

CLIMATE CHANGE ADAPTATION STRATEGIES FOR THE TOLERANT HARDWOOD FORESTS OF EASTERN CANADA

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Report for the
Climate Change Impacts and Adaptation Program
Natural Resources Canada

March 31st 2008

ABSTRACT

In this report, we describe the development of adaptation strategies to climate change for the hardwood forest of eastern Canada. At the outset, we felt that it was necessary that the proposed adaptation strategies be socially acceptable over the full known range of potential future conditions, since there is considerable uncertainty about the exact nature of the future climate and about the impacts of climate on hardwood forest ecosystems. These adaptation strategies were developed through the use of a set of modeling tools that are capable of (i) cumulating the effects of multiple disturbance agents over a forested landscape, (ii) simulating various adaptation strategies and predicting their result, (iii) balancing multiple objectives and constraints, and (iv) quantifying the costs and benefits of implementation. The set of modeling tools included a stochastic landscape dynamics model (ImpaCC-1), built specifically for the project, and a spatially-explicit forest management optimization model (Patchworks-Outaouais). The stochastic landscape dynamics model brings together expert knowledge on forest ecology, forest management, tree physiology, insects and disease, silviculture, and climate in order to simulate the dynamics of a forested landscape over time under the influence of succession, climate, harvesting, windthrow, defoliation, disease, and tree planting. This model is innovative, since it models rate-based stand dynamics and integrates several stochastic and deterministic disturbance agents. Results show that, given the state of our understanding, all climate change scenarios lead to serious impacts on the composition and dynamics of the tolerant hardwood forest. The greatest impacts are expected to be caused by beech bark disease. Adaptation strategies are proposed to

minimize these impacts and to promote landscape structure and composition that meet the criteria of the public participation group.

INTRODUCTION

It has become apparent that the climate is changing (IPCC 2001); in fact, evidence is showing that the rate of change is greater than had been expected (Canadell et al. 2007). While effort to limit the future impacts climate change must be stimulated, we as a society must prepare for the eventuality that there will be important changes to the biosphere as a result of human induced climate change.

Over the past decade, many studies have examined the potential impacts of future climate change on forested ecosystems throughout the world (Peng 2000, Foley et al. 2000, Cramer et al. 2001, Knapp et al. 2001, Bakkenes et al. 2002, van der Meer et al. 2002, Yamasaki et al. 2008). Projected impacts to forest ecosystems include the following: modified fire regimes; change in the species composition of forests; increased damage due to windthrow; change in the impacts of existing insects and disease; introduction of exotic species, insects, and disease.

The project had the following objectives:

- to derive a set of forest values that are expected to remain desirable over time (e.g., a productive forest industry, landscape aesthetics, wildlife habitat, recreation) through a process of consultation with regional stakeholders
- to determine the expected impacts of a variety of CC scenarios on the hardwood forest through a concerted and collaborative process of consultation and discussion with domain experts (in silviculture, plant physiology, CC impacts, forest entomology and pathology)
- to develop a phenomenological landscape model that is capable of integrating and scaling up (to the landscape scale) the impacts described by domain experts
- to develop adaptation strategies within the cumulative impacts landscape model that will maintain the set of desirable forest values identified by stakeholders through a process of trial and error
- to develop detailed management plans from these adaptation strategies for the study area, while tracking the costs and benefits
- given the costs and benefits and the relative success of strategies over the range of tested CC conditions, determine the most desirable adaptation strategies through a process of consultation with stakeholders
- establish forest management guidelines and generalize to policy initiatives for the region based on the strategies selected

METHODOLOGY

Overview

The work presented here evolved through three phases (Fig. 1). The first phase consisted of consultation with regional government to develop a set of forest values that were expected to remain desirable over the long-run. The second phase involved the development of adaptation strategies that were consistent with these forest values, through an iterative process of simulation and adaptation strategy design. And the third phase sought to optimize each adaptation strategy with a forest management planning tool (Patchworks) to derive estimates of costs and benefits for each strategy.

This project strived to identify the most important potential impacts of climate change on the tolerant hardwood forest, based on the knowledge of participating experts. The modelling framework developed for this project attempted to minimize the amount of detail, in order to simplify model implementation, to reduce data input requirements, and to limit the number of assumptions required to build the models. The benefits of this approach include more latitude to explore climate variability, more transparency in the implementation of the models, and faster simulation times.

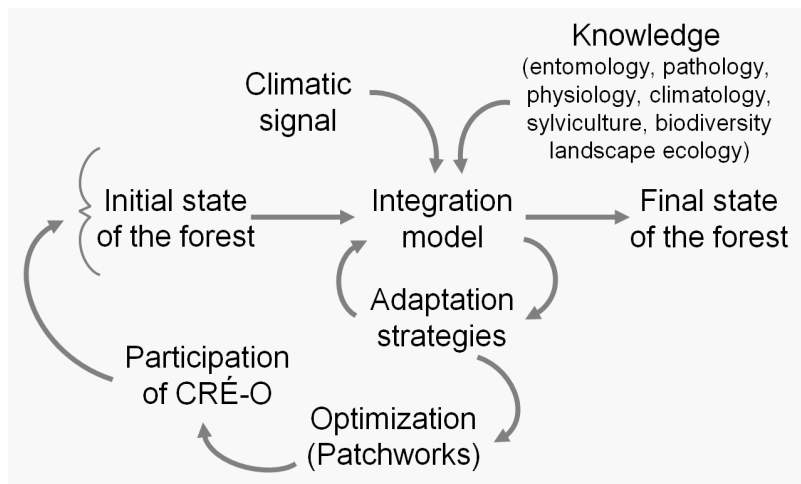


Fig. 1. Overall structure of the project: Input from CRÉ-O to define forest values, development of adaptation strategies through a process of trial and error with the integration model, and optimization of the adaptation objectives in Patchworks.

Study area

The study area for the project was the Forest Management Area (FMA) number 72-51 (Fig. 2). This area, covering over 140 000 ha, is located in the Outaouais region of Quebec, and is mostly composed of temperate hardwood forest.

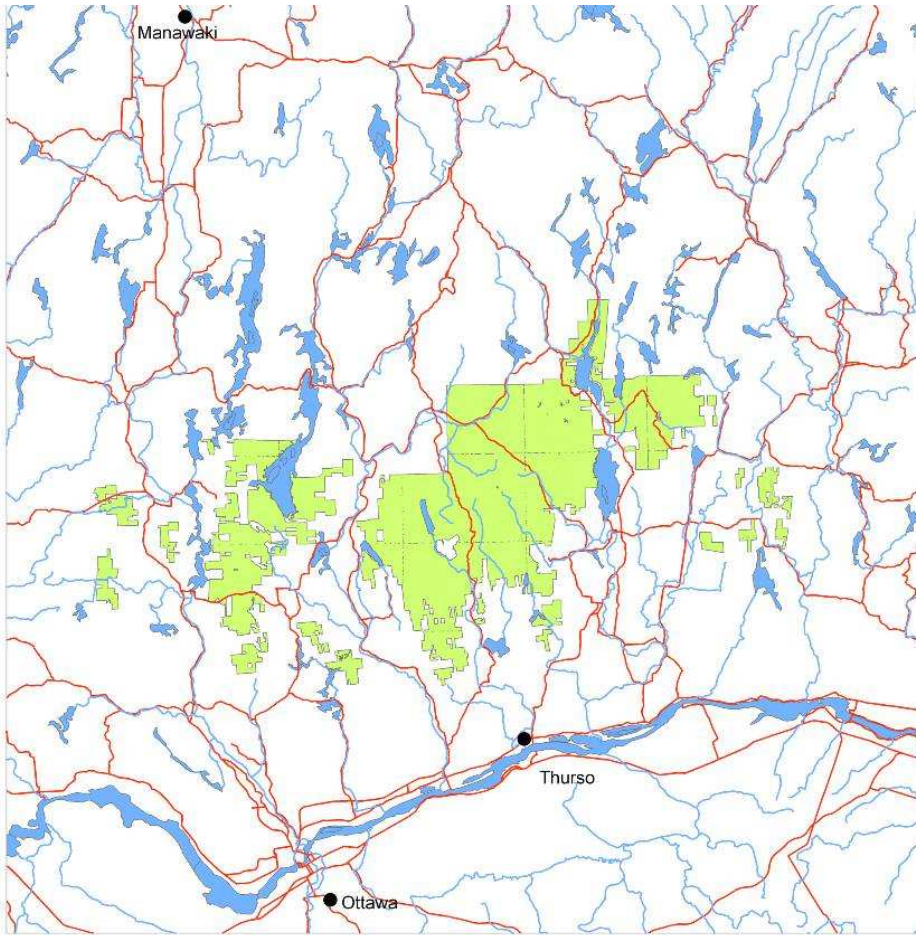


Fig. 2. The proposed study area, in green, is the Forest Management Area 72-51 in the Outaouais region of Quebec, a commercially productive hardwood forest.

Climate data

In all, 12 climate time series were generated for the study from either global circulation model (GCM) output or from a regional climate model, the Canadian Regional Climate Model, version 4 (CRCM4) (Table 1) output.

| Climate model | Resolution | Emissions scenarios | Model runs |
|-------------------------------|---------------|---------------------|-------------------|
| CGCM3– T47 ^{1, 2, 3} | 3,7° X 3,7° | A2, A1b, B1 | 4, 5 |
| ECHAM4 ⁴ | 2,8° X 2,8° | A2, B2 | 1 |
| HadCM3 ⁵ | 2,25° X 3,75° | A2, B2 | a |
| CRCM4 ^{6, 7} | | A2 | 4, 5 ⁸ |

Table 1. A list of the climate models that produced the climate data used in this study, along with the emission scenarios that guided these models (¹ Scinocca et al. 2008, ² McFarlane et al. 2005, ³ Kim et al. 2002, ⁴ Roeckner et al. 1996, ⁵ Gordon et al. 1999, ⁶ Music and Caya 2007, ⁷ Brochu and Laprise 2007); ⁸ the CRCM4 simulations were in fact driven at the boundaries by the CGCM3 running A2 runs 4 and 5.

In order to extract data for the study area from GCM data, a reference zone was established centered on the 72-51 study area (Fig. 3).

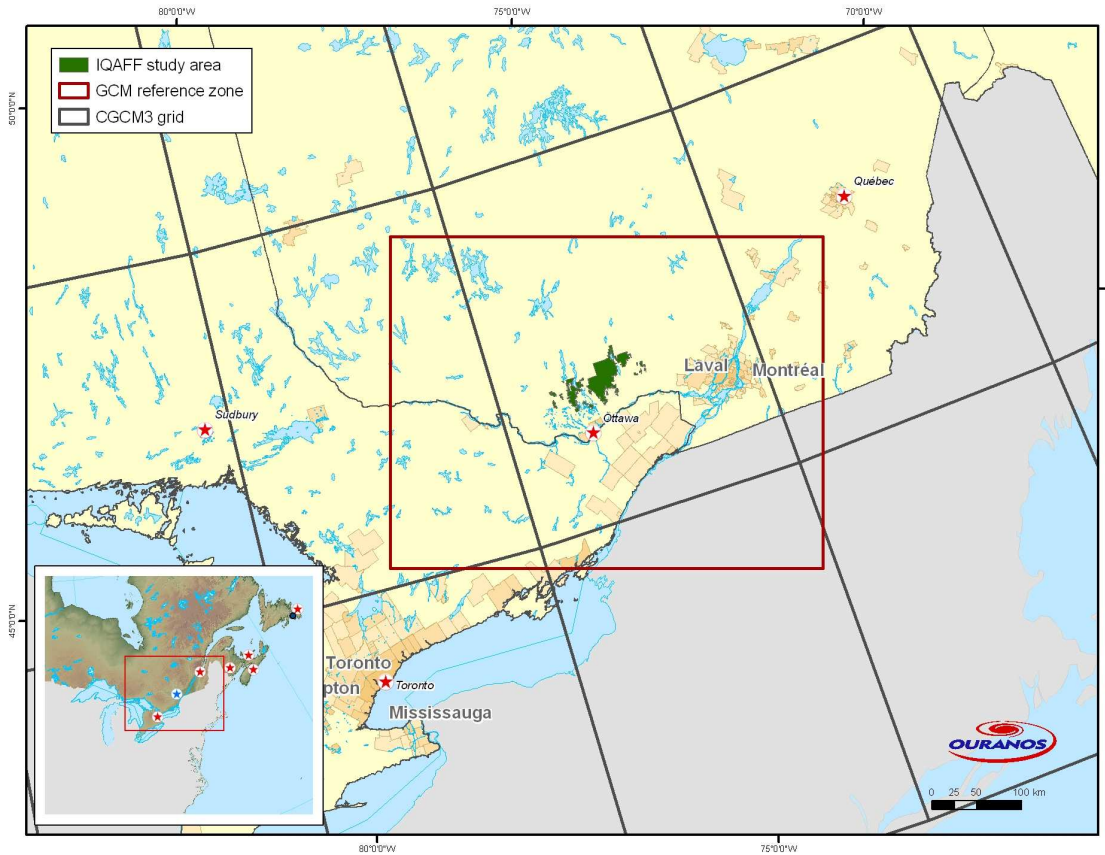


Fig. 3. Map showing the study area (in green), the GCM reference zone (in red), and the CGCM3 grid (in grey). Courtesy of Ouranos.

