Forest Ecology and Management 405 (2017) 284–294

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Rapid 21st century climate change projected to shift composition and growth of Canada's Acadian Forest Region

Anthony R. Taylor[a,*], Yan Boulanger[b], David T. Price[c], Dominic Cyr[b], Elizabeth McGarrigle[d], Werner Rammer[e], John A. Kershaw Jr.[f]

[a] Natural Resources Canada, Canadian Forest Service - Atlantic Forestry Centre, 1350 Regent Street, P.O. Box 4000, Fredericton, NB E3B 5P7, Canada
[b] Natural Resources Canada, Canadian Forest Service - Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Québec, QC G1V 4C7, Canada
[c] Natural Resources Canada, Canadian Forest Service - Northern Forestry Centre, 5320 122nd Street NW, Edmonton, AB T6H 3S5, Canada
[d] Nova Scotia Department of Natural Resources, Forestry Division, 15 Arlington Place (Suite 7), Truro, NS B2N 0G9, Canada
[e] Institute of Silviculture (Institut für Waldbau), Department of Forest and Soil Sciences, BOKU - University of Natural Resources and Life Sciences, Vienna, Peter Jordanstr. 82, A-1190 Wien, Austria
[f] Faculty of Forestry and Environmental Management, University of New Brunswick, P.O. Box 4400, 28 Dineen Drive, Fredericton, NB E3B 5A3, Canada

ARTICLE INFO

Keywords:
Climate change
Succession
Community
Growth
Biomass
Modeling
Process-based
Boreal
Temperate

ABSTRACT

The impact of climate change on forests is expected to vary globally and regionally. Canada's Acadian Forest Region lies in the transition between the North American boreal and temperate forest biomes and may be particularly sensitive to changes in climate because many of its component species are currently at their southern or northern climatic range limits. Although some species may be lost, others may exhibit major productivity boosts—affecting the goods and services we derive from them. In this study, we use a well-established forest ecosystem simulation model, PICUS, to provide the first exploration of the impact of climate change on the composition and growth of the Acadian Forest Region for the period 2011 to 2100 under two radiative forcing scenarios, RCP 2.6 and RCP 8.5.

In the short term (2011–2040), little to no changes in forest composition or growth were projected under either forcing scenario compared with current forest conditions (simulated for 1981–2010 baseline climate); however, by mid-century, PICUS projected increasing departures from the baseline simulations in both composition and growth, with the greatest changes occurring under RCP 8.5 during the late 21st century (2071–2100). Our study indicates that under rapid 21st century warming, Canada's Acadian Forest Region will begin to lose its boreal character (i.e., "deborealize") as key tree species fail to regenerate and survive. Furthermore, increased growth and establishment by warm-adapted, temperate tree species may be unable to keep pace with the rapid loss of boreal species. This potential "lag effect" may lead to a temporary decrease in forest growth and wood supply during the late 21st century.

1. Introduction

Global temperatures have warmed significantly since the beginning of the industrial revolution, with 2016 being the warmest year to date (NOAA, 2017). Already, some North American forests are showing signs of climate-induced changes, including alteration to physiological processes and natural disturbance regimes (e.g., Michaelian et al., 2011; Girardin et al., 2014). Future impacts are expected to vary regionally across North America with some areas facing decreases in forest productivity, due to increased drought and insect outbreaks, while other areas may experience boosts in growth and diversity (Vose et al., 2012; Charney et al., 2016; D'Orangeville et al., 2016), implying that successful adaptation of forest management practices will require local-scale knowledge of the responses of forest structure and function to changes in climate (Price et al., 2013; Franklin et al., 2016).

