250 stems/ha), low density (target 500 stems/ha), medium density (target 1000 stems/ha), high density (target 2000 stems/ha), and unthinned (at least 4000 stems/ha). Fertilization treatments were applied to one half of each of the thinned units, resulting in a total of nine stands per study area: (1) 250 stems/ha, (2) 250 stems/ha with fertilization, (3) 500 stems/ha, (4) 500 stems/ha with fertilization, (5) 1000 stems/ha, (6) 1000 stems/ha with fertilization, (7) 2000 stems/ha, (8) 2000 stems/ha with fertilization, and (9) unthinned (Table 1). The restriction on randomization for the allocation of fertilizer treatment (i.e., applied to one-half of each density treatment) resulted in an overall split-plot design, with density as the main-plot effect and fertilization as the split-plot effect. A fertilized unthinned experimental unit was not included as this treatment combination would not be part of any management prescription. Pruning (3-m lift) was carried out within all stands with densities <2000 stems/ha in 1998, 5 years after PCT.

2.3. Density and fertilization treatments

The initial treatment was PCT of pine in autumn of 1993. Fertilization treatments were designed as large-scale "optimum nutrition" applications initiated in November 1994 using a blended

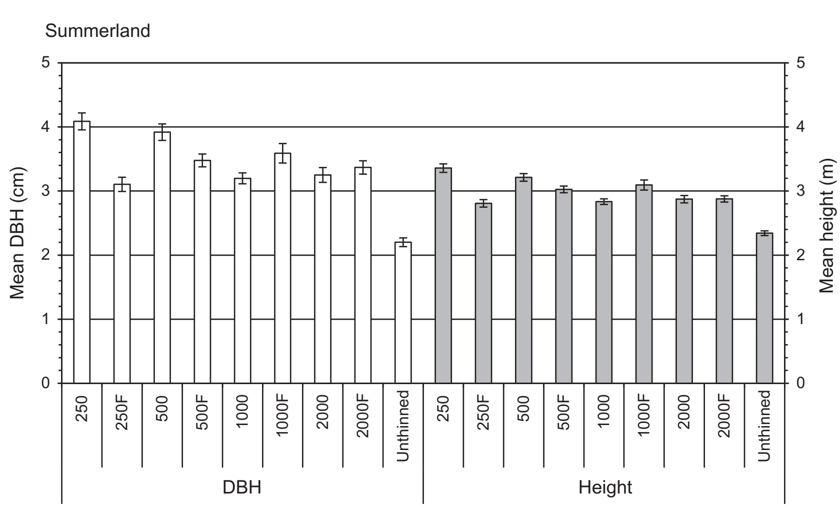

Fig. 1. Mean DBH (cm) and top height (m) of 12- to 14-year old lodgepole pine crop trees immediately post-thinning (fall of 1993) at the Summerland study area. Numbers along the *x*-axis represent target thinning densities (stems/ha) for each of the treatment stands. The unthinned stand had a density of ca. 10,700 stems/ha. The F identifies stands selected for repeated fertilization treatments. Error bars indicate SE.