Climatic data for GCM grid cells intersecting this zone were extracted from each GCM simulations. The dimensions of the reference zone were such that a minimum of 4 GCM grid cells were included from each simulation. The climatic projections for each of the variables of interest are the result of a weighted average of extracted grid cell values for a given GCM. The weight applied was the proportion of the area that each individual grid cell occupied within the reference zone. Data were extracted for the 1961-2099 period. This method offered the advantage of consistently calculating projected climate conditions based on the same area / territory regardless of differences in GCM resolution.

The methodology to extract data from the CRCM was somewhat different than for the GCM. A total of 9 CRCM grid cells, centered on the study area (Fig. 4) were selected. Corresponding grid cell data for variables of interest from the two CRCM 4.1.1 simulations (ACU and ADC) were extracted for the period 1961-2099. For each variable the resulting 9 grid cell series were then averaged together in order to provide a single local climate data series for the study area.

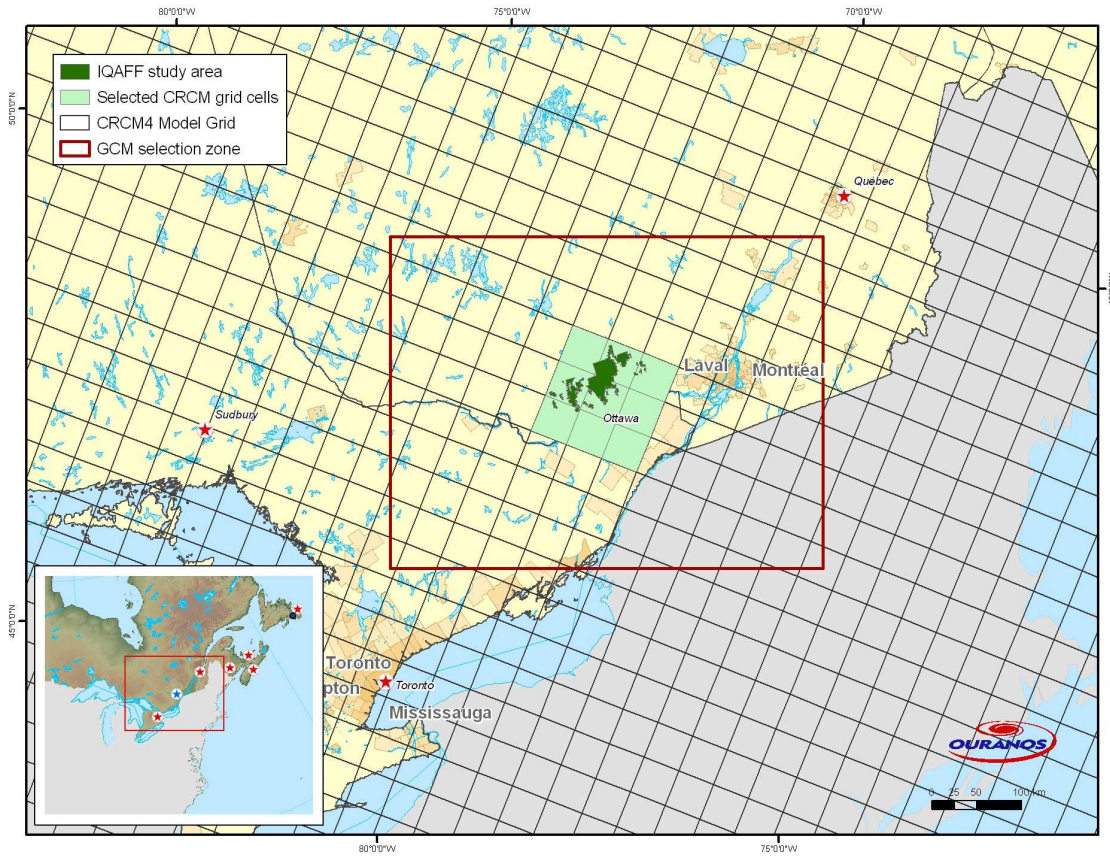


Fig. 4. CRCM 4.1.1 grid superimposed over the study sites; the 9 tiles surrounding the study site were extracted for use in study.

| Year | CO2 concentration (ppm) | | | |
|------|-------------------------|-----|-----|-----|
| | A1B | A2 | B1 | B2 |
| 1970 | 325 | 325 | 325 | 325 |
| 1980 | 337 | 337 | 337 | 337 |
| 1990 | 353 | 353 | 353 | 353 |
| 2000 | 369 | 369 | 369 | 369 |
| 2010 | 391 | 390 | 388 | 388 |
| 2020 | 420 | 417 | 412 | 408 |
| 2030 | 454 | 451 | 437 | 429 |
| 2040 | 491 | 490 | 463 | 453 |
| 2050 | 532 | 532 | 488 | 478 |
| 2060 | 572 | 580 | 509 | 504 |
| 2070 | 611 | 635 | 525 | 531 |
| 2080 | 649 | 698 | 537 | 559 |
| 2090 | 685 | 771 | 545 | 589 |
| 2100 | 717 | 856 | 549 | 621 |

Table 2. The concentrations of atmospheric CO₂ by decade from the IPCC Third Assessment (IPCC 2001).

The climate variables and indices calculated from climate model data included monthly average temperature, precipitation, moisture stress, and wind speed, as well as annual length of growing season. The concentrations of atmospheric CO₂ (Table 2) were drawn directly from the 2001 IPCC report (IPCC 2001), and joined to the corresponding climate data. Length of the growing season was taken as the number of days between the last frost in the spring (the last day where the daily minimum is below zero) and the first frost in the fall (the first day where the daily minimum is below zero). Annual moisture stress was derived from daily values of the Canadian Drought Code (CDC) values (Stocks et al. 1989, FCFDG 1992). Value for the CDC were calculated for the period of April 1st to October 31st of every year using the extracted GCM and RCM data for daily maximum temperature and daily total precipitation. From a reference period of 1961-1990, a threshold value corresponding to the 50th percentile of CDC was obtained from each climate model. The numbers of days exceeding this threshold value was then determined for each year of each simulation in order to produce the resulting number of days of above reference period median CDC value. In order to be integrated into the model, all climate data were expressed either as an absolute difference from 1961-1990 reference values (temperature) or as a proportion of 1961-1990 reference values (precipitation, growing season, moisture stress, and wind speed). An example of a climate profile for the CGCM3 model running the A2 scenario is provided in Fig. 5. In order to extend the climate data beyond the period for which they were available, the last 10 years of the climate data record (2091-2100) were repeated as needed.

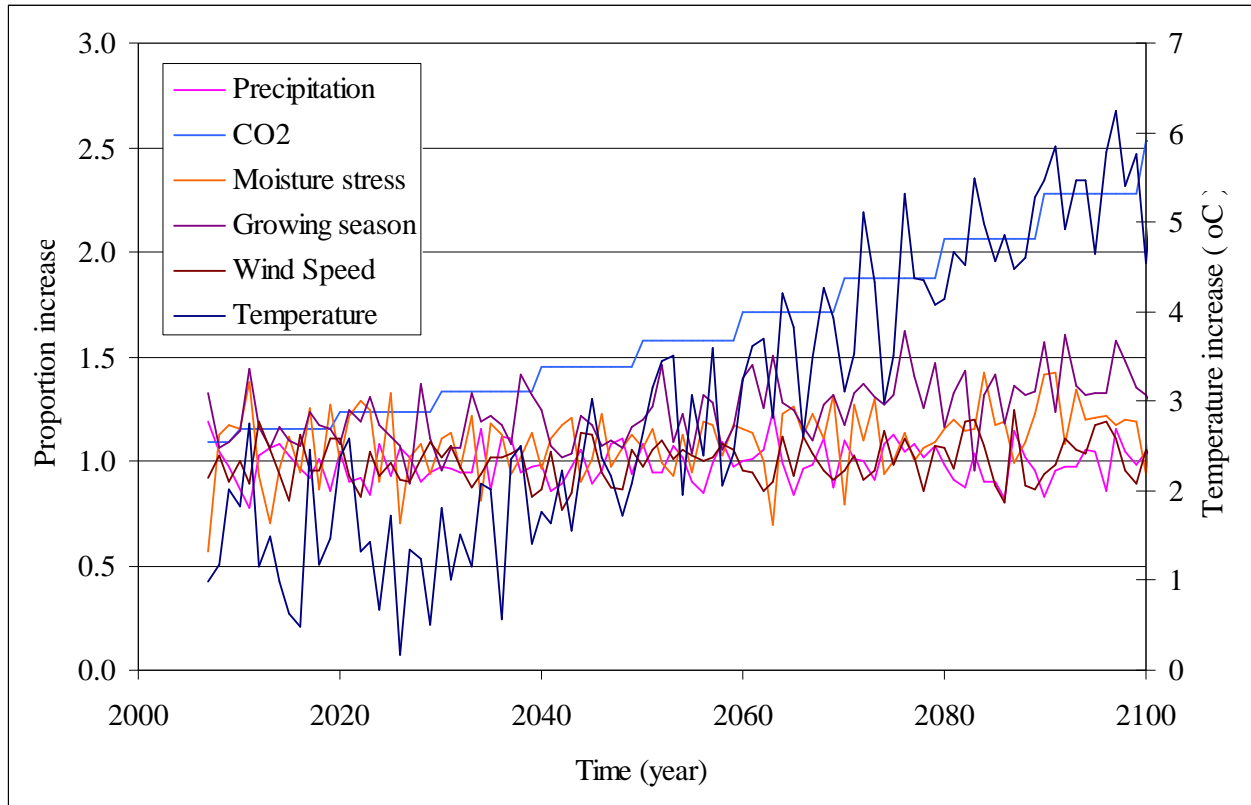


Fig. 5. One of the climate data time series that fed into the ImpaCC-1 model, the A2 (member 4) scenario as modeled by the CGCM3; temperature is expressed in absolute change from the 1961-1990 reference period (ordinate axis on the right), while the other variables are expressed as a proportion of the values from the same period (ordinate axis on the left).

Phase one: public participation

At the outset of the project, regional stakeholders were consulted in order to develop a set of forest values that are expected to remain desirable over the long run. We use "forest values" here to mean the goods and services produced by the forest (Erdle and Sullivan 1998). To this end, we involved the Conférence Régionale des Élus de l'Outaouais (CRÉ-O), the tier of government to which the provincial government is transferring high-level strategic forest planning. More specifically, it was the regional commission for the protection of the environment, land management, and regional transportation that participated in the exercise.

During the course of this meeting with the CRÉ-O, a presentation on climate change and expected impacts were presented to the group. Then a brainstorming session was carried out, in order to establish a list of all the forest values members of the commission expected to be of significance over the course of the 150 years to come. Once this list of 44 forest values was established, individual members of the commission were asked to rate each forest value on a scale from 1 to 5, where 1 is essential, 3 is important, and 5 is not important to maintain on the landscape. The forest values identified unanimously as essential to maintain on the landscape during this process were employed later on to determine if adaptation strategies were successful.

Phase two: development of the integrated impacts model

In order to develop adaptation strategies for the forest landscape, a model that integrates climate signals with natural and anthropogenic disturbances was required. Thus, the ImpaCC-1 model was built to synthesize and scale up multidisciplinary expert knowledge to derive the likely future state of the forest under a range of possible CC scenarios, given either status quo forest management or newly developed adaptation strategies.

Integration of expert knowledge

In order to develop the integration model that predicted the impacts of climate change on the forest, we first gathered expert knowledge on the range of potential future climates and their anticipated impacts. Members of the panel of experts assembled for this exercise included all authors of this report, as well as Daniel Houle and Travis Logan (Ouranos Consortium). The potential impacts later served as the basis for the development of the conceptual model of ImpaCC-1 and its eventual implementation as a functioning landscape model. In order to develop the structure of the model, meetings were held between the model builder (Yamasaki) and all other experts individually, to define how each impact would be represented in the model. A conscious effort was made to simplify model behaviours, in order to reduce the time required for implementation and model parameterization, and to improve model transparency.

