Forest Ecology and Management 409 (2018) 683–693

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Does commercial thinning improve stand-level growth of the three most commercially important softwood forest types in North America?

Arun K. Bose[a,e,*], Aaron Weiskittel[a], Christian Kuehne[a], Robert G. Wagner[b], Eric Turnblom[c], Harold E. Burkhart[d]

[a] School of Forest Resources, University of Maine, 5755 Nutting Hall, Orono, ME 04469-5755, United States
[b] Department of Forestry & Natural Resources, Purdue University, West Lafayette, IN 47907-2061, United States
[c] School of Environmental and Forest Sciences, University of Washington, Box 352100, Seattle, WA 98195-2100, United States
[d] Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA 24061, United States
[e] WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Zurcherstrasse 111, CH-8903 Birmensdorf, Switzerland

A R T I C L E I N F O

Keywords:
Commercial thinning
Softwood species
Dominant trees
Stand age at thinning
Mixed-effect modelling
Pacific Northwest US
Southeast US
Northeast US

A B S T R A C T

Thinning is expected to improve both individual tree- and stand-level growth efficiency since more environmental resources (growing space, light, water, and nutrients) become available to fewer trees. However, thinning can also promote asymmetric competition among residual trees, and potentially increase mortality and growth stagnation by creating an immediate and often dramatic change in stand micro-environments. To strengthen our understanding of stand-level responses to thinning, we used long-term and replicated experiments for the three most commercially important softwood forest types in the North America, including: shade-intolerant loblolly pine (*Pinus taeda* L.), moderately shade-tolerant Douglas-fir (*Pseudotsuga menziesii* Mirbel), and shade-tolerant red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* L.). The primary objectives of this study were to quantify the stand-level and dominant tree (100 largest trees ha^{-1}) response to various thinning treatments in terms of relative (*RVG*) and cumulative volume growth (*CVG*), while evaluating the effects of stand conditions, timing/intensity of thinning, and key stand-level biotic factors. Our results showed relatively limited differences between the stand-level and dominant-tree responses. Thinning generally increased the *RVG* of all three forest types, but the effect was dependent on time since treatment for spruce-fir. When compared to unthinned stands, thinning increased the overall *RVG*, but the pattern of change over time since thinning was negative for both loblolly pine and Douglas-fir. *CVG* was generally higher in unthinned than thinned stands across the three forest types. Thinning intensity had a positive effect on the *RVG* of Douglas-fir and loblolly pine, but negative on *RVG* of spruce-fir forest type. Relative age (based on age of maximum periodic annual increment) and stand density at time of thinning had negative effects on the *RVG* of dominant trees for all species examined, except spruce-fir. Overall, our results highlight a range of responses to thinning among three distinct softwood forest types, and revealed that thinning does not always improve the growth efficiency of dominant trees, and that the responses are governed largely by a variety of stand characteristics at the time of thinning.

1. Introduction

Thinning is one of the most commonly used silvicultural practices, which is generally prescribed in forest stands to capture mortality, provide early financial return for landowners, and redistribute growing space to fewer trees to increase future merchantable volume and financial value (Curtis et al., 1997). A general assumption is that by reallocating growing space and reducing competition for resources, thinning improves the growth efficiency of residual trees (i.e., higher growth rates than same sized trees of unthinned stands) (O'Hara, 1989). However, thinning can also increase tree mortality by wind damage and water stress (Lagergren et al., 2008; Kuehne et al., 2016) and cause growth stagnation (Harrington and Reukema, 1983; Sharma et al., 2006) of residual trees, which may cause reductions in stand volume and increment, respectively (Mäkinen and Isomäki, 2004b,a; Moulinier et al., 2015).

Growth responses to thinning or to any other types of partial harvesting depend on individual-tree characteristics, pre- and post-thinned

* Corresponding author at: WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Zurcherstrasse 111, CH-8903 Birmensdorf, Switzerland.
E-mail addresses: arun.bose@wsl.ch (A.K. Bose), aaron.weiskittel@maine.edu (A. Weiskittel), christian.kuehne@maine.edu (C. Kuehne), rgwagner@purdue.edu (R.G. Wagner), ect@uw.edu (E. Turnblom), burkhart@vt.edu (H.E. Burkhart).

https://doi.org/10.1016/j.foreco.2017.12.008
Received 6 October 2017; Received in revised form 4 December 2017; Accepted 4 December 2017

