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Climate change impacts on boreal forest timber supply

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A B S T R A C T

Recent studies have assessed the ecological effects of climate change on boreal forests; however, our understanding of the economic impacts of climate change on timber supply remains limited. Forestry is an important boreal industry; hence, it is necessary to better understand the ecological impacts that directly and indirectly affect this sector. We reviewed published literature concerning ecological impacts of climate change on biome shifts, regional forest disturbances, and tree growth, mortality and species compositional shifts in established forest stands. Subsequently, we examined how each factor influences timber supply and forestry. Tree species ranges have been and will continue migrating north to find more suitable growing conditions, but at a slower rate than climate change. Biome shifts from forests to shrub or grasslands may occur under persistent drought conditions. Warmer temperatures and lower climate moisture availability increase forest disturbances; notably fire and insect outbreaks, creating younger forests dominated by pioneer species and limiting harvestable material. While tree growth and mortality rates are spatially variable across established forest regions, tree mortality has temporally increased with climate change; accompanied by reduced growth or increased growth at a rate lower than mortality loss, resulting in a reduced rate of volume accumulation and timber available for harvest. Moreover, climate change favors pioneer species (*Pinus* spp. and *Populus* spp.) over late successional species (*Picea* spp. and *Abies* spp.). Our findings suggest that climate change has strong negative effects on boreal timber supply but may prompt operational adaptations, opening opportunities for forest industry to incorporate species such as *Populus*.

1. Introduction

The boreal forest is one of Earth's largest forest biomes, with an area of 1.2 billion hectares; stretching from Russia, across Scandinavia and throughout North America (van Lierop et al., 2015). The boreal forest constitutes approximately 30% of the world's most densely forested area (Crowther et al., 2015), while storing nearly half of the global forest carbon, primarily within soils (Gauthier et al., 2015a; Soja et al., 2007). This forest region is immensely critical to the global timber products market. Roughly 33% of lumber and 25% of paper exports in the global market originate from the boreal forest (Gauthier et al., 2015a). However, most ecological functions and processes, such as tree growth, proceed slowly in the boreal forest due to short growing seasons with severe, cold winters (Fettig et al., 2013; Kellomaki, 2000). Despite similar presences of tree genus (*Picea, Pinus, Populus, Larix,* and *Betula*), disturbance regimes and management histories and strategies differ between Eurasian and North American boreal forest regions (Gauthier et al., 2015a; Rogers et al., 2015; Schaphoff et al., 2016).

Climate change has a profound impact on global forestry, and continues to accelerate with increasing anthropogenic greenhouse gas emissions (IPCC, 2014). Higher latitudinal areas are expected to undergo the largest increases in temperature (Diffenbaugh and Field, 2013) and experience variable shifts in precipitation regimes (Gauthier et al., 2015a; Reyer et al., 2015). Changes in site conditions and frequency of disturbance regimes have also affected the boreal forest as a result of climate change (Price et al., 2013). Understanding climate change impacts on boreal forest dynamics and timber supply is crucial to the continued viability of boreal forest industry.

Timber supply, defined in this review as the quality and quantity of standing timber available for harvesting, directly impacts the forest industry; in both the short run and long run. The difference between the two timelines is the amount of time required to transition between capital investments in equipment and product development (Zhang and Pearse, 2011). Short run supply occurs within a timeframe that is too short for industry to adjust their capital stock and standing timber inventory; slower growth rates and higher rotation ages (particularly in the boreal forest) slow this process. This lack of flexibility means that industry can only adjust their variable inputs (fuel and labour) or utilize their facilities more intensively. In the long run, industry is able to reinvest in profitable areas and change supply to better suit the market

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(Zhang and Pearse, 2011). The duration of the long run depends on products (lumber or engineered wood products), industry (logging or pulp and paper) and geographic location (boreal forest or tropical). However, long run timber supply is difficult to anticipate because of a number of factors that affect trees: growth and mortality rates, disturbances, harvesting rotation schedules and demand of forest products (Zhang and Pearse, 2011). Climate change further complicates this process of product evaluation and timber supply (Sohngen, 2014). Analyses of the impacts of climate change on boreal timber supply should involve both short term and long-term research to properly forecast the implications of ecological change on the economy.

Recent advances have been made toward understanding climate change impacts on forest productivity, species range shifts and forest disturbances (Boisvenue and Running, 2006; Hofgaard et al., 2013; Kurz et al., 2008), though there have been few publications synthesizing these impacts. Several published reviews on the boreal forest and climate change include: global boreal forest health (Gauthier et al., 2015a), impacts to North American forests and ecosystems (Price et al., 2013), implications to forest carbon balance (Kurz et al., 2013; Schaphoff et al., 2016), forestry adaptation practices (Gauthier et al., 2014), and a recently proposed concept of using biodiversity to mitigate climate change impacts on ecosystem functioning (Hisano et al., 2018). However, the impact of climate change on industrial timber supply and its economic implications is an area that demands continued investigation. The existing forestry related reviews suggested that there would likely be increases in global timber supply (though high regional variation) from greater forest productivity (Kirilenko and Sedjo, 2007) leading to probable decreases in wood product prices and demand (Sohngen and Tian, 2016).

