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Survival and growth of residual trees in a variable retention harvest experiment in a boreal mixedwood forest

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ABSTRACT

Long-term sustainability of forest resources is in question given wide-spread use of conventional clear-cut silviculture. In response, variable retention (VR) harvest has been increasingly promoted as a landscape-based approach to enhance sustainability by maintaining biodiversity and other ecosystem functions in managed forests. Although the success of the VR approach depends on post-harvest stand dynamics, little is known about growth and mortality of residual trees after harvest and how such trees respond to interactions between amount of retention and tree or site level covariates. We use data from three censuses distributed over a 10-year period of the main merchantable species to study the effects of retention level (i.e., percent of trees retained), mixedwood cover type, tree species, and three tree or terrain covariates (tree stem diameter, percent live crown, and soil wetness) on survival and growth of residual trees in a retention harvest experiment in NW Alberta, Canada. Both mortality and growth of residual trees were negatively related to retention levels. During the first five-year period after harvest, effects of retention levels on mortality were more evident for white spruce (*Picea glauca*) than for *Populus* spp., but effects on growth were weaker for white spruce. Tree mortality decreased through time following VR harvest for all species and in most cover types, while trends in tree growth varied by species. During the second five-year period after harvest, growth of residual *Populus* spp. had decreased from high levels observed in the first period. In contrast, growth of residual white spruce was greater in the second five-year period than in the first period. After the original harvest, re-entry of stands for additional harvest focused mainly on hardwoods may be economically rewarding and ecologically justified, depending on the overall objectives for retention. The positive effect of increased retention level on tree survival was strongest for trees with larger diameter and longer crowns. Thus, retention patches are a management option to protect large trees and trees with greater crown length when retaining such trees is a management goal.

1. Introduction

Forests are important for the supply of wood and fiber; however, the ecological sustainability of conventional clear-cut silvicultural systems has been questioned in relation to a broader appreciation of forest values (Bliss, 2000; Lindenmayer et al., 2012). Variable retention harvest (VR) that retains single trees and/or forest patches at the time of harvest is increasingly employed with the aim of maintaining biodiversity and other ecosystem functions (Fedrowitz et al., 2014; Franklin et al., 1997; Spence, 2001).

In VR systems, retained trees provide wildlife habitat, store carbon, and influence future regeneration and succession. Thus, an understanding of post-harvest growth and mortality of retained trees, under various retention prescriptions, is critical to assessing success of the VR approach. Although impacts of boreal retention harvests on biodiversity have been investigated for many taxa, including understory plants, invertebrates, and vertebrates (e.g., Gandhi et al., 2004; Lance and Phinney, 2001; Macdonald and Fenniak, 2007; Moses and Boutin, 2001), relatively little is known about post-harvest growth and mortality of residual trees, and how these processes are influenced by interactions among amount of retention and site and tree level covariates, particularly for the western Canadian boreal mixedwood (see Bose et al., 2014a; Prévost et al., 2010; Prévost and Dumais, 2014; Smith et al., 2016 for results from eastern Canada).

The boreal forest is the largest terrestrial biome on Earth and also the major forest biome in which the VR model is currently practiced (Fedrowitz et al., 2014; Gustafsson et al., 2012). Several studies from the boreal zone have demonstrated enhanced growth rates and elevated mortality of retained trees after partial harvest (Bose et al., 2014a; Prévost et al., 2010; Rosenvald et al., 2008; Solarik et al., 2012).

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However, post-harvest responses could vary considerably among species, levels of retention, and study areas. For example, enhanced growth of trembling aspen (*Populus tremuloides*) was significant only in the lower retention treatment (< 1/3 retention vs. no effect on > 2/3 retention) applied in a boreal mixedwood forest in northwestern Quebec, Canada (Bose et al., 2014a). In contrast, diameter growth of residual trees increased linearly with partial harvest intensity in a trembling aspen–conifer mixed stand in southeastern Quebec (Prévost et al., 2010). Improved understanding of such effects could be used in planning harvests that are fiber efficient and contribute to biodiversity conservation and recovery.

Several unanswered questions about the fate of retention trees are important both for understanding forest function and improving management. For instance, previous studies suggest a general pattern in post-harvest growth, i.e., a short lag period immediately after harvest is followed by a gradual increase up to a peak that gives way to a period of reduced growth toward pre-harvest rates (Bose et al., 2014a; Smith et al., 2016). Yet, little is known about how this pattern may vary among species or stand types. Although site factors such as soil wetness contribute to variation in tree growth and mortality (e.g., Hogg et al., 2005), few studies have examined growth and mortality of trees remaining after partial harvest in relation to such factors (Solarik et al., 2012). Models that simultaneously incorporate harvest effects, intrinsic tree characteristics, and extrinsic environmental factors could improve understanding of post-harvest stand dynamics.