Data on stand dynamics: the COHORTE model

Information on the development of stands over time were derived from the output of the COHORTE model, a stand scale model that had been calibrated previously for the 72-51 study area in the context of the Patchworks-Outaouais Project (Forget and Doyon 2007). From the raw data produced by the model (essentially data on each individual stem modeled within COHORTE over the course of approximately 120 years), a database was compiled. This database contained data on recruitment (the rate at which basal area is recruited into the 9-24 cm class), growth (rate of basal area growth), and mortality (the basal area that dies off) rates for every stand type (66 composition types and 2 site types, rich and poor) and every 5-year period of simulation, by species group (13 species groups, Table 3) and diameter class (3 diameter classes).

| Group code | Species in group |
|------------|---|
| OHA | Other hardwoods (<i>Fraxinus spp.</i> , <i>Tilia americana</i> , <i>Ulnus spp.</i> , <i>Juglans spp.</i>) |
| OCO | Other softwoods (<i>Thuja occidentalis</i> , <i>Larix laricina</i>) |
| YBI | Yellow birch (<i>Betula alleghensis</i>) |
| PBI | Paper birch (<i>Betula papyrifera</i>) |
| OAK | All oaks (<i>Quercus spp.</i>) |
| SPR | All spruce (<i>Picea spp.</i>) |
| RMA | Red maple (<i>Acer rubrum</i>) |
| SMA | Sugar maple (<i>Acer saccharum</i>) |
| ABE | American beech (<i>Fagus grandifolia</i>) |
| POP | All poplars (<i>Populus spp.</i>) |
| PIN | All Pines (<i>Pinus spp.</i>) |
| HEM | Hemlock (<i>Tsuga canadensis</i>) |
| BFI | Balsam fir (<i>Abies balsamea</i>) |

Table 3. Listing of the 13 species groups modeled in the ImpaCC-1 model, and the species that compose each group.

In total, the database contained 5744 records. This data was the basis of the estimation of parameters to predict the rates of recruitment (Eq. 1), growth (Eq. 2), the transfer of basal area from one diameter class to the next (Eq. 3), and mortality (Eq. 4 and 5) from various stand characteristics. To this end, the GLM procedure in SAS was used, and the coefficients recovered.

$$\ln(\text{Rec}_{\text{total}}) = \text{BA}_{\text{total}} \quad (\text{Eq. 1})$$

Where $\ln(\text{Rec}_{\text{total}})$ is natural log of total recruitment for the stand, and BA_{total} is cell's total basal area.

$$\text{Gr}_{\text{ax}} = \text{BA}_{\text{total}} + \text{PercBA}_{\text{ax}} + \text{SiteType} \quad (\text{Eq. 2})$$

for $x = \{1, 2, 3\}$

Where Gr_{ax} is the growth of species a in diameter class x, BA_{total} is cell's total basal area, $\text{PercBA}_{\text{ax}}$ is percentage of the cell occupied by species a diameter class x, and SiteType is site type, either rich or poor.

$$\text{Tr}_{\text{axy}} = \text{Gr}_{\text{ax}}, \quad (\text{Eq. 3})$$

for $x = \{1\}$ and $y = \{2\}$, and
for $x = \{2\}$ and $y = \{3\}$

Where Tr_{axy} is transfer of basal area from diameter class x to diameter class y, and Gr_{ax} is growth of species a in diameter class x.

$$\ln(\text{PercMo}_{ax}) = \text{BA}_{\text{total}} + \text{PercBA}_{ax} + \text{SiteType} \quad (\text{Eq. 4})$$

for $x = \{1, 2\}$

Where $\ln(\text{PercMo}_{ax})$ is natural log of percent mortality for species a in diameter class x.

$$\ln(\text{PercMo}_{ax}) = \text{BA}_x + \text{PercBA}_{ax} + \text{SiteType} \quad (\text{Eq. 5})$$

for $x = \{3\}$

Where $\ln(\text{PercMo}_{ax})$ is natural log of percent mortality for species a in diameter class x, and BA_3 is the total basal area for the third diameter class.

The equations obtained from this analysis were applied within the ImpaCC-1 model in order to simulate the recruitment, growth, and mortality of all species and diameter classes within a stand.

Overall structure of the integration landscape model

The knowledge gathered as part of the *Integration of expert knowledge* guided the development of the landscape model, ImpaCC-1. This model is capable of cumulating the impacts proposed by the various domain experts and also scales impacts and processes from the stand scale to the landscape scale, and from the landscape scale (climate) down to the stand scale. It simulates the behaviour of natural (succession, regeneration, windthrow, defoliation) and anthropogenic (tree planting, harvesting, vegetation control) processes. Thus, this tool permits the design and evaluation of adaptation strategies at the landscape scale.

Once again, we did not strive to simulate a great amount of ecological detail and complexity. Rather, our aim was to produce ecosystem behaviour that is consistent with the experts' expectations for the response of ecosystems to anticipated CC. The tool used for the development of this integration model is SELES (Fall and Fall 2001), a landscape model building tool that has been applied extensively to natural disturbance modeling (Fall et al. 2004), and climate change research (Yamasaki et al. 2008). This tool makes possible the modeling of spatially explicit phenomena (*e.g.*, insect outbreaks and regeneration), and permits the implementation of stochastic as well as deterministic processes.

In the ImpaCC-1 model, the stand's basal area by species and diameter class (there were three diameter classes: 9-24 cm, 24-40 cm, and greater than 40 cm) is the quantity that describes the composition of the stand. In order to simulate succession, the model calculates, at every time step and for every cell, the recruitment, growth and mortality of every species and diameter class. Since diameter classes rather than individual stems were to be tracked by the model, it was also necessary to model the amount of basal area that is transferred from one diameter class to the next at every time step. While this approach is considerably more difficult to implement than a simple look up table of basal area as a function of stand type and age (the most common approach to modeling the evolution of forests over time), we felt that it offered the compositional and structural flexibility required to adequately simulate alternative silvicultural treatments (adaptations), climate change impacts, disease, and defoliation in uneven-aged forest ecosystems.

Composition of the seedling bank is tracked within the model as two layers: the seedlings that are between 0 and 20 years, and the seedlings that are between 20 and 40 years. For each cell, the model tracks the age of the seedlings in each of these as one single cohort. Age is increment annually. The proportion of each species is determined by the regeneration sub-model (detailed below). In order to recruit basal area for each species, the succession sub-model multiplies that overall amount of recruited basal area by the proportions in the 20-40 year seedling bank for each of the species.

The ImpaCC-1 model is composed of several sub-models, each sub-model simulating the behaviour of a natural or anthropogenic process (Fig. 6). The sub-models that compose ImpaCC-1 are the following:

- succession (recruitment, growth, and mortality)
- model initialization (applies initial condition)
- 10-year cycle defoliation (forest tent caterpillar, gypsy moth)
- 30-year cycle defoliation (spruce budworm)
- harvesting (both partial and clear-cut harvesting)
- beech bark disease
- tree regeneration
- tree planting (as per various strategies)
- windthrow (catastrophic and partial)
- reporting (outputs data on inventory annually)

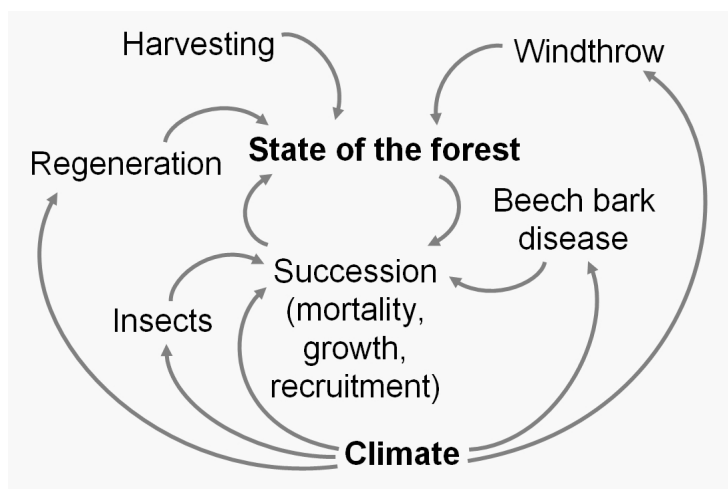


Fig. 6. Schematic representation of the ImpaCC-1 model, showing processes that modify the state of the forest, and which of these processes are affected by climate.

Sample-plot cells in the model

Throughout the ImpaCC-1 model, we have dispersed a series of cells that are closely tracked by the model. For each of these cells and for every year of simulation, the model tracks the amount of basal area by species and diameter class, as well as the annual rates of recruitment, growth, transfer from one diameter class to the next, and mortality. We suggest that these cells are analogous to sample-plots, as sample-plots are used in the context of forest inventory and growth

and yield programs. When looking at modeling output at the landscape scale, it is often difficult to discern exactly what is happening, because trends in one cell can mask opposite trends in another cell. These virtual sample-plots provide us with a detailed look at the behaviour of individual cells. Although they do not illustrate generalized trends at the landscape scale, they can often provide clearer information on the functioning of the landscape model. For this reason, and especially if an illustration of stand dynamics is required, we will often present output data from this network of virtual sample-plots (4 in the model currently, although there is no theoretical limit on the number).

The succession sub-model

The succession sub-model is the component that drives the inner dynamics of the stand. It begins by calculating base rates of recruitment by species, and growth, mortality, and transfer of basal area from one class to the next by species and diameter class, based on the parameters that are estimated in the analysis described above (Eq. 1-5). All parameter values are provided in Appendix A. The recruitment by species is obtained by multiplying the overall rate of recruitment (in terms of basal area) by the proportion of each species in the seedling 20-40 year bank (Eq. 6). A description of the 20-40 year regeneration bank is included in the description of the regeneration sub-model.

$$\text{Rec}_a = e^{(\beta_0 + \beta_1 \cdot \text{BA}_{\text{total}})} \cdot \text{PropRegen}_a \quad (\text{Eq. 6})$$

for $x = \{1, 2, 3\}$

Where Rec_a is the recruitment for species a in a given cell,
 e is the mathematical constant, roughly equal to 2.71828,
 BA_{total} is cell's total basal area,
 β_0 and β_1 are the coefficients estimated in Eq. 1, and
 PropRegen_a is the proportion of species a in the 20-40 year regeneration bank

Growth (Eq. 7), transfer from one diameter class to the next (Eq. 8), and mortality (Eq. 9 and 10) are also calculated based on the results of the analysis of the COHORTE data.

$$\text{Gr}_{ax} = \beta_0 + \beta_1 \cdot \text{BA}_{\text{total}} + \beta_2 \cdot \text{PercBA}_{ax} + \text{SiteType}_i \quad (\text{Eq. 7})$$

for $x = \{1, 2, 3\}$

Where Gr_{ax} is the growth of species a in diameter class x ,
 BA_{total} is cell's total basal area,
 PercBA_{ax} is percentage of the cell occupied by species a diameter class x ,
 β_0 , β_1 , and β_2 are the coefficients estimated in Eq. 2, and
 SiteType_i is the effect of site i .

$$\text{Tr}_{axy} = \beta_0 + \beta_1 \cdot \text{Gr}_{ax}, \quad (\text{Eq. 8})$$

for $x = \{1\}$ and $y = \{2\}$, or
for $x = \{2\}$ and $y = \{3\}$

Where Tr_{axy} is transfer of basal area from diameter class x to diameter class y ,

Gr_{ax} is growth of species a in diameter class x, and β_0 and β_1 are the coefficients estimated in Eq. 3.

$$\text{PercMo}_{ax} = e^{(\beta_0 + \beta_1 \cdot BA_{total} + \beta_2 \cdot \text{PercBA}_{ax} + \text{SiteType}e)} \quad (\text{Eq. 9})$$

for $x = \{1, 2\}$

Where PercMo_{ax} is the percent mortality for species a in diameter class x, e is the mathematical constant, roughly equal to 2.71828, BA_{total} is cell's total basal area, PercBA_{total} is percentage of total basal area that is species a and diameter class x, β_0 , β_1 , and β_2 are the coefficients estimated in Eq. 4.

$$\text{PercMo}_{ax} = e^{(\beta_0 + \beta_1 \cdot BA_{ax} + \beta_2 \cdot \text{PercBA}_{ax} + \text{SiteType}e)} \quad (\text{Eq. 10})$$

for $x = \{3\}$

Where BA_{ax} is the basal area for species a in diameter class x, and β_0 , β_1 , and β_2 are the coefficients estimated in Eq. 5.

