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Incorporating uncertainty into forest management planning: Timber harvest, wildfire and climate change in the boreal forest

Colin J. Daniel [a,b,*], Michael T. Ter-Mikaelian [c], B. Mike Wotton [d], Bronwyn Rayfield [b], Marie-Josée Fortin [a]

[a] Department of Ecology & Evolutionary Biology, University of Toronto, 25 Willcocks St., Toronto, ON M5S 3B2, Canada
[b] Apex Resource Management Solutions, 937 Kingsmere Ave, ON K2A 3K2, Canada
[c] Ontario Forest Research Institute, Ontario Ministry of Natural Resources and Forestry, 1235 Queen St. E., Sault Ste. Marie, ON P6A 2E5, Canada
[d] Canadian Forest Service – Natural Resources Canada, Faculty of Forestry, University of Toronto, 33 Willcocks St., Toronto, ON M5S 3B3, Canada

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ABSTRACT

In an effort to ensure the sustainability of their forests, boreal forest managers often use forest planning models to make future projections of timber supply and other key services, such as habitat for wildlife. Projecting the fate of these services has proven to be challenging, however, as major uncertainties exist regarding the principal drivers of boreal ecosystem dynamics, including the future spatial and temporal distribution of wildfire and timber harvesting. Existing forest planning models are not well suited to dealing with this uncertainty because they produce deterministic projections based on central tendencies of these drivers.

Here we present a new approach for incorporating uncertainty into forest management planning, which we demonstrate using two landscapes in the Canadian boreal forest. Our approach takes the assumptions contained within the latest forest management plans for each of these landscapes, including parameterizations of their deterministic forest planning models, and converts these assumptions into equivalent parameterizations of a stochastic, spatially-explicit state-and-transition simulation model (STSM). We then use Monte Carlo simulations with the STSM to "stress-test" the forest management plan with respect to a range of possible future uncertainties, including uncertainties in future levels and patterns of wildfire and timber harvest, along with the possible changes in wildfire that might result from future climate change.

Our analysis demonstrates the importance of incorporating stochastic variability into projections of future ecosystem condition. The STSM projections that acknowledged variability in wildfire and timber harvest differed from the deterministic forest planning model projections that were based solely on mean values. Our analysis also suggests that there is an increased risk of shortfalls in timber harvest, for both boreal landscapes, associated with future projections for changes in wildfire due to climate change, and that management strategies aimed at reducing the future level of timber harvest offer an opportunity to mitigate these risks. We believe our approach provides a new risk-based framework for incorporating uncertainty into forest management, including the effects of climate change.

1. Introduction

As one of the world's four major forest biomes, the boreal forest contains approximately 30% of the world's forested area, and provides a number of key services, including the provision of wildlife habitat, the sequestration of carbon, and the supply of timber (Brandt et al., 2013). Historically, wildfire has played a dominant role in shaping the dynamics of the boreal forest (Gauthier et al., 2015); in the Canadian boreal forest, for example, wildfire has been estimated to burn an average of 0.7% of the forested land annually (Stocks et al., 2003), with considerable spatial and temporal heterogeneity in this fire regime due principally to variability in weather and climate (Flannigan and Wotton, 2001). In addition to wildfire, over the past several decades the levels of anthropogenic disturbance in the boreal forest have steadily increased (Burton et al., 2010; Venier et al., 2014); over two-thirds of the boreal forest is now considered to be managed forest, much of which includes industrial wood production (Gauthier et al., 2015).

* Corresponding author at: Department of Ecology & Evolutionary Biology, University of Toronto, 25 Willcocks St., Toronto, ON M5S 3B2, Canada.

E-mail addresses: colin.daniel@apexrms.com (C.J. Daniel), michael.termikaelian@ontario.ca (M.T. Ter-Mikaelian), mike.wotton@utoronto.ca (B.M. Wotton), bronwyn.rayfield@apexrms.com (B. Rayfield), mariejosee.fortin@utoronto.ca (M.-J. Fortin).

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Consequently, timber harvesting – namely clearcut logging – has become as important a driver of forest dynamics as wildfire in many parts of the boreal forest (Brandt et al., 2013; Venier et al., 2014).

Current climate-change projections suggest that the boreal forest will undergo greater warming than any other forest biome (Price et al., 2013; IPCC, 2014). As a result there is considerable uncertainty regarding the effect climate change may have on the tree communities of the boreal forest, and how these changes may impact the boreal forest's ability to provide key services (Gauthier et al., 2015). Several studies have suggested that the projected increases in temperature due to climate change will lead to an increase in the amount of wildfire in the boreal forest (Bergeron et al., 2010; Price et al., 2013). There is, however, considerable uncertainty regarding the extent of this projected increase in wildfire. In the province of Ontario, Canada, for example, projections for the increase in area burned over the next 100 years range from as low as 1.7 to as high as 8 times the current area burned (Flannigan et al., 2005; Balshi et al., 2009; Podur and Wotton, 2010; Boulanger et al., 2014).