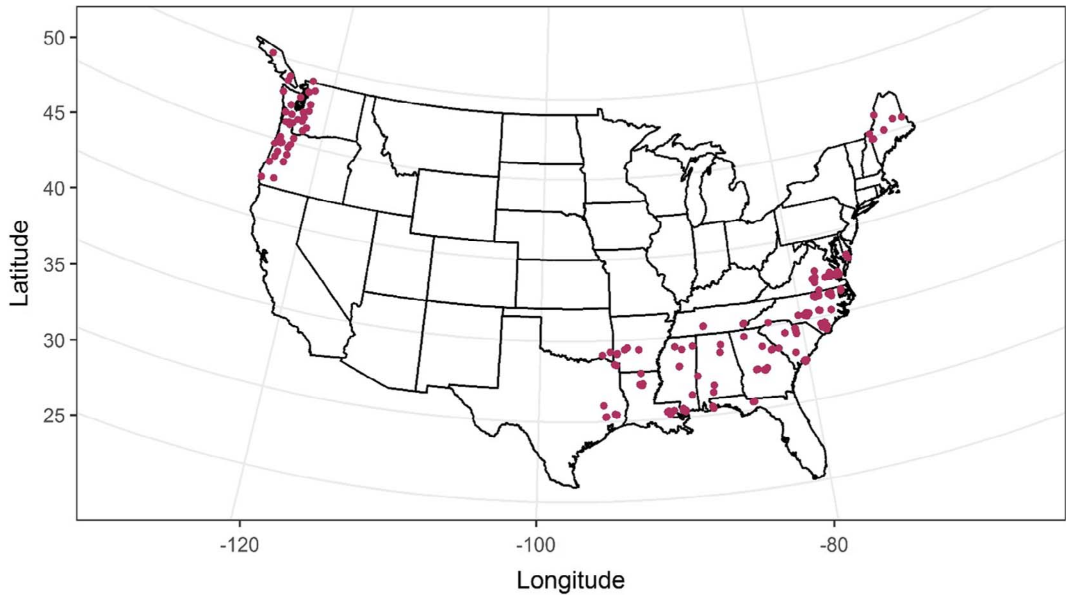

Fig. 1. Locations of study sites for the three forest types and geographic regions in North America examined in this analysis.

stand characteristics, and time since treatment (Bose et al., 2014; Girona et al., 2017). Thinning generally reduces competition among residual trees since fewer trees are using the available resources (light, water, and nutrients). Conversely, the improved growing conditions (i.e., resource availability) may intensify asymmetric competition (Thomas et al., 1999), where larger individuals obtain a disproportionately larger share of resources, and suppress the growth of smaller individuals (Schwinning and Weiner, 1998; Berntson and Wayne, 2000). However, when trees reach maximum growth potential at a certain age/size and become mature canopy trees, they are less likely to respond to changes in resources than are smaller and younger trees (Ryan et al., 1997). Recent studies showed that large trees can still maintain a positive trend in above-ground biomass growth (Sillett et al., 2010; Stephenson et al., 2014; Sillett et al., 2015). The general assumption is that younger trees of shade-intolerant species will have larger growth gains in response to increased light levels than shade-tolerant species, but they will also reach a plateau of annual growth at younger ages than trees of shade-tolerant species (Pothier and Margolis, 1991; Ryan et al., 1997; Jones et al., 2009). Therefore, stand-level responses to thinning are dependent upon interactions of the size and age of residual trees, physiological traits of the tree species, and the availability of resources including light, water, and nutrients.

Because of the high degree of variability across studies and the general absence of long-term data, researchers have not been able to conclusively answer some of the most important questions associated with stand-level responses to thinning (Weiskittel et al., 2011). For example, some of the most important include: (1) what is the optimal time to apply thinning to achieve maximum volume growth response? (2) How do species physiological traits influence volume increment following thinning? (3) Does thinning at certain sites and/or stands become ineffective to improving volume increment? and (4) How long is the effect of thinning usually sustained?

In this context, long-term data for the three most important North American softwood forest types including shade-intolerant planted loblolly pine (*Pinus taeda* L.) of southeastern US, mid-tolerant planted Douglas-fir (*Pseudotsuga menziesii* Mirbel) of Pacific Northwest US, and tolerant naturally-regenerated red spruce-balsam fir (*Picea rubens* Sarg & *Abies balsamea* (L.) Mill.) of northeastern US were synthesized and analyzed. The primary goal of this study was to quantify both the stand-level and dominant-tree (largest 100 trees ha^{-1}) responses to thinning in terms of relative volume growth (i.e., relative to previous years) (*RVG*) for understanding the maximum volume growth potential and its association with species, time since thinning, and stand-level factors. In addition, cumulative volume growth (*CVG*) was quantified in association with these various factors to better understand the pattern of absolute growth performance.

To address these research goals, the following hypotheses were tested: i) thinning will increase the annual volume increment of residual trees relative to unthinned stands, and the magnitude of increase will be based on species light use efficiency, which would result in the following ranking, shade-intolerant loblolly pine > mid-tolerant Douglas-fir > tolerant spruce-fir, ii) *RVG* will increase with more release from competition, higher site productivity (i.e., site index or dominant height), and with more release from competition, but decrease with increasing stand age, iii) *CVG* will be higher in unthinned than thinned stands during initial years since thinning (< 10 years), but lower in unthinned than thinned stands during the later years (> 10 years) since thinning, iv) *CVG* will plateau earlier in thinned than unthinned treatments, and the time to reach this plateau will depend upon the shade tolerance of the species, and v) similar to *RVG*, *CVG* of dominant trees that receive thinning will increase with higher thinning intensities and site productivity (i.e., site index), but decrease with greater stand ages.

2. Methods

2.1. Study sites

We considered three softwood forest types including planted loblolly pine (*Pinus taeda* L.) of southeastern US, planted Douglas-fir (*Pseudotsuga menziesii* Mirbel) of Pacific Northwest US, and naturally regenerated red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* L.) of northeastern US (Fig. 1). These species are commercially managed across a vast region of the US and Canada. Each of the datasets used are described in detail below. However, any plot that had received other silvicultural treatments including pre-commercial thinning, pruning, fertilizer application, and/or herbicide spray was excluded from the analysis. For consistency, plots with a total basal area lower than $< 1\ m^2\ ha^{-1}$ at time of treatment (thinned or unthinned) also were not considered in the analysis.

2.1.1. Loblolly pine sites

In the dormant seasons of 1980–81 and 1981–82, permanent plots were established at 186 locations of plantations throughout the native