Once the base rates of growth are calculated for all species and diameter classes in a given cell (49 rates of growth for each cell), they are multiplied by a series of modifiers based on (i) climate, (ii) beech bark disease and its interaction with climate, and (iii) defoliation history and its interaction with climate. The impacts of future climates on growth can thus be cumulated by multiplying out all the impacts modifiers with the base rates of growth and mortality (Eq. 11). All the information that served to derive the modifiers was provided by the panel of experts.

$$\text{GrFin}_{ax} = \text{GrBase}_{ax} \cdot \text{ModC}_{ax} \cdot \text{ModT}_{ax} \cdot \text{ModP}_{ax} \cdot \text{ModM}_{ax} \cdot \text{ModG}_{ax} \cdot \text{ModB}_{ax} \cdot \text{ModD}_{ax} \quad (\text{Eq. 11})$$

for $x = \{1, 2, 3\}$

Where GrFin_{ax} is the rate of growth applied to a cohort of species a and class x, GrBase_{ax} is the base rate of growth without climatic impacts, ModC_{ax} is the modifier for the effect of CO₂, ModT_{ax} is the modifier for the effect of temperature, ModP_{ax} is the modifier for the effect of precipitation, ModM_{ax} is the modifier for the effect of moisture stress, ModG_{ax} is the modifier for the effect of growing season length, ModB_{ax} is the modifier for the effect of beech bark disease, and ModD_{ax} is the modifier for the effect of defoliation on growth.

Temperature, CO₂ concentration, annual precipitation, annual moisture stress and growing season length were selected as the most important climatic factors to influence tree growth. Functions were defined for the relationships between the climate variables and the growth modifier, for each species and each diameter class. Equations for the calculation of the growth modifiers all follow simple 1st - 4th order polynomials (Eq. 12) or exponential functions (Eq. 13); the type of function to relate climate variables and the modifiers and the coefficients are presented in Appendix A. An

example of growth rates for various species under the influence of the A2 scenario is provided in Fig. 7.

$$\text{Mod}_{ax} = \beta_{0ax} + \beta_{1ax} \cdot (\text{ClimateVar})^1 + \dots + \beta_{pax} \cdot (\text{ClimateVar})^p \quad (\text{Eq. 12})$$

for $x = \{1, 2, 3\}$

Where Mod_{ax} is a p-order modifier, for species a and diameter class x,
p is the order of the polynomial,
 β_{0ax} , β_{1ax} , and β_{pax} are coefficients for species a and diameter class x, and
ClimateVar is a given climatic variable.

$$\text{Mod}_{ax} = e^{(\beta_{0ax} + \beta_{1ax} \cdot \text{ClimateVar})} \quad (\text{Eq. 13})$$

for $x = \{1, 2, 3\}$

Where Mod_{ax} is an exponentiated modifier, for species a and diameter class x,
 β_0 and β_1 are coefficients for species a and diameter class x, and
ClimateVar is a given climatic variable.

Relationships for the effect of temperature on growth were developed based on McKee and Woodward (1994), and on Kienast and Luxmoore (1988) for the effect of CO₂ concentration. The impact of precipitation and moisture stress on growth was based on Chaves and Pereira (1992), Hanson et al. (2001), and Auclair et al. (2005). Finally, the relationship with growing season length was developed based on the recent findings of Hardy et al. (2004), Parmesan (2007) and Springer and Ward (2007). In general, expert judgement, as well as other important and relevant studies (Iverson and Prasad 2001, He et al. 2002, Bergh et al. 2005), also helped in the development of the growth and climate relationships.

The modifiers on mortality (Eq. 14) function much in the same manner as the modifiers on growth, with the exception of the modifier for defoliation (Eq. 15). It was considered important that the rate of mortality ramp up from the base rate of mortality to a maximum rate (this rate was set to 100% for this report), based on the number of years a cell experienced defoliation in a given cycle and the rise in temperature from the reference period of 1961-1990. Coefficients for the impact of climate and defoliation on mortality are provided in Appendix A.

$$\text{PercMoFin}_{ax} = \text{PercMo}_{ax} \cdot \text{ModP}_{ax} \cdot \text{ModM}_{ax} \quad (\text{Eq. 14})$$

for $x = \{1, 2, 3\}$

Where PercMoFin_{ax} is the rate of growth applied to a cohort of species a and class x in a cell, and
 PercMo_{ax} is the base rate of growth without climatic impacts.

$$\text{PercMoFinDefol}_{ax} = \text{PercMoFin}_{ax} \cdot (k_{axt})^{-1} \cdot (1 + e^{(-\alpha_{axt} \cdot \text{yearsDefol} - \delta_{axt})}) \quad (\text{Eq. 15})$$

for $x = \{1, 2, 3\}$

Where $\text{PercMoFinDefol}_{ax}$ is the rate of mortality after applying the effect of defoliation,
 k_{axt} , α_{axt} , δ_{axt} are constants for species a, diameter class x and Δ Temperature t, and
yearsDefol is the number of years of defoliation in a given cycle.

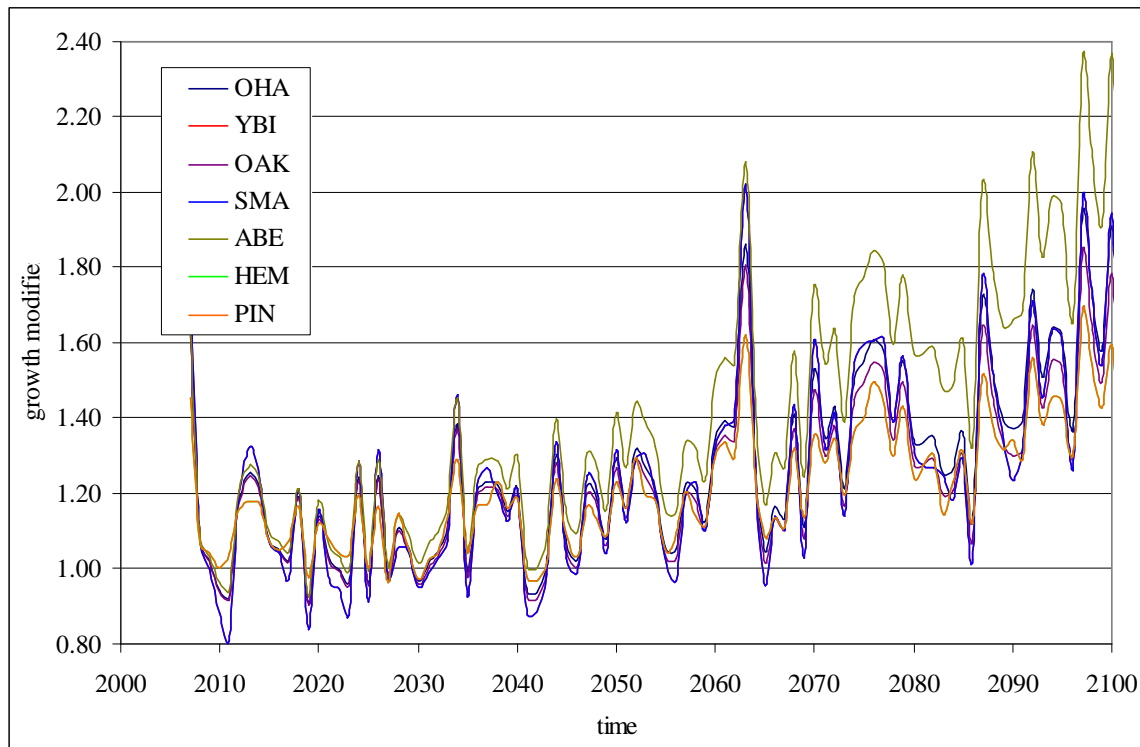


Fig. 7. Evolution of the growth modifier for the greater than 40 cm diameter class of selected species based the A2 (member 4) scenario as modeled by the CGCM3; since each species responds differently to climate variables and CO₂, the trajectories of the modifiers are not parallel (species abbreviations are provided in Table 3).

The relationships between moisture stress, precipitation, and tree mortality by species were developed based on Hanson et al. (2001), Lorimer (2001), Latty et al. (2003) and Auclair et al. (2005) studies. Equations for the calculation of the mortality modifiers all follow 3rd order polynomials; the coefficients are presented in Appendix A.

Beech bark disease (BBD) was integrated into the model as a series of modifiers altering 3 types of processes: the species composition of recruitment, growth, and mortality. A cell is affected by these modifiers only if BBD is present in that cell; the BBD sub-model manages this aspect of BBD and is described below. It is worth noting that there is no direct effect of BBD on any species other than beech. However, recruitment, growth and mortality of other species are affected indirectly since all species are influenced by the composition of the stand (which is itself influenced by the presence of beech). Essentially, the succession sub-model simulates BBD-caused increased root sprouting by modifying the species composition of the 0-20 year regeneration bank (the species composition having been previously determined by the natural regeneration model); the proportion of the cell's regeneration as beech is multiplied by the BBD recruitment coefficient (Tables A2 and A3 in Appendix A), and the proportion of other species in the same bank is subsequently and accordingly adjusted. For growth and mortality of beech in affected cells, the rates are multiplied by modifiers that are obtained as a function of temperature and precipitation (Tables A2 and A3 in Appendix A). The manner in which BBD impacts the recruitment of HEG is based on the results of Le Guerrier et al. (2001). The relative importance of

the direct effects of BBD on growth and mortality of HEG was based on Le Guerrier et al. (2001), Griffin et al. (2003), and Latty et al. (2003).

The succession sub-model outputs data on the landscapes annual rate of net growth (growth + recruitment - mortality). The sub-model also tracks the species composition (in terms of basal area by species and diameter class) of several cells in the model; these cells can be imagined to be virtual sample plots within which the details of succession, disturbance, and climate effects can be observed.

The 10 and 30 year defoliation sub-models

Within the ImpaCC-1 model, we do not model climate-insect interactions through the modeling of effects on insect population. Climate change may affect population dynamics positively (e.g., by increasing developmental and survival rates because of higher temperatures) or negatively (e.g., higher temperatures altering the rate at which the nutritional quality of the insect's diet changes with leaf phenology). The balance between positive and negative feedbacks of climate change on population dynamics is the result of processes that are beyond the modelling resources of this project. Thus, our approach was to assume that climate change may increase the overall effects of defoliation on tree growth and mortality, despite that fact that we do not know for certain if defoliation rates will increase or not in the future. This approach is equivalent to asking "what if" types of questions and is well suited to finding tipping points, where ecosystems cannot maintain their integrity in both space and time under certain defoliation regimes.

Thus, two sub-models for defoliation were developed: one for a 10-year cycle of epidemics, and another for a 30-year cycle. The 10-year cycle represents the impact of forest tent caterpillar and gypsy moth, while the 30-year cycle represents the impact of spruce budworm. The species and diameter classes affected by each of these insects are presented in Table 4. The intensity of epidemics, interpreted within the model as the proportion of potential host cells affected by the defoliator, follows a truncated and transposed sine function; the intensity of epidemics varies between 0 and 1 (Fig. 8). We note here that yellow birch, if it were to become more abundant, may come to be impacted by defoliating insects; however, at the moment we have no empirical data to support the modeling of impacts. Similarly, if hemlock were to become more important in the landscape, hemlock looper may become a problem for this species. Also, while beech may be attacked by forest tent caterpillar and gypsy moth, anecdotal evidence suggests that impacts are negligible.