Eastern Canada's Acadian Forest Region (Rowe, 1972; Loo and Ives, 2003) is part of an ecological transition zone occurring along the United States–Canada border area that links conifer-dominated boreal forest to the north with temperate deciduous forests to the south. Such transition zones are considered particularly susceptible to changes in tree species growth and other drivers of stand-level competition because many species that coexist in these ecosystems are close to their extreme

* Corresponding author.
E-mail addresses: anthony.taylor@canada.ca (A.R. Taylor), yan.boulanger@canada.ca (Y. Boulanger), david.price@canada.ca (D.T. Price), dominic.cyr@canada.ca (D. Cyr), emcgarrigle@gmail.com (E. McGarrigle), werner.rammer@boku.ac.at (W. Rammer), kershaw@unb.ca (J.A. Kershaw).

http://dx.doi.org/10.1016/j.foreco.2017.07.033
Received 14 March 2017; Received in revised form 19 July 2017; Accepted 21 July 2017
Available online 27 September 2017

southern or northern climatic limits (Heyder et al., 2011; Fisichelli et al., 2014). Climate-driven influences on competitive interactions are expected to cause changes in forest composition (Adler et al., 2012; Price et al., 2015; Reich et al., 2015); for example, cold-adapted boreal conifers, such as balsam fir (*Abies balsamea* L.) and black spruce (*Picea mariana* (Mill.) B.S.P.), which are currently at their southern limit in the Acadian Forest, are likely to compete poorly under a warming climate, decreasing in both growth and abundance (Bourque and Hassan, 2008; Girardin et al., 2015; Pedlar and Mckenney, 2017). Conversely, temperate species, such as red maple (*Acer rubrum* L.) and red oak (*Quercus rubra* L.), are expected to benefit from warming, allowing them to compete more successfully (Iverson et al., 2008; Rogers et al., 2016). This could potentially cause a shift in the overall composition of the Acadian Forest toward dominance by temperate species. Even though temperate species can be expected to perform better in a warmer regional climate, the overall growth of the Acadian Forest may still decrease for some period because the rate of climate change projected for the 21st century will likely outpace the ability of southern species to colonize newly available sites and offset decreases in growth from the loss of cold-adapted boreal species (Zhu et al., 2012; Corlett and Westcott, 2013).

Projecting the effects of climate change on forest ecosystems has become a central challenge for global change ecology (McMahon et al., 2011; Franklin et al., 2016). Correlative species distribution models (niche models) are most commonly used to assess species vulnerability to climate change. These models usually project rapid poleward migration of species' suitable habitat under the most aggressive anthropogenic climate forcing scenarios (e.g., Iverson et al., 2008; McKenney et al., 2011b; Rogers et al., 2016). However, these models have well-known limitations that impede their capacity to project future forest conditions, including the inability to account for species population dynamics and community-level interactions (Thuiller et al., 2008; Araújo and Peterson, 2012). Furthermore, known constraints on species dispersal will likely limit the average rate of tree migration (depending also on local terrain and microclimatic conditions) to less than 10–20 km over the next 100 years (Hampe, 2011; Iverson et al., 2011; Corlett and Westcott, 2013). Therefore, understanding how climate change will directly affect the demographics and competitiveness of tree species already present in the Acadian Forest is likely most important for projecting near-term (50–100 years) forest conditions and their implications for forest management (Adler et al., 2012; Zhu et al., 2014; Searle and Chen, 2016).

Several of the limitations of species distribution models may be overcome through the use of process-based forest simulation models (Thuiller et al., 2008; Urban et al., 2016). Landscape-scale forest simulation models (e.g., LANDIS-II, Gustafson et al., 2014) are capable of simulating large areas (10^3–10^7 ha), including spatially explicit simulation of disturbances and tree seed dispersal, but they do so at the cost of simplifying or omitting tree-level details, notably the dynamics and interactions of individual trees which are undoubtedly important in assessing forest responses to climate change (McMahon et al., 2011; Shugart et al., 2015). Alternatively, individual tree-based "forest gap" models (e.g., FORSKA, FAREAST) that simulate the establishment, growth, and mortality of individual trees on a defined unit of forest area (i.e., a forest gap), usually the size of a forest inventory plot (100–1000 m^2) permit simulating the direct effects of climate change on individual species' demographic processes, biotic interactions, and community dynamics (e.g., Price et al., 1999; Shuman et al., 2011).