In addition, understanding interactions between partial harvest treatments and other covariates would facilitate tests of hypotheses about drivers of tree growth and mortality. For example, it has been widely shown that size-based asymmetric competition for resources affects tree mortality and growth (Metsaranta and Lieffers, 2008; Schwinning and Weiner, 1998). Thus, we expect to see different effects of harvest intensity on the performance of trees based on their relative size. In this study, we hypothesized that interaction between stem diameter and harvest treatments would affect tree growth and mortality. Specifically, the reduction of competition at lower retention levels should benefit smaller trees more than larger trees because smaller trees suffer more from competition in unharvested forests (Smith et al., 2016). Likewise, mortality should be reduced for smaller trees with reduced competition. This could counteract increased post-harvest mortality, especially if windthrow mortality is the dominant part of post-harvest mortality.

The EMEND (Ecosystem Management Emulating Natural Disturbance) experiment in northwestern Alberta (Volney et al., 1999) is among the largest and longest-running experiments assessing ecological consequences of partial harvest to different retention levels, and is providing critical information to guide sustainable management of boreal forests (Gustafsson et al., 2012). In this paper, we expanded upon previous work about mortality of residual trees at EMEND (Solarik et al., 2012) to examine the effects of retention level, tree level characteristics, site wetness, and their interactions on both post-harvest tree growth rates and survival probability across species and cover types. The data analyzed here are from a dispersed retention treatment where retained trees were chosen according to a consistent prescription and relatively evenly distributed in space (see *Materials and methods*). Specifically, our study focused on the following two objectives: (1) model growth rates and survival probabilities over 10-years following partial harvest using retention level, tree diameter, tree crown length, site wetness, and potential interactions between retention level and the other covariates, and (2) better understand variation in post-harvest growth and survival responses among species and cover types.

2. Materials and methods

2.1. Study site

The EMEND experimental site is located on the boreal mixedwood plain, approximately 90 km northwest of Peace River, Alberta (56°46′13″N, 118°22′28″W) with elevation ranging from 677 to 880 m asl. Data collected 1981–2010 at a nearby weather station (Eureka River, 56°29′N, 118°44′W) give a mean annual precipitation of 440 mm with 65% of this occurring during the growing season from May to September. Mean annual temperature is 0 °C, with a January mean of −16.9 °C and a July mean of 15.0 °C (Environment Canada, 2013). EMEND includes approximately 1000 ha of treated compartments embedded within a c. 24 km^2 forested landbase. Forests at EMEND fall into four cover types according to the proportions of dominant overstory trees: (1) deciduous-dominated stands (DD), which have > 70% deciduous trees (mainly trembling aspen and balsam poplar (*Populus balsamifera*)) in the canopy, (2) deciduous stands with coniferous understory (DU), as in DD but with understory of white spruce (*Picea glauca*) at least 30% as tall as canopy at the time of harvest, (3) mixedwood stands (MX), which have both deciduous and coniferous components comprising 40–50% of the canopy trees, and (4) coniferous-dominated stands (CD), which have > 70% coniferous trees (mainly white spruce) in the canopy. Stand age within each of the four cover types was relatively homogenous and the mean age of DD, DU, MX, and CD stands when the harvests were applied was ~80, 80, 100, 125 years, respectively (Spence and Volney, 1999). A summary of pre-treatment stand structure for each cover types can be found in Table 1. Experimental compartments (each c. 10 ha in size) were established in previously unmanaged natural stands in the summer of 1998, and during the winter of 1998–99, a set of harvest treatments was applied across these compartments. Retention levels (percentage of retained stems) within compartments were set at 10%, 20%, 50%, 75%, and 100% (unharvested control), and three replicate compartments for each retention level were distributed over three blocks in each of the four cover types (Fig. S1). Mean post-harvest tree densities for these retention levels were 238, 368, 431, 658, and 1068 living trees per ha with diameter at breast height (DBH) ≥5 cm, respectively. Retention harvesting was conducted using north-south facing 5-m-wide machine corridors that alternated with 15-m-wide retention strips. All trees within machine corridors and a prescribed proportion of trees within retention strips were harvested to achieve experimentally desired levels of dispersed retention. A 75% retention level was created by only machine corridors through compartments. Lower retention levels were achieved by harvesting additional trees, strictly in the order encountered and regardless of species, from the retention strips at the following ratios: 1:2 (cut:left) for 50% retention, 3:1 for 20% retention, and 7:1 for 10% retention (see Work et al., 2010 for fuller account of design).

2.2. Tree survival and growth

Six permanent plots (2 × 40 m each) were randomly located 40 m or more from the edges of each compartment in mid-late summer 1998 before harvest treatments were applied. All plots were oriented perpendicular to the machine corridors so as to include equivalents of two 5-m-wide machine corridors and two 15-m-wide retention strips. All living trees in these permanent plots with DBH ≥ 5 cm were tagged and measured, and most plots were re-visited in 1999 (to establish post-

Table 1
A summary of pre-treatment compartment-level stand structure for the four cover types.

	Basal area (m^2/ha)		DBH (cm)		Maximum height (m)		90% quantile of tree height (m)	
Cover type	Mean	SE	Mean	SE	Mean	SE	Mean	SE
DD	35.34	1.56	23.37	0.94	28.91	0.57	25.40	0.23
DU	47.30	1.47	21.09	1.16	29.13	1.02	25.59	0.77
MX	45.50	1.76	26.65	1.80	33.10	0.74	28.97	0.85
CD	45.15	2.84	26.36	1.31	32.19	0.71	28.64	0.48