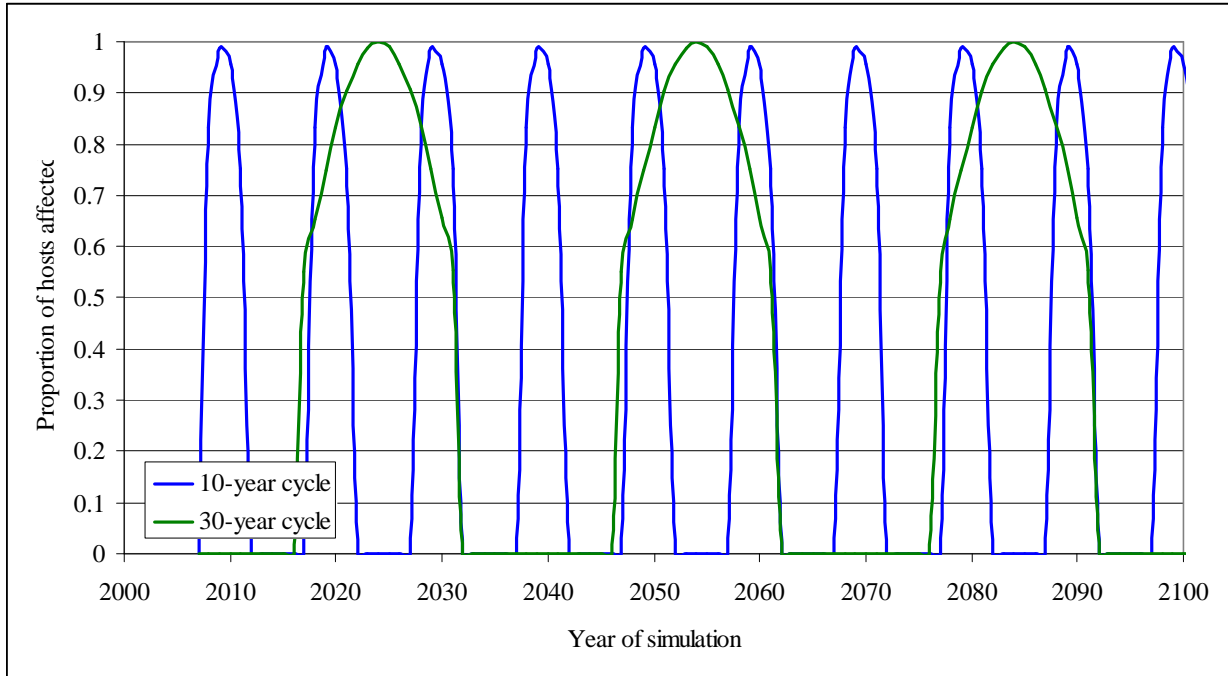


Fig. 8. Graph showing the intensity of epidemic over the landscape over time; when the proportion of hosts affected is equal to 1, all hosts are affected by the defoliators.

Each cycle culminates with all potential hosts being defoliated. In order to carry this out, the defoliation sub-models track the number of cells that contain potential hosts (Table 4) and defoliate the appropriate number of cells. The model tracks the number of years each cell is defoliated, and this number is used in the succession sub-model to derive the reduction in growth and increase in mortality due to defoliation.

All parameters for the impact of defoliation on growth and mortality are provided in Appendix A. Parameters for the effect of defoliation on growth and mortality were adapted from Muzika and Liebhold (2001), Davidson et al. (2001), Piene (1998), Pothier and Mailly (2006), and Gottschalk et al. (1998), and drawn from unpublished results by F. Lorenzetti.

| Species | Insect | Cycle length (years) | Diameter class affected by insect | | |
|---------|-------------------------|-------------------------|-----------------------------------|----------|------|
| | | | 9 to 24 | 24 to 40 | 40 + |
| OHA | none | n.a. | No | No | No |
| OCO | none | n.a. | No | No | No |
| YBI | none | n.a. | No | No | No |
| PBI | Forest tent caterpillar | 10 | Yes | Yes | Yes |
| OAK | Gypsy moth | 10 | No | Yes | Yes |
| SPR | Spruce budworm | 30 | Yes | Yes | Yes |
| RMA | Gypsy moth | 10 | Yes | No | No |
| SMA | Forest tent caterpillar | 10 | No | Yes | Yes |
| ABE | none | n.a. | No | No | No |
| POP | Forest tent caterpillar | 10 | Yes | Yes | Yes |
| PIN | Gypsy moth | 10 | Yes | No | No |
| HEM | none | n.a. | No | No | No |
| BFI | Spruce budworm | 30 | Yes | Yes | Yes |

Table 4. Species and diameter classes affected by defoliation in the ImpaCC-1 model.

The regeneration sub-model

The regeneration sub-model behaves like a kind of dual layer memory. It stores in a geographic layer of information, called the 0-20 year regeneration bank, the composition of regeneration, based on the conditions found at each site at the time of the most recent disturbance and ages this composition until it reaches 20 years, at which point it is transferred to another layer of information, the 20-40 year regeneration bank. When the succession sub-model looks to determine the species composition of recruited stems, it will look at the 20-40 year regeneration bank, and so only after regeneration has reached the age of 20 can it be recruited by the model into the stand.

Propagules for regeneration are either seed or from vegetative reproduction. Only the 24-40 and 40+ diameter classes are considered potential seed sources, to reflect the role of sexual maturity (20 years for poplar, 60 years for shade tolerant species) in seed production (Loehle 1988). Most species in the hardwood forest have limited dispersal ranges due to the size of the seed (Howe and Smallwood 1982, Westoby et al. 1996). Indeed, beyond 100 m, seed densities lower than 1 seed / m² have been observed (Clark et al. 1999). Since cells in the model are 100 m wide, only immediate neighbours are used as seed sources for cells in the model. Based on this premise, the composition of contributing seed trees for each species is calculated according to Eq. 16.

$$\text{Comp}_i = 0.5 \cdot (0.75 \cdot 40\text{plus}_i + 0.25 \cdot 24\text{to}40_i) + 0.0625 \cdot \sum_j (0.75 \cdot 40\text{plus}_{ij} + 0.25 \cdot 24\text{to}40_{ij}) \quad (\text{Eq. 16})$$

for j = 1 to 8.

Where Comp_i is the amount of propagules of species i in a regenerating cell,

$40plus_i$ is the basal area for species i in the greater than 40 cm diameter class,
 $24to40_i$ is the basal area for species i in the 24 to 40 cm diameter class,
 \sum_j is the summation over the 8 neighbour cells,
 $40plus_{ij}$ is the basal area for species i in neighbour cell j in the 40 + diameter class, and
 $20to40_{ij}$ is the basal area for species i in neighbour cell j in 24 to 40 cm diameter class.

Two assumptions underlie this formula. First, we assume that 50% of the seed input comes from within the regenerating cell, and 50% from its neighbours. This approach is supported by the work of Clark et al. (1999). The other assumption relates to the production of propagules as a function of stem diameter, and this is supported by the work of Niklas (1993).

The quantity of propagules in a cell is then multiplied by a series of modifiers that express the influence of light conditions at the ground, vegetative reproduction, moisture stress, and the quantity of microsites suitable for seedling establishment. Modifiers greater than 1 increase the abundance of a given species in a given cell, and modifiers less than 1 reduce the number of propagules in a given cell (Eq. 17).

At the beginning of the process, a modified basal area is obtained by adding a modification factor to a cell's basal area, based on the type of disturbance that has occurred (Table 5). The modifier for light is obtained as a function of the cell's modified residual basal area (Fig. 9). The modifier for vegetative reproduction (applied to vegetative reproduction propagule numbers) is derived from the percent disturbed basal area (Fig. 10). The modifier on moisture stress is obtained through several steps. First, a modified drainage class is obtained as a function of moisture stress due to climate change; for a given drainage class, a modified drainage class is obtained as a function of the proportional increase in moisture stress (Fig. 11). Then, a second modified drainage class is determined as a function of disturbance type (Table 5). This class is again modified based on the amount of residual basal area; if between 0 and 4 m.sq., the drainage class is decreased by 2, if between 4 and 11, the drainage class is decreased by 1, and for basal area greater than 11 m.sq., the drainage class is not modified. Finally, the final modifier on regeneration for moisture is obtained as a function of this final modified drainage class (Fig. 12). The modifier for the effect of exposed mineral soil is also obtained through several steps. First, the base percent exposed mineral soil is obtained as a function of parent material (Table 6). To this percentage is added the remaining unexposed mineral soil that is disturbed by the most recent disturbance (Table 5). From this sum exposed mineral soil is obtained the modification factor due to exposed mineral soil (Fig. 13).

Modifiers for light were based on the work of Kobe et al. (1995), Kaelke et al. (2001), Boardman (1977), and Bazzaz (1979). Modifiers for moisture stress were based on the work of Federer and Gee (1976), Cavender-Bares and Bazzaz (2000), and Caspersen and Kobe (2001). Modifiers for the influence of microsites were based on Gray and Spies (1997) and Burns and Honkala (1990). Before being stored in the appropriate data layers, the abundance of regeneration for each species is scaled so that the sum of all composition by species is equal to 100%.

$$\text{Regen}_i = (\text{Comp}_i + \text{Dist}_i * \text{Mod}_{\text{veg}-i}) * \text{Mod}_{\text{light}-i} * \text{Mod}_{\text{moist}-i} * \text{Mod}_{\text{micro}-i} \quad (\text{Eq. 17})$$

Where Regen_i is the amount of regeneration for species i ,

Dist_i is the amount of basal area disturbed for species *i* in the cell,
 Mod_{veg-i} is the modifier for vegetative reproduction for species *i*,
 Mod_{light-i} is the modifier for light tolerance for species *i*,
 Mod_{moist-i} is the modifier for drought tolerance for species *i*, and
 Mod_{micro-i} is the modifier for microsite establishment preference for species *i*.

| Disturbance type | Modification | | |
|--------------------------------|--------------|-------------------------|----------------------|
| | Basal area | Modified drainage class | Percent mineral soil |
| Single tree partial harvesting | + 0 | + 0 | 15 |
| Aggregated partial harvesting | - 4 | - 1 | 25 |
| 2 pass harvesting | - 1 | + 0 | 25 |
| Clear-cutting | + 0 | - 2 | 60 |
| Shelter-wood | + 4 | - 1 | 40 |
| Partial windthrow | + 0 | - 1 | 40 |
| Catastrophic windthrow | + 0 | + 0 | 60 |
| Fire | + 0 | - 2 | 80 |
| Defoliation | + 0 | + 0 | 15 |

Table 5. Table of initial modification factors for basal area, drainage class, and percent mineral soil, as a function of disturbance type.

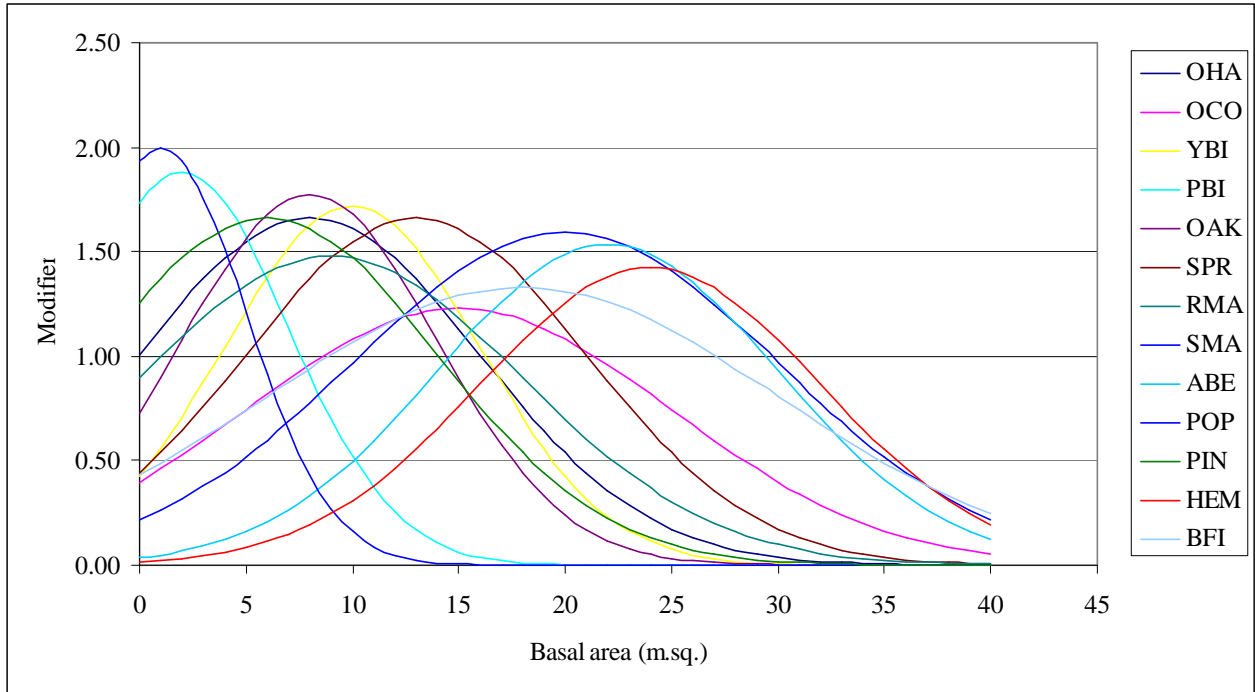


Fig. 9. Modifiers for the effect of light on the regeneration of species.