In this paper, we provide an assessment of the impact of climate change on Canada's Acadian Forest Region using the well-established forest gap model, PICUS (http://picus.boku.ac.at). We used PICUS to explore the impacts of climate change on the composition and growth of the Acadian Forest Region using the "census" technique, whereby regional-level trends may be inferred from a detailed forest gap model by simulating a large number of forest sample plots across the region of interest (Shuman et al., 2011; Shugart et al., 2015).

More specifically, we investigated how two radiative forcing scenarios, known as Representative Concentration Pathways (RCP; van Vuuren et al., 2011), namely RCP 2.6 and RCP 8.5, would affect forest composition and growth. We hypothesized that under the "business-as-usual" high radiative forcing scenario (RCP 8.5), the Acadian Forest would undergo significant change in species composition and corresponding decreases in average growth (current annual increment, $m^3 \cdot ha^{-1} \cdot yr^{-1}$) by the end of the 21st century as the climate becomes increasingly unsuitable for cold-adapted, boreal tree species and outpaces the ability of temperate species to replace them. Conversely, we would expect little to no change in composition or growth due to climate change under RCP 2.6 (the low forcing scenario) as the projected moderate warming is unlikely to perturb the current forest beyond the limits of its natural variability.

2. Material and methods

2.1. Study area

Our study area includes the three Canadian Maritime Provinces: New Brunswick, Prince Edward Island, and Nova Scotia, totaling approximately 10.5 million ha (Fig. 1). The climate is largely determined by prevailing continental westerly winds, but moderated by the Atlantic Ocean, resulting in high humidity, frequently fluctuating weather conditions, mild winters, and cool summers. Mean January and July temperature are −8.2 °C and 17.5 °C, respectively, while mean annual temperature is 5.0 °C with an average annual frost-free period of 150 days. Mean annual precipitation is 1275 mm with approximately 20% of this occurring as snowfall (Environment Canada, 2016). Elevations vary from sea level to roughly 820 m further inland, as much of the study area lies within the northern extent of the Appalachian Mountain range. The high average annual precipitation, combined with cool, humid summers, encourages soil podzolization, resulting in relatively infertile, acidic surface soils in coastal areas. However, soil conditions vary substantially, and many upland ridges and rich river flood plains are well-drained and fertile, supporting high tree species diversity (Loo and Ives, 2003).

The Acadian Forest Region is a unique assemblage of approximately 32 tree species (Rowe, 1972; Loo and Ives, 2003). Red spruce is considered the forest's defining tree species, but other common species include sugar maple (*Acer saccharum* Marsh.), red maple, yellow birch (*Betula alleghaniensis* Britt.), American beech (*Fagus grandifolia* Ehrh.), white ash (*Fraxinus americana* L.), red oak, eastern hemlock (*Tsuga canadensis* (L.) Carrière), red pine (*Pinus resinosa* Ait.), and eastern white pine (*Pinus strobus* L.), which are characteristic of the more southern, temperate forest types. Conversely, white birch (*Betula papyrifera* Marshall), trembling aspen (*Populus tremuloides* Michx.), tamarack (*Larix laricina* K. Koch), jack pine (*Pinus banksiana* Lamb.), eastern cedar (*Thuja occidentalis* L.), balsam fir, black spruce (*Picea mariana* (Mill.) B.S.P.), and white spruce (*Picea glauca* (Moench) Voss), are typically found in the more northerly and cooler boreal forest types.

Large-scale, stand-replacing natural disturbances, such as wildfire, are rare in the Acadian Forest (Seymour et al., 2002). Historical analyses suggest fire played a minor role in the pre-European settlement Acadian Forest, with return intervals of 800 years and longer (Wein and Moore, 1977, 1979). The predominant form of natural disturbance is small, gap-forming perturbations, in which individual trees or small groups of trees succumb to minor blow down, localized insect infestation (mainly spruce budworm outbreaks) and disease, or natural senescence. Because of long intervals between stand replacing disturbances, the historic, pre-European Acadian Forest is estimated to have been > 50% old (> 100 years) forest (Betts and Loo, 2002; Lorimer, 1977). Today, old forests have been reduced to < 5% of the landscape due to colonization, the introduction of non-indigenous pests and diseases, and forest management history (Loo and Ives, 2003).