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Economic analysis of forest management alternatives: Compositional objectives, rotation ages, and harvest methods in boreal forests

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ABSTRACT

Timber production and economic gain are important forestry objectives. Boreal forests have long been an important contributor to commodity products. However, in recent decades, commercial production in the boreal forest industry is undergoing a fundamental shift from traditional wood products to multiple value-added products including residues for bioenergy production. In order to help decision makers select economically optimal forest management alternatives, we conducted an empirical study, the first of its kind, to explore the impact of varying silvicultural intensities, forest compositions, rotation ages, and harvest methods on profits in a portion of boreal forest in Northwestern Ontario. We found that silvicultural intensity, forest composition, rotation age, and harvest method significantly affected profit. The profit was on average the highest from coniferous stands, followed by mixedwood and broadleaved compositions. The profits in mixedwood stands increased continuously with rotation age using both Full-Tree to Roadside Tree-Length-to-Mill harvesting method (FT-TL) and Full-Tree to Roadside Shortwood-to-Mill method (FT-SW), and increased with rotation age but decreased at late-succession stage using Cut-to-Length method (CTL). The profits were on average higher using FT-TL than using FT-SW and CTL. The maximum profit ($3305/ha) was solved for low silvicultural intensity (conifer – conifer), with a rotation age of 100 years, using the FT-TL harvest method. This analysis provides an example of finding economically optimal forest management solutions.

1. Introduction

As one of the world's most important bio-geoclimatic areas (Bradshaw et al., 2009; Brandt, 2009), boreal forests account for 30% of global terrestrial phytomass and constitute approximately 45% of the global growing stock of timber, which is an important source of economic gain (Vanhanen et al., 2012). Boreal forests in Canada comprise about one third of the global boreal forest area (Canadian Council of Forest Ministers, 2005), and contribute significantly to the Canadian economy (Thompson and Pitt, 2003; Wagner et al., 2006). Although boreal forests have been primarily used for production of commodity products such as lumber, pulp and paper products, in recent decades, commercial production in boreal forest industry is undergoing a fundamental shift from traditional wood products to multiple value-added forest products, including increasing economic potential of forest residues for bioenergy production (Mabee et al., 2011; Puddister et al., 2011; Thiffault et al., 2011). This shift is in line with the changing demand trends of global markets in natural resource consumption (Foley et al., 2005).

In order to produce a range of value-added products from forest fibre, a number of forest management alternatives with different economic gains have been applied to the boreal forests (Pyorala et al., 2014). Previous economic analyses have mainly focused on the impacts of individual silvicultural treatments (Bell et al., 1997; Tong et al., 2005; Cao et al., 2008; Mathey et al., 2009; Lindenmayer et al., 2012; Pyorala et al., 2014; Halbritter and Deegen, 2015; Tahvonen, 2016). Review of financially viable, intensive forest management alternatives for broadleaved stands (Anderson and Luckert, 2007), stand-level of a profit maximization with the optimal rotation age and harvest volume (Yin and Newman, 1997; Yin and Sedjo, 2001), stand-level economic analysis comparing the net present values of various silviculture activities and harvesting prescriptions of boreal mixedwoods (Rodrigues, 1998), and financial analysis of several alternative management scenarios of boreal mixedwoods (Yemshanov et al., 2015) have also been reported. However, the combined effects of silvicultural intensity, forest composition, rotation age and harvesting method associated with forest management alternatives remains unexplored.

Forest management alternatives include a range of silvicultural operations and intensities to achieve specific objectives (e.g., stand structure, density, composition, rotation age, and control of site

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productivity) that can provide a framework for decision making on economic gains from forestry operations (Bell et al., 2008; Duncker et al., 2012). Forest management alternatives in the boreal forest include two dominant regeneration methods (natural and artificial) to control changes in species composition from the current stand condition to the desired stand condition. Site preparation, planting or seeding, tending, and thinning are silvicultural operations manipulated to different intensities in renewing the forest and achieving different forest compositions (Fu et al., 2007; Bell et al., 2008). Where pre-disturbance composition contains a broadleaved species, no silviculture, low and high silvicultural intensities usually lead to broadleaved, mixedwood, and coniferous stands, respectively (Soalleiro et al., 2000; Montigny and MacLean, 2006).

Silvicultural intensity associated with controlling species composition can affect fibre production and tree growth in boreal forests (Montigny and MacLean, 2006; Bell et al., 2008). Coniferous and broadleaved species usually generate wood products with different qualities and values, therefore the economic returns differ strongly among forest stands with different tree species compositions. Coniferous species are usually harvested for saw logs, while the majority of broadleaved tree species are harvested for pulp logs and bioenergy with relatively lower economic values (Mathey et al., 2009). As for gross total volume, mixed-species stands may be more productive than the average of single-species counterparts at late stages of forest succession in both managed and natural forests (Knoke et al., 2008; Zhang et al., 2012). In addition, mixed plantations are less vulnerable to disturbances such as insect outbreaks or disease (Jactel and Brockerhoff, 2007), and may have a lower financial risk (Yachi and Loreau, 1999). However, when considering costs, monocultures could be more efficient and cheaper to manipulate and produce homogenous products (Paquette and Messier, 2009), while mixed-species stands have higher harvesting costs per unit volume due to demand for higher harvester skill levels and logistical difficulties in operations (Royer-Tardif and Bradley, 2011).