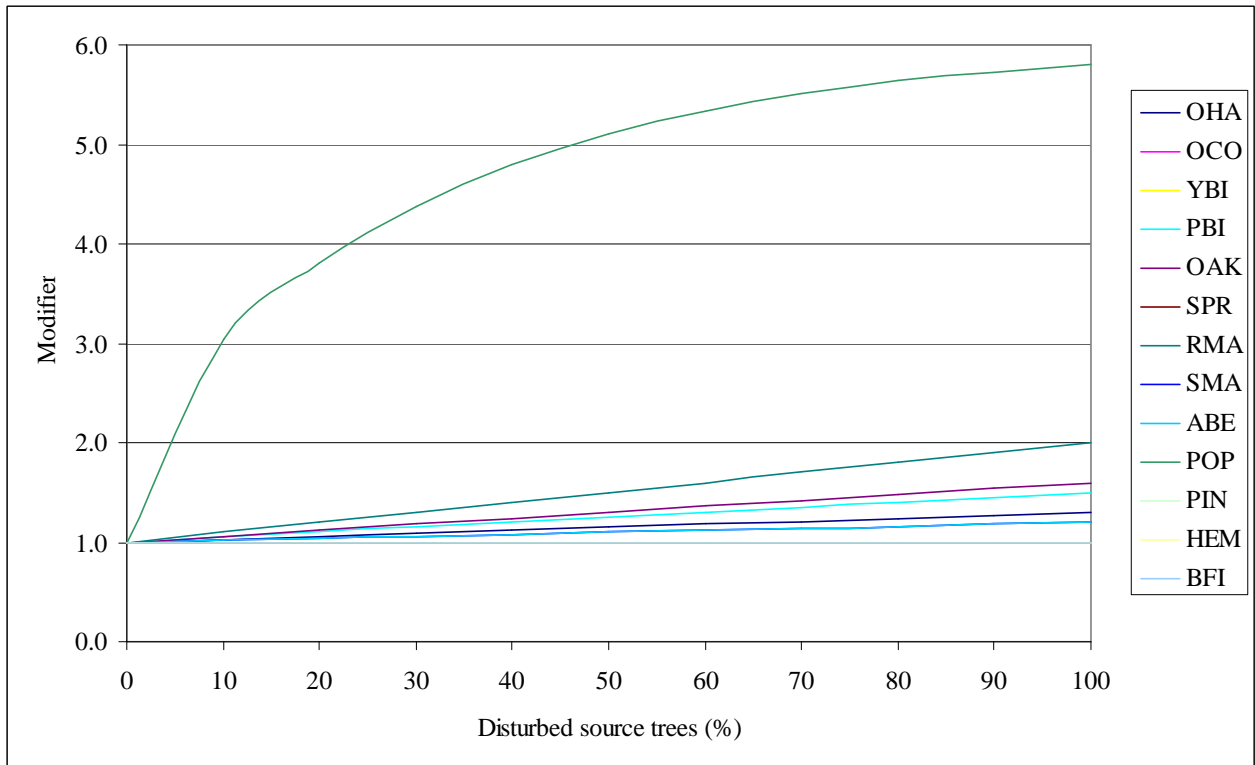


Fig. 10. Modifiers for vegetative reproduction as a function of the percentage of source trees that are disturbed.

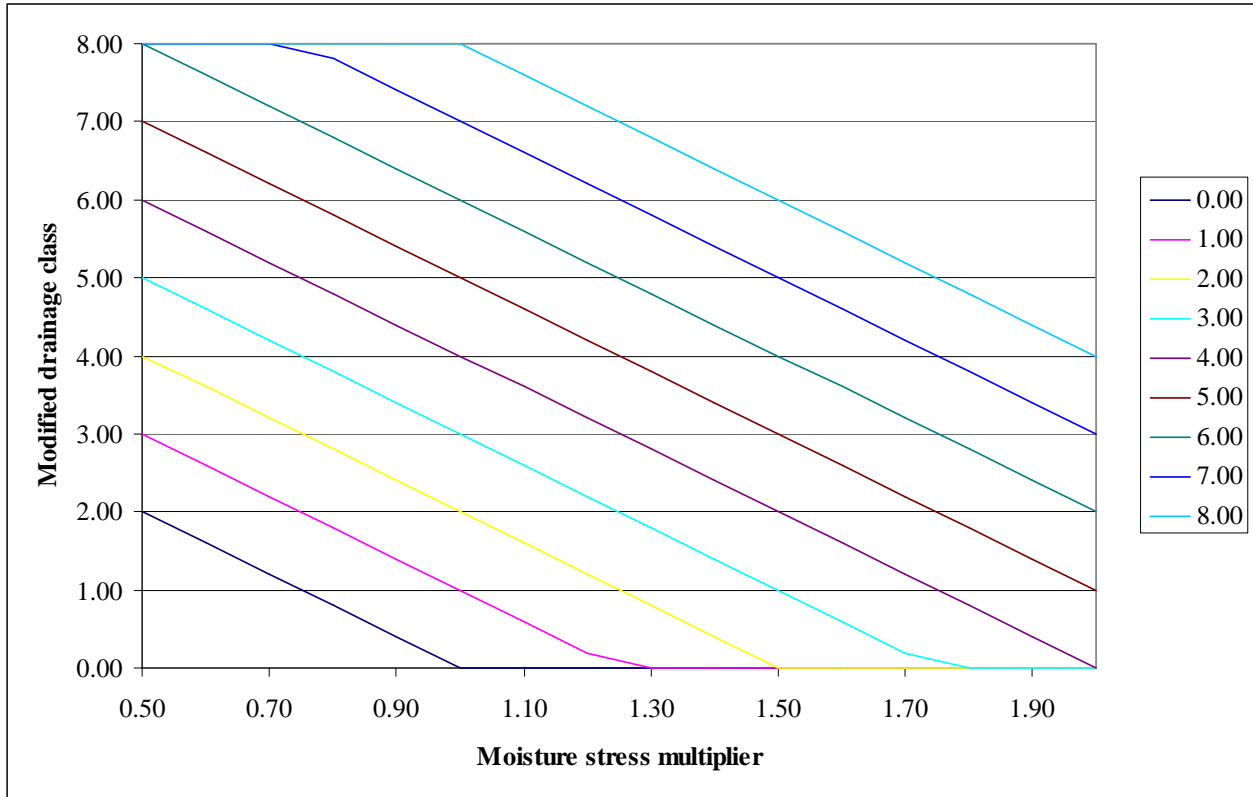


Fig. 11. Modified drainage class as a function of initial drainage class (the different lines in the graph) and the moisture stress multiplier obtained from the climate change data.

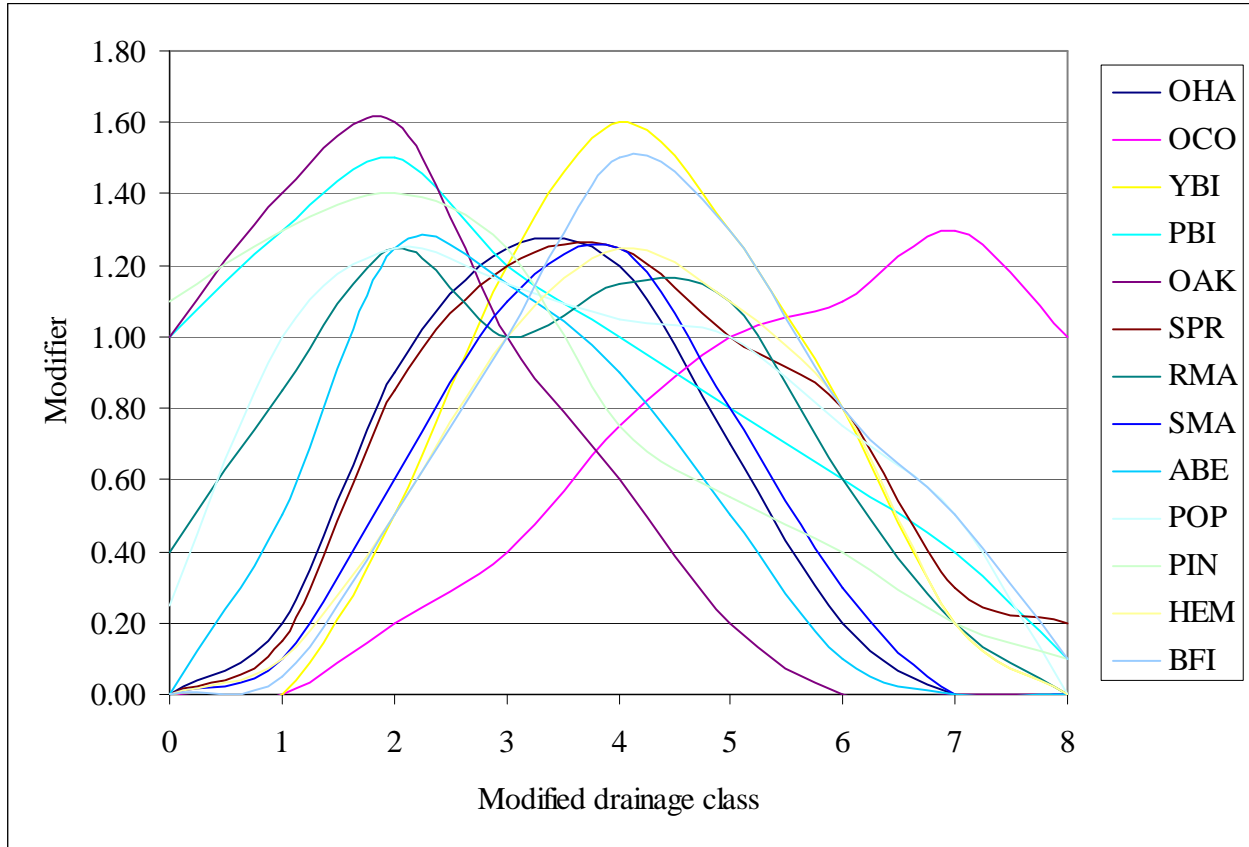


Fig. 12. Final modifier on regeneration from drainage class.

| Surficial geology | Percent exposed mineral |
|-------------------|-------------------------|
| Thick glacial | 5 |
| Thin glacial | 20 |
| Bedrock | 40 |
| Fluvio-glacial | 15 |
| Other | 0 |

Table 6. Base amounts of exposed mineral soil as a function of parent material.

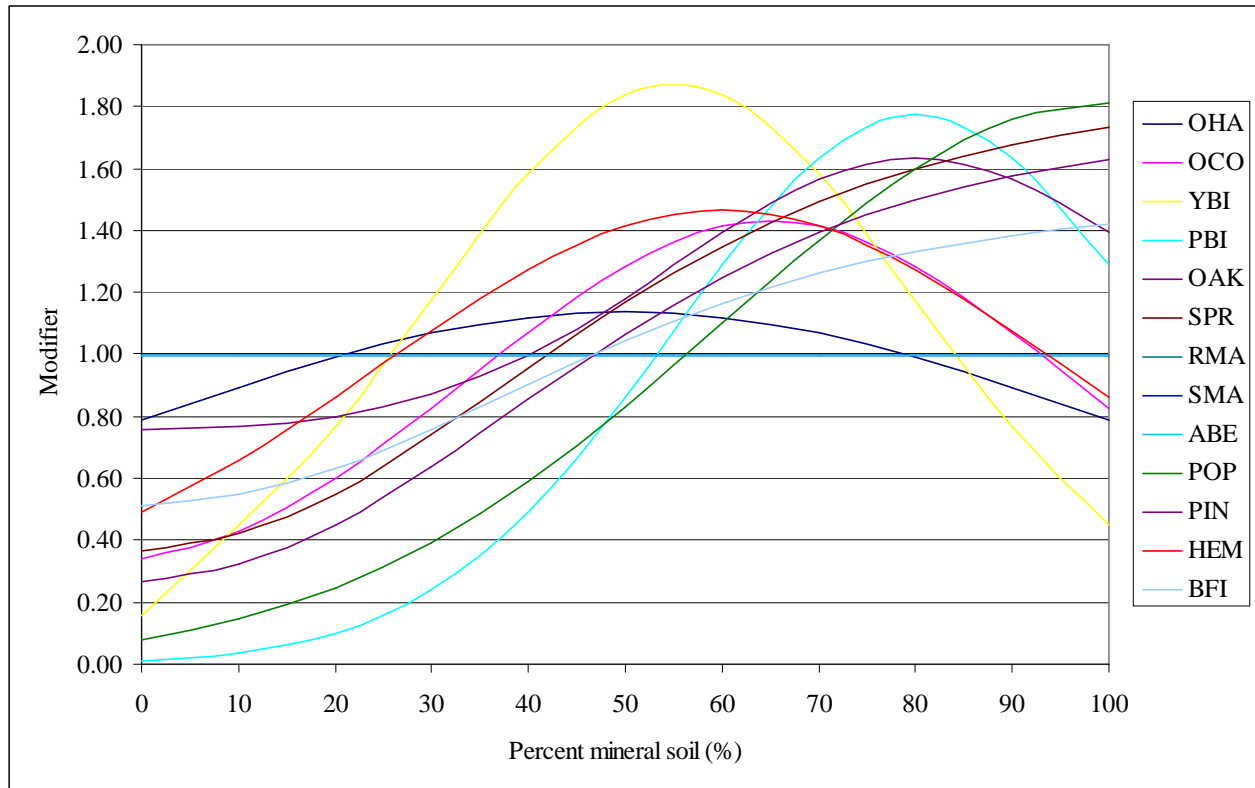


Fig. 13. Relationship between the effective percent exposed mineral soil and the modifier for the effect of exposed mineral soil on regeneration.