As with all human-influenced ecosystems, quantitative models play an important role informing policy and management decisions in the boreal forest, by projecting the future consequences of human actions – in particular forestry management activities – on the structure and composition of the forest (Messier et al., 2003; Carpenter et al., 2009). To date, most forest management plans in the boreal forest are based on projections from a family of quantitative models known as "forest planning" (also called "harvest scheduling" or "forest management") models (Bettinger and Chung, 2004; Boston et al., 2015). These models use linear programming and other heuristic optimization techniques to generate a single deterministic projection for a future harvest schedule, over space and time, that optimizes some objective function (e.g. total value of timber harvested), subject to a series of constraints, such as silvicultural budgets, operational constraints, and targets for future forest condition (Gunn, 2007; Bettinger et al., 2009). Examples of software products that follow this approach, and are widely used in boreal forest management planning, include Woodstock (Walters et al., 1999; Remsoft, 2016), Patchworks (Lockwood and Moore, 1993; Spatial Planning Systems, 2016) and the Strategic Forest Management Model (Davis, 1993; Kloss, 2002).

A key challenge when using a quantitative model for forecasting the future is how to handle the "cascade of uncertainties" (Pilkey and Pilkey-Jarvis, 2007) regarding the modelled system's behaviour, as these uncertainties can have a significant impact on a model's projections, and thus on the management decisions that rely on these forecasts (Clark et al., 2001; Messier et al., 2016). Uncertainty can come in several forms (Morgan and Henrion, 1992), including: (1) uncertainties regarding our understanding of the underlying processes, and thus the structure of the models; (2) uncertainty in the values for the various parameters driving the model dynamics; and (3), the so-called unknown unknowns, or "ecological surprises" (Williams and Jackson, 2007) – i.e. uncertainties for which we have as of yet little or no knowledge, including the possible effects of a changing climate and the future human responses to ecosystem change (Carpenter, 2002). Because forest planning models are generally deterministic, providing only a single projection for future forest condition for a given set of model assumptions, it can be difficult to incorporate uncertainties, including the effects of climate change, into their projections. While various studies have explored incorporating uncertainties regarding wildfire into forest planning models, to-date it has proven challenging to translate these efforts into applied forest management (Bettinger, 2010). Consequently, forest managers today have been left in a difficult position – knowing the future is uncertain, yet not having the tools to adequately deal with this uncertainty.

One approach that is commonly used to project the effects of uncertainties across forested landscapes is simulation modelling, whereby the consequences of uncertainty can be assessed by varying model assumptions across a range of alternative "what-if" future scenarios (Bettinger, 2010; Norton, 2015). A wide range of simulation models has been developed for use with forested landscapes (Keane et al., 2004; Wimberly et al., 2015); however, because most of these simulation models include assumptions regarding forest dynamics that differ from those typically used in forest management planning models, historically it has been difficult for forest managers to integrate the projections of these models into their existing forest management planning process. One particular approach to simulation modelling, known as a *state-and-transition simulation model* (STSM; Daniel et al., 2016), offers the possibility of overcoming this divergence between forest planning and landscape simulation models. The STSM method divides a landscape into a set of spatial units, and then simulates the state class and age of each spatial unit forward in time as a discrete-time, non-stationary stochastic process, in response to discrete transitions, using a Monte Carlo approach. STSMs have been applied to a wide range of questions and ecological systems (Kerns et al., 2012; Wilson et al., 2014), including forested landscapes (e.g. Costanza et al., 2015; Miller et al., 2015; Costanza et al., 2017). Because of their general, empirical approach for representing vegetation dynamics, along with their inherent representation of stochasticity, STSMs offer the prospect of developing scenario-based simulation models that remain true to a forest planning model's assumptions of forest dynamics.

In this paper, we show how uncertainty can be integrated into forest management planning using a stochastic, spatially-explicit STSM. Our objectives with this approach are twofold: (1) to account for a range of future uncertainties, including those that might reasonably be characterized based on past patterns (e.g. spatial and temporal variability in wildfire), and those for which our understanding is more speculative (e.g. effects of climate change); and (2), to do so in a way that is directly connected to existing forest management planning models, and thus relevant to forest managers. We illustrate our approach using two study areas in the managed portion of the Canadian boreal forest. For each study area, we start with an existing forest management plan, including its associated parameterization of a deterministic forest planning model using historic mean fire cycles. We then demonstrate how the ecological and management assumptions contained within this plan can be reproduced in a corresponding STSM. The resulting stochastic representation of the forest management plan is then used to "stress-test" this plan with respect to future uncertainties in wildfire, in order to assess the risk to the future supply of timber. Finally, we explore how the results of these analyses can provide guidance to managers with respect to actions that could be taken to potentially mitigate the future risks with respect to timber supply.

2. Material and methods

2.1. Study areas

Our study areas consist of two provincial Forest Management Units within the boreal forest region of the province of Ontario, Canada: the 1,013,000 ha Trout Lake Forest (TLF), centred at 51.04°N and 92.79°W, and the 718,000 ha Caribou Forest (CF), centred at 50.67°N and 90.67°W (Fig. 1). Characterized by their location on the Canadian Shield, the bedrock geology of both landscapes consists of Precambrian granitic and metamorphic rocks; topography in both landscapes is rolling, with elevations ranging from 360 to 490 m above sea level. Soils in both landscapes are characterized by a mix of well-drained sand/gravel uplands and