The choice of forest rotation age (i.e., one complete growing cycle of economic products) also directly impacts the product mix through size and distribution of trees in the stand (Liski et al., 2001; Asante and Armstrong, 2012). While searching for the optimal rotation age with maximum biomass production is the key to developing an economically productive forest, short rotations motivated by short-term profits may result in degraded forest stands that do not contribute to long-term ecological health and social benefits (Erickson et al., 1999). Although longer ecological rotations may not be economically optimal in terms of mean annual timber production (Pyorala et al., 2014), they may one day yield additional value from higher quality wood products, while also contributing to maintaining objectives related to biodiversity and ecosystem functioning, including maintenance of gap dynamics stage, accumulation of soil organic matter, and provision of biodiversity and social benefits (Curtis, 1997; Erickson et al., 1999; Harmon and Marks, 2002; Thompson et al., 2009). However, tree mortality increases with forest ageing (Luo and Chen, 2011), accompanied with reduced net biomass production (Pretzsch et al., 2014; Chen et al., 2016a). Long rotation ages could also result in decayed wood with low merchantable volume and economic value (Willcocks et al., 1997).

While wildfire is the major stand-replacing natural disturbance in the boreal forest (Landres et al., 1999; Ward et al., 2014), anthropogenic disturbances, primarily harvesting, also play an important role in shaping forest structure and composition, both of which affect merchantable volume. In Canadian boreal forests, full-tree harvesting (i.e., removing the entire above-stump portion of the tree including tops and branches from site to maximize biomass extraction from the forests) and stem-only harvesting (cut-to-length or tree-length for saw logs and pulp logs, leaving logging residues including tops and branches on site) are common operations (Canadian Council of Forest Ministers, 2005). Increased demand for forest residues in bioenergy is better suited to a full-tree harvesting system with a lower harvesting cost (Mabee et al., 2011; Puddister et al., 2011; Thiffault et al., 2011). Although stem-only harvesting provides a slightly better benefit in terms of lumber recovery per cubic metre, net revenue from the full-tree harvesting is higher (Plamondon and Pagé, 1997; Adebayo et al., 2007).

Despite the diverse forest management alternatives associated with varying silvicultural intensities, compositional objectives, rotation ages, and harvest methods used in boreal forests (Soalleiro et al., 2000; Montigny and MacLean, 2006; Saunders and Arseneault, 2013), there exists no comprehensive economic analysis exploring economic efficiency and profitability associated with forest management alternatives. In order to provide decision makers with an empirical evidence that might help select optimal forest management alternative, we analyzed how different forest management alternatives affect the profits ($/ha). The specific objectives are: (i) to determine the impact of silvicultural intensity on compositional objectives, (ii) to assess gross total volume (GTV; m^3/ha) and net merchantable volume (NMV; m^3/ha) from stands of different species compositions, rotation ages and harvesting methods, and (iii) to estimate the costs and profits associated with different combinations of forest management alternatives.

2. Materials and methods

2.1. Study area and data collection

Our study area is located north of Lake Superior and west of Lake Nipigon, approximately 100 km north of Thunder Bay, Ontario, Canada, between 49°44′N and 49°65′N, and 89°16′W and 90°13′W. This area is characterized by warm summers and cold, snowy winters. A mean annual temperature of 1.9 °C and mean annual precipitation of 824.8 mm were recorded at the closest meteorological station in Cameron Falls, Ontario, Canada (Environment Canada, 2015). Dominant tree species include trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh), jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* (L.) Mill.). Broadleaved and coniferous stands were defined as having > 65% broadleaved or coniferous tree species composition by basal area, while all other stands were classified as mixedwood stands (Hume et al., 2016). Stand replacing wildfire is the dominant natural disturbance in the study area, with an average fire return interval of approximately 100 years, resulting in a mosaic of stand ages in the area (Senici et al., 2010). There has been a 40-year history of commercial logging with diverse harvest methods in the study area (Shrestha and Chen, 2010).

We randomly selected chronosequences of stands in four age classes: 34, 99, 147, and 210 years since fire with the use of forest resource inventory maps (Table 1), representing late stem exclusion, early canopy transition, late canopy transition, and gap dynamic stages of stand development, respectively (Chen and Popadiouk, 2002). Within each of the selected stands, we established a randomly located 0.04-ha (11.28-m radius) fixed-area circular plot, located > 50 m from the forest edge, to represent the stand (Luo and Chen, 2015). The stands were allocated several kilometers apart from each other to ensure that the sampled stands were interspersed and spatial autocorrelation and edge effects were minimized (Legendre and Legendre, 1998; Harper et al., 2005). We recorded the species, diameter at breast height (DBH, 1.3 m above root collar), and total heights of all trees within each plot. Basal area by species was summed at the plot level and then scaled up to per ha.

2.2. Forest management alternatives

In order to explore the impacts of silvicultural intensity on species composition, rotation age, and harvesting method on economic profitability, we examined three initial stand conditions (defined as species compositional types: broadleaf, mixedwood, and conifer), silvicultural intensities (no, low, high) leading to three compositional objectives (broadleaf, mixedwood, and conifer), eight rotation ages (50, 75, 80,