The windthrow sub-model

The windthrow sub-model executes two types of windthrow: catastrophic (wind severities greater than 0.7) and partial windthrow (wind severities less than 0.7) (Fig. 14). The model applies catastrophic windthrow to 4% of the windthrow events, and partial windthrow to the remainder. On average, 2% of the forested area is windthrown annually, and of this 2% only 4% is catastrophically windthrown (for a total of, on average, 0.08% of the forested area disturbed by catastrophic windthrow annually). The average size of windthrow events is of 5 ha (with a standard deviation of 20), and the actual size of events is drawn from a normal distribution $\mathcal{N}(5, 20)$. Windthrow events are initiated in forested cells and spread out into other forested cells until the actual size of the event is reached.

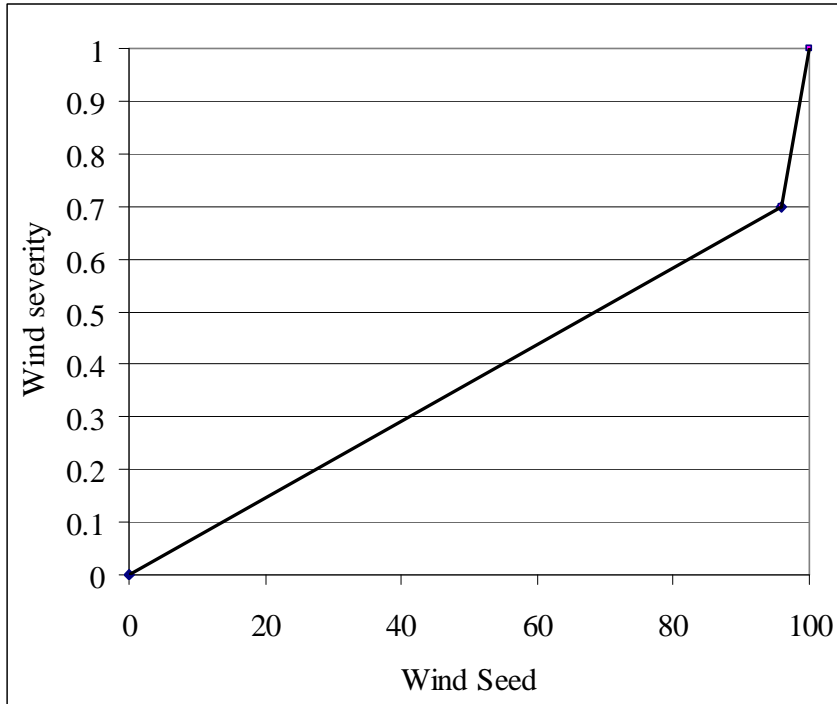


Fig. 14. Relationship between the randomly drawn wind seed (from 0 to 100) and the unit-less wind severity of a given windthrow event.

The sub-model applies the conceptual model of windthrow presented by Canham et al. (2001). According to this conceptualization of windthrow, a windthrow event possesses an intensity (from 0 to 1) and affects each stem differently, depending on the species and diameter of the stem. Thus, from a given wind intensity, the sub-model calculates the proportion of each species and each diameter class that is windthrown. The parameters employed for this process were estimated by Nolet et al. (2008). The windthrow model also registers the amount of basal area by species that is disturbed by the event; this amount will be used by the regeneration sub-model in order to derive the species composition of regeneration.

The sub-model outputs the area windthrown annually, as well as the amount of basal area by species and diameter class that is windthrown every year.

The beech bark disease sub-model

The beech bark disease (BBD) sub-model simply identifies the cells within the model where BBD is present; it is the succession sub-model that applies impacts due to BBD on recruitment, growth, and mortality. All parameters for the effect of BBD on recruitment, growth, and mortality are provided in Appendix B. Essentially, the BBD sub-model simulates the spreading of disease from the south to the north at a fixed rate. The BBD sub-model works on two parameters: the number of years into simulation when BBD begins to affect the southern-most area in the model, and the number of years required to reach the top of the model. For all runs presented here, arrival of BBD in the model occurs in the first years, and the disease requires 10 years to reach the top of the model. These rates of invasion by BBD are purely speculative.

The tree planting sub-model

The tree-planting sub-model establishes the composition of the 0-20 year regeneration bank within the model. Tree planting is applied only to cells that have been harvested, and then only if tree planting is permitted to take place. Otherwise, natural regeneration is allowed to take place. In certain instances and in order to simulate vegetation control, the 20-40 year regeneration bank is also reset. This does not require the assumption that planted seedlings are at least equivalent to 20 year old saplings, but rather that when recruitment occurs, the species composition of the recruited stems will be that of the planted stems.

The harvesting sub-model

The harvesting sub-model simulates partial and clear-cut harvesting by removing a certain amount of basal area from one or many diameter classes. The proportion of each basal area to remove is determined by the harvesting treatment. In the work presented here, only two harvesting treatments were applied: clear-cut harvesting (100% of all diameter classes harvested) and status quo partial harvesting (30% from each diameter class is harvested). The total amount of basal area to harvest is obtained as a proportion of the landscape total annual increment. In the work presented here, a proportion of 0.8 (or 80%) of the landscape total annual increment was generally applied, since this proportion maintained a stable amount of basal area on the landscape. In certain cases, still lower harvest rates were applied and in these cases the proportion applied is indicated.

The sub-model outputs data on the annual harvest target, the area remaining to harvest at the end of the year (if there are shortfalls), the number of blocks, the area harvested, as well as the amount of basal area by species and diameter class that is harvested.

Development of adaptation strategies

Based on the forest values identified by public participation group and the outcome of the climate change scenario, adaptation strategies were developed with the model. The adaptation strategies sought to maintain the forest values identified by the public participation group through various virtual silvicultural strategies. They were developed through an iterative process of simulation and strategy design. The silvicultural tools employed were: tree planting (replacing the content of the 0-20 year regeneration bank with the planted species), targeted harvesting of certain species (the probability to initiate harvesting is greater if the amount of basal area of the target species is greater), vegetation control (replace the 20-40 year regeneration bank with the species being planted), and doing nothing.

Geographical information inputs

Forest inventory data, as well as data on surficial geology, elevation, and moisture regime were obtained from the Patchworks-Outaouais Project (Forget and Doyon 2007). The forest inventory data, represented in the model as the basal area by species and diameter class was derived from a combination of the Québec provincial government's mapping of public forests and field data on the precise composition of stands from the permanent and temporary sample plot network within

the study area. Other sources of data were also used and are described in Forget and Doyon (2007).

Phase three: optimize the deployment of adaptations

Having developed the adaptation strategies with the ImpaCC-1 model, we operationalized these strategies using the Patchworks-Outaouais (PO) optimization model (Forget and Doyon 2007). The PO model is based on the Patchworks modeling tool, developed by Spatial Planning Systems (SPS 2008). One of the key features of the PO model is that it is capable of tracking costs (road building and maintenance, harvesting, hauling, etc.) and benefits (e.g., revenues from harvesting, provincial credits for silviculture) as well as employment over time, while searching for a pseudo-optimal solution to the scheduling of harvesting and other silvicultural prescriptions. For all adaptation strategies, the PO model sought to maintain a fixed harvest rate (194 000 m³ annually) while maximizing profits for the industry. The cost and benefits structure are those reported by Forget and Doyon (2007), with a few additions. We assumed a total cost of 500\$ per ha for planting, and 815\$ per ha for vegetation control. Planting and vegetation control generated 0.053 jobs per ha. Three scenarios were tested with the PO model: (i) partial harvesting only, (ii) clear-cut harvesting only, and (iii) 50% split between clear-cut and partial harvesting, on an area basis. Simulations were run for 150 years. Only the first 25 years are presented in the results, since the optimization model tends to liquidate growing stock at the end of simulations (since there are no repercussions possible past the end of the simulation time horizon).

RESULTS AND DISCUSSION

Public participation

The public participation group provided very precise and useful indications about the forest values that were expected to remain of importance over the next 150 years. There seemed to be a generalized consensus that economic activity would be able, over the course of a century or more, to adapt to change provided that forest ecosystems remain diversified and healthy. Indeed, none of the economic values proposed at the beginning of the exercise were considered as essential by a majority of the participants (Table 7). The values that were judged essential by all relate directly to either ecosystem function and health or ecosystem diversity (Table 7). This information guided the development of the adaptations. Thus, an adaptation strategy was to be considered successful if it succeeded in maintaining a diversity of forest types over the landscape, and if forest productivity (taken here as a proxy for forest health) was maintained. Since all other preoccupations (such as the species composition of the landscape, for example) were considered of secondary importance, no other criterion was applied to the exercise to evaluate the success of adaptations.

It is important to note that there is a set of forest values for which there is no clear consensus. Indeed, there is a set of values with a mean score varied between 2 and 3 (Fig. 15, Table 7), with individual scores between 1 and 5 (Fig. 15). This indicates that these forest values were judged essential by some and not important by others. We suggest that attention be paid to these values, as they may be the source of conflict in the future. Further discussion and education may help to clarify these points and move the participants closer to consensus.

| Value class | Forest values | Mean score |
|------------------------------------|---|------------|
| All consider essential | | |
| Social | Functional ecosystems | 1.0 |
| Recreational | Maintenance of important cycles (water, carbon, etc.) | 1.0 |
| Environmental | Diversity of ecosystems | 1.0 |
| Environmental | Health of ecosystems | 1.0 |
| Most consider essential | | |
| Environmental | Air Quality | 1.2 |
| Environmental | Water Quality | 1.2 |
| Environmental | Healthy wildlife populations | 1.2 |
| Social | Stable supply of potable water | 1.3 |
| Environmental | Animal and plant diversity | 1.3 |
| Environmental | Ecosystem integrity | 1.5 |
| Environmental | Soil quality | 1.5 |
| Some consider essential | | |
| Environmental | Carbon storage | 2.0 |
| Recreational | Large forested areas without industrial activity | 2.0 |
| Social | Mature forests in close proximity to urban areas | 2.3 |
| Social | Maintain species | 2.3 |
| Economic | Other non-timber forest products | 2.3 |
| Recreational | Landscape esthetics | 2.3 |
| Economic | Diversity of ecosystem products and services | 2.4 |
| Economic | Optimisation of the resource | 2.4 |
| Social | Diversity of forestry jobs | 2.5 |
| Environmental | Productivity of forest soils | 2.5 |
| Environmental | Stabilize hydrological cycles | 2.6 |
| Social | Presence of mature forests in given area | 2.7 |
| Social | Education / raising awareness | 2.7 |
| Social | Maintain large expanses of forest | 2.7 |
| Environmental | Maintain wildlife species | 2.7 |
| Environmental | Conservation areas | 2.8 |
| Social | Direct and indirect forestry jobs | 2.8 |
| Environmental | Indigenous species / no exotic species | 2.8 |
| Social | Stability of forestry related jobs | 3.0 |
| Social | Interpretation / education | 3.0 |
| None considers essential | | |
| Recreational | Recreational opportunities close to urban areas | 3.0 |
| Recreational | Abundance of game for hunting | 3.0 |
| Recreational | Abundance of fish for sport fishing | 3.0 |
| Recreational | Abundance of wildlife for observation | 3.0 |
| Economic | Biomass / bioenergy | 3.2 |
| Economic | Long term net benefits of forestry for the state | 3.3 |
| Economic | High value forest products | 3.5 |
| Economic | Profit per hectare | 3.6 |
| Social | Adapt existing species to new climate | 3.7 |
| Economic | Fire wood | 3.8 |
| Economic | Short term net benefits of forestry for the state | 4.0 |
| Economic | Maple syrup production | 4.0 |
| Most consider not important | | |
| Economic | Presence of indigenous species only | 4.5 |

Table 7. A listing of the forest values proposed during the public participation process, indicating qualitatively and quantitatively the global response of participants, as well as the class of forest value; a score of 1 indicates the value is essential, 3 important, and 5 not important.

