Available online at www.sciencedirect.com
SCIENCE DIRECT®

Forest Ecology and Management 205 (2005) 169–182

Forest Ecology and Management

www.elsevier.com/locate/foreco

The impact of climate change on growth of local white spruce populations in Québec, Canada

Christophe Andalo[a,b,c,*], Jean Beaulieu[a], Jean Bousquet[b]

[a]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 3800, Sainte-Foy, Que., Canada G1V 4C7
[b]Centre de recherche en biologie forestière, Pavillon Charles-Eugène-Marchand, Université Laval, Sainte-Foy, Que., Canada G1K 7P4
[c]Laboratoire d'Evolution et Diversité Biologique-UMR 5174, Bâtiment IVR3, Université Paul Sabatier, 118 route de Narbonne, 31062 Toulouse cedex 4, France

Received 1 December 2003; received in revised form 31 August 2004; accepted 12 October 2004

Abstract

In the near future, forest tree species growing in eastern Canada are expected to be affected by climate change due to an increase of human-induced greenhouse gas emissions. In this study, models were developed to estimate the impact of climate change on growth in white spruce (*Picea glauca* (Moench) Voss). Data were collected in a genecological test, replicated in three locations, and involving 45 distinct geographical seed sources, most of them represented by five open-pollinated families. Transfer models predicting the performance of seed sources were developed, based on temperature and precipitation differentials between the geographical origin of seed sources and the experimental site locations. These models were validated using data collected in a second genecological test series. We found that white spruce populations located within the sampled area were optimally adapted to their local environment for thermal conditions but not for moisture conditions; populations that originated from sites receiving more precipitation generally showed higher tree growth than the local sources. We predict that the adaptive lag currently related to precipitation will increase under global warming conditions. Simulations of growth under various scenarios of climate change indicated that it would be diminished tangibly under more intense warming. However, for a given temperature increase, the relative loss in growth will be less if precipitation is reduced than if it increases. Consequently, predictions based solely on temperature change appear inaccurate, and more effort should be directed toward better anticipating the magnitude and the direction of changes in precipitation patterns at the regional scale. The necessity of human intervention to assist tree migration under climate change is examined.

Keywords: *Picea glauca*; Genetic response; Growth; Genecological test; Climate change; Local adaptation; Seed sources

* Corresponding author. Tel.: +33 5 61 55 67 59; fax: +33 5 61 55 73 27.
E-mail address: andalo@cict.fr (C. Andalo).

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2004.10.045

1. Introduction

General circulation models (GCM) developed over the last 20 years to estimate the impact of greenhouse gas emissions (e.g., Hansen et al., 1983; Flato et al., 2000) predict a rapid climate change. Following the models' estimates, the mean annual temperature in the northern hemisphere will rise, and patterns of precipitation will be modified. Over the last two decades, many studies have attempted to evaluate the potential impact of these global phenomena on forest ecosystems and more precisely on their composition, functioning and productivity (e.g., in Ontario for North American boreal forest, Papadopol, 2000; Lasch et al., 2002). However, the response of complex biological systems such as forest ecosystems, species or populations is difficult to assess, especially because the magnitude and the direction of the predicted climate changes at the regional scale remain poorly known (Chen et al., 2003).

Davis and Shaw (2001) underlined the importance of microevolution and migration associated with range shifts in plant response to climate change. The current rate of global warming, together with potential modification of migration through human land use, can threaten adaptation. The prediction of a lag in tree response to change is exacerbated by the long life span of tree species and potential genetic constraints (Etterson and Shaw, 2001), which limit their capacity to respond to selection pressure triggered by rapid environmental change. The study of differentiation in adaptive traits in relation to environmental heterogeneity within a species' natural range should help understand the potential evolutionary response to climate change. Most forest tree species show genetic variation at the regional scale, in response to variation in environmental conditions (Morgenstern, 1996). In this respect, replicated test plantations of seed sources should be helpful to obtain indirect estimates of the potential response of individual species to climate change (Mátyás, 1996). These tests should also be very helpful to quickly identify potential seed sources for assisting populations to maintain their evolutionary potential in the face of environmental change or to colonize new empty favorable sites (Hufford and Mazer, 2003). In these trials, many seed sources from various locations are tested. The performance of any seed source can be expressed in differential terms with regard to that of the local seed source in each test plantation site. One can then develop general transfer models, relating relative seed source performance to geographical or ecological distances existing between the origins of the seed sources and the location of the planting sites. The adaptation of a given seed source to its local environment is assessed by comparing its actual performance with the optimum predicted by the transfer model. The response of local seed sources to climate change can also be simulated by estimating the impact of moving seed sources along environmental gradients within the range of environments covered by the sites available for study. Climate shift associated with the transfer of the seed sources is supposed to mimic scenarios of future climate change. Such studies have been recently carried out for various tree species (Schmidtling, 1994; Carter, 1996; Mátyás, 1996; Persson, 1998; Rehfeldt et al., 1999a,b).

One potential weakness of the recently developed transfer models is that they only use one climatic or one geographic independent variable to predict the responses of seed sources, generally the mean annual temperature or the latitude. Moreover, they are not always validated with independent data sets. In the present study, we developed general transfer functions using multiple regression analysis with both temperature and precipitation predictors, and we employed an extensive validation procedure. General circulation models provide fairly inaccurate estimates of precipitation patterns (Loehle and LeBlanc, 1996; Bergeron et al., 1999). However, since precipitation is one of the main factors affecting forest tree growth and survival, estimates of the response of seed sources to variation in precipitation and in temperature should be useful to obtain more precise estimates of the potential impacts of climate change.

White spruce (*P. glauca* (Moench) Voss) occurs naturally across almost all Canadian territory (Farrar, 1995) and is found as a major forest component in all forested regions except the Pacific coast. This species has a central ecological position in the North American boreal forest and is intensively harvested for lumber production. Actual growth and adaptive traits of local populations could be affected by a change in environmental conditions (Corriveau et al., 1990; Li et al., 1993). Despite its importance for the Canadian economy, very few studies have been carried out to estimate the potential impact of climate change