Modeling studies have addressed the economic impacts of climate change in specific countries or regions (Mendelsohn et al., 2000; Ochuodho et al., 2012; Solberg et al., 2003), whereas others have considered the forest industry in a global context (Lindner et al., 2002; Perez-Garcia et al., 2002; Sohngen et al., 2001; Tian et al., 2016). Older global timber models suggest higher timber productivity from tropical regions, compared to temperate regions with on-going climate change (Perez-Garcia et al., 2002; Sohngen et al., 2001), whereas, the latest global timber model predicts a similar overall increase in forest productivity in both regions (Tian et al., 2016). Generally, timber resources are expected to increase across the globe and result in lower product prices (Sohngen and Tian, 2016; Tian et al., 2016). However, empirical evidence from tropical forests revealed that climate change has led to greater biomass loss through tree mortality than growth gain, resulting in less standing biomass (Brienen et al., 2015). Further, these studies typically simulated consistent future disturbance regimes possibly leading to yield inaccuracies (McKenney et al., 2016). Nevertheless, these modeling studies do not specifically analyze the productivity of the boreal forest under climate change; rather they have focused on temperate and tropical forests. Therefore, modeling climate change impacts on boreal forest timber supply remains needed.

The purpose of this review is to synthesize the impacts of climate change on boreal forest dynamics directly relating to available timber supply (Fig. 1). Specifically, this review will: i) examine how climate change has affected boreal ecological processes at a variety of spatial scales (biome, regional, stand and individual levels), since the impacts to ecological processes differ across scales, ii) analyze how these ecological changes will impact timber supply, iii) detail management adaptations, and iv) identify gaps in current knowledge for future research.

2. Literature selection criteria

Papers were systematically selected for this review via the online search engine ISI Web of Science. The reference sections of selected papers were also reviewed for relevant literature. This was done in order to capture all applicable and available literature. Key words including climate change impacts, boreal forest timber supply, and forest sector implications were used in various combinations for the search. Because of the rapid development of the study topic, we focused on reviewing recent literature; largely post 2000. Literature was subsequently analysed, initially by title and abstract, and then through more in depth reading. Titles were selected by having some mention of climate change and timber supply associated ecological processes including biome shift, range shift, species composition, disturbance, growth, and mortality. Papers that did not explicitly address climate change were excluded. Both reviews and original articles were considered to gather evidence from a range of perspectives. Topics were divided into themes and research was synthesized to explain the various ways climate change impacts boreal timber supply (Fig. 1).

3. Biome shifts

Biome shifts represent a landscape's transition over time from one biome to another, such as forest biome to shrub land and/or grassland biome (Beck et al., 2011). Biome shifts are adaptations that take place between vegetation types and contrasting climates (Donoghue and Edwards, 2014); the process of transition is dependent on the state of an ecosystem and the speed of climate change. In high latitude systems, biome shifts have been observed over temporal scales of multiple years or decades (Beck et al., 2011). Climate is a key factor toward determining the geographic distribution of plant species (Fei et al., 2017; Fettig et al., 2013). As the climate changes, sites can become less suitable for certain plant species over time causing them to regress or die, whereupon other more suitable species take their place (Gonzalez et al., 2010). Biome shifts tend to occur along the edge of biomes (Davis and Shaw, 2001), as evidenced by the transition from forests to shrub lands under extended droughts (Anderegg et al., 2013; Donoghue and Edwards, 2014). Most of the world's forests are regarded as being extremely vulnerable to biome shifts as a result of climate change (Gonzalez et al., 2010), which stresses the importance of understanding the risks of shifting biomes.

Boreal forests have been seen steadily migrating northward in response to global warming. Researchers have observed shifts in plant and animal species ranges for decades, signifying the effect of changing climate (Chen et al., 2011; Parmesan and Yohe, 2003). Tree migration has been observed most clearly in areas with temperature extremes,

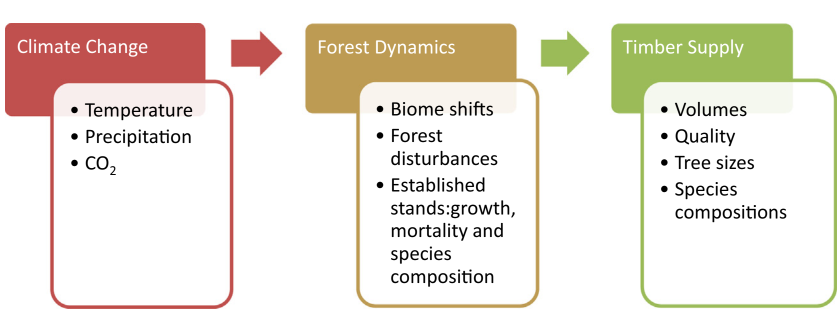

Fig. 1. A simple representation of the focus for this review and the related factors and variables associated with each. Climate change (changes in temperature, precipitation and CO_2 levels) will influence forest dynamics (growth, mortality, species range and disturbance interactions) which then impact the volume, quality, and species of timber supply available for industrial harvest and use in the boreal forest.