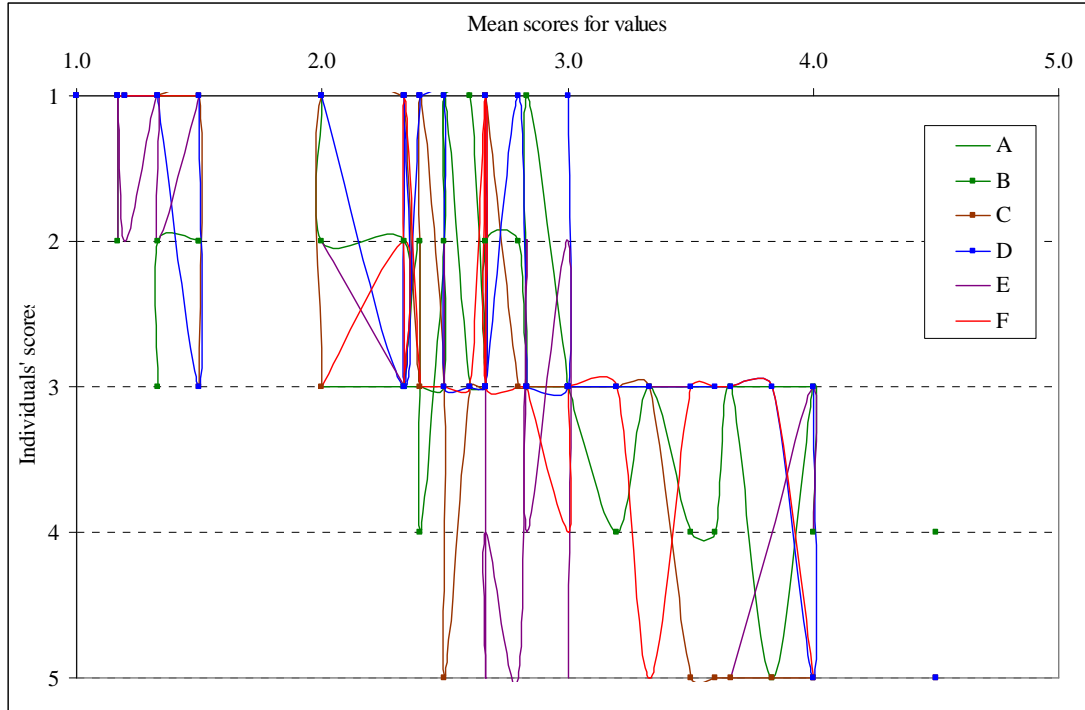


Figure 15. Results from the public participation process showing the scores given by each of the five participants (as the ordinate) and mean score over all participants (as the abscissa).

Analysis of COHORTE data

Analysis of the COHORTE data yielded reliable estimates of the coefficients for the prediction of the various productivity parameters (growth, mortality, recruitment, and transfer from one diameter class to the next), as described above (Eq. 1-5). Total amount of recruitment was predicted with an r-square of 83.3% and a p-value of less than 0.0001.

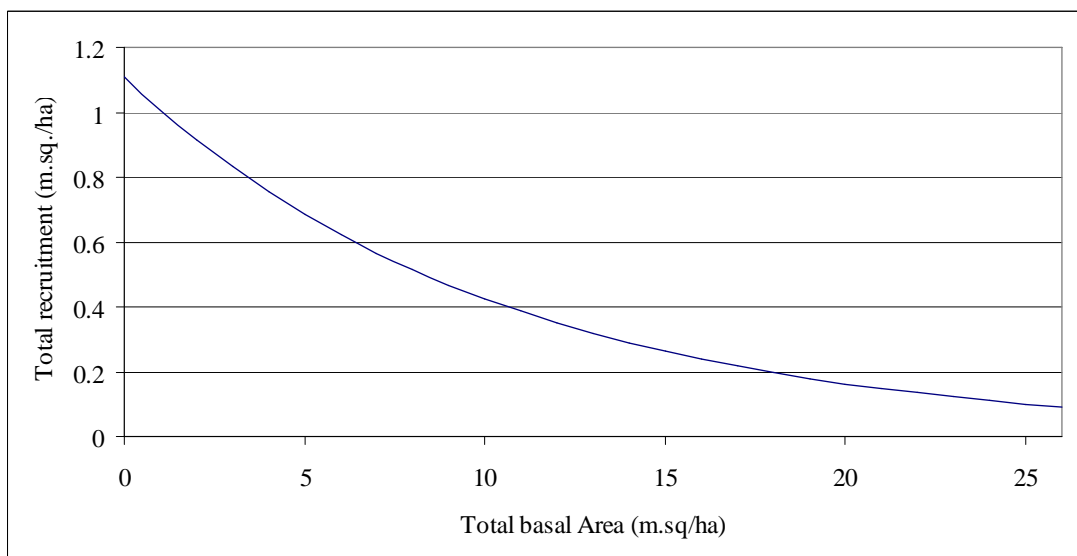


Fig. 16. Relationship between a stand's total basal area and the recruitment for that stand.

The model for the prediction of growth also performed well, with all r-square values for the 13 species and 3 diameter classes all above 90%, while p-values were all highly significant (Table 8). The analysis of the data on the transfer of basal area from one class to the next yielded models with considerably lower power of prediction, although all models were highly significant (Table 9); this is due to the large sample size which was in many cases greater than 2000. The performance of models for the prediction of mortality was variable in terms of variability explained, although all model were highly significant (Table 10).

The relationship between a cell's total basal area and the recruitment for that cell is illustrated in Fig. 16, and shows that as the stand's total basal area increases, recruitment of new biomass decreases. Graphic representations of the predicted values of mortality as a function of basal area for paper birch (Fig. 17) and eastern hemlock (Fig. 18) demonstrate that the relationships follow expected trends (mortality increase with increasing total basal area) and that mortality is much higher for shade intolerant species (such as paper birch) at high total basal area, than for shade tolerant species, such as hemlock.

| Species | Classes | R-square | Probability |
|---------|---------|----------|-------------|
| OHA | 9 - 24 | 0.9600 | < 0.0001 |
| OHA | 24 - 40 | 0.9759 | < 0.0001 |
| OHA | 40 + | 0.9577 | < 0.0001 |
| OCO | 9 - 24 | 0.9963 | < 0.0001 |
| OCO | 24 - 40 | 0.9637 | < 0.0001 |
| OCO | 40 + | 0.9795 | < 0.0001 |
| YBI | 9 - 24 | 0.9967 | < 0.0001 |
| YBI | 24 - 40 | 0.9930 | < 0.0001 |
| YBI | 40 + | 0.9855 | < 0.0001 |
| PBI | 9 - 24 | 0.9934 | < 0.0001 |
| PBI | 24 - 40 | 0.9929 | < 0.0001 |
| PBI | 40 + | 0.9928 | < 0.0001 |
| OAK | 9 - 24 | 0.9958 | < 0.0001 |
| OAK | 24 - 40 | 0.9873 | < 0.0001 |
| OAK | 40 + | 0.9905 | < 0.0001 |
| SPR | 9 - 24 | 0.9867 | < 0.0001 |
| SPR | 24 - 40 | 0.9864 | < 0.0001 |
| SPR | 40 + | 0.9820 | < 0.0001 |
| RMA | 9 - 24 | 0.9804 | < 0.0001 |
| RMA | 24 - 40 | 0.9661 | < 0.0001 |
| RMA | 40 + | 0.9657 | < 0.0001 |
| SMA | 9 - 24 | 0.9831 | < 0.0001 |
| SMA | 24 - 40 | 0.9621 | < 0.0001 |
| SMA | 40 + | 0.9656 | < 0.0001 |
| ABE | 9 - 24 | 0.9872 | < 0.0001 |
| ABE | 24 - 40 | 0.9791 | < 0.0001 |
| ABE | 40 + | 0.9723 | < 0.0001 |
| POP | 9 - 24 | 0.9861 | < 0.0001 |
| POP | 24 - 40 | 0.9626 | < 0.0001 |
| POP | 40 + | 0.9705 | < 0.0001 |
| PIN | 9 - 24 | 0.9853 | < 0.0001 |
| PIN | 24 - 40 | 0.9827 | < 0.0001 |
| PIN | 40 + | 0.9871 | < 0.0001 |
| HEM | 9 - 24 | 0.9785 | < 0.0001 |
| HEM | 24 - 40 | 0.9528 | < 0.0001 |
| HEM | 40 + | 0.9671 | < 0.0001 |
| BFI | 9 - 24 | 0.9866 | < 0.0001 |
| BFI | 24 - 40 | 0.9886 | < 0.0001 |
| BFI | 40 + | 0.9864 | < 0.0001 |

Table 8. R-square and p values for the prediction of growth, by species and diameter class.

| Species | Classes | R-square | Probability |
|---------|---------------|----------|-------------|
| OHA | 9-24 to 24-40 | 0.1810 | < 0.0001 |
| OCO | 9-24 to 24-40 | 0.1518 | < 0.0001 |
| YBI | 9-24 to 24-40 | 0.2414 | < 0.0001 |
| PBI | 9-24 to 24-40 | 0.1847 | < 0.0001 |
| OAK | 9-24 to 24-40 | 0.2372 | < 0.0001 |
| SPR | 9-24 to 24-40 | 0.1074 | < 0.0001 |
| RMA | 9-24 to 24-40 | 0.0638 | < 0.0001 |
| SMA | 9-24 to 24-40 | 0.0843 | < 0.0001 |
| ABE | 9-24 to 24-40 | 0.2108 | < 0.0001 |
| POP | 9-24 to 24-40 | 0.4325 | < 0.0001 |
| PIN | 9-24 to 24-40 | 0.2328 | < 0.0001 |
| HEM | 9-24 to 24-40 | 0.1232 | < 0.0001 |
| BFI | 9-24 to 24-40 | 0.0981 | < 0.0001 |
| OHA | 24-40 to 40+ | 0.2540 | < 0.0001 |
| OCO | 24-40 to 40+ | 0.1284 | < 0.0001 |
| YBI | 24-40 to 40+ | 0.1717 | < 0.0001 |
| PBI | 24-40 to 40+ | 0.1275 | < 0.0001 |
| OAK | 24-40 to 40+ | 0.2027 | < 0.0001 |
| SPR | 24-40 to 40+ | 0.2659 | < 0.0001 |
| RMA | 24-40 to 40+ | 0.0475 | < 0.0001 |
| SMA | 24-40 to 40+ | 0.0887 | < 0.0001 |
| ABE | 24-40 to 40+ | 0.1755 | < 0.0001 |
| POP | 24-40 to 40+ | 0.3346 | < 0.0001 |
| PIN | 24-40 to 40+ | 0.2231 | < 0.0001 |
| HEM | 24-40 to 40+ | 0.1527 | < 0.0001 |
| BFI | 24-40 to 40+ | 0.2050 | < 0.0001 |

Table 9. R-square and p values for the prediction of transfer of basal area from one diameter class to the next, by species and diameter class.

| Species | Classes | R-square | Probability |
|---------|---------|----------|-------------|
| OHA | 9 - 24 | 0.2837 | < 0.0001 |
| OHA | 24 - 40 | 0.1628 | < 0.0001 |
| OHA | 40 + | 0.0760 | < 0.0001 |
| OCO | 9 - 24 | 0.3572 | < 0.0001 |
| OCO | 24 - 40 | 0.1239 | < 0.0001 |
| OCO | 40 + | 0.6819 | < 0.0001 |
| YBI | 9 - 24 | 0.9950 | < 0.0001 |
| YBI | 24 - 40 | 0.9954 | < 0.0001 |
| YBI | 40 + | 0.5842 | < 0.0001 |
| PBI | 9 - 24 | 0.9367 | < 0.0001 |
| PBI | 24 - 40 | 0.8016 | < 0.0001 |
| PBI | 40 + | 0.8900 | < 0.0001 |
| OAK | 9 - 24 | 0.9029 | < 0.0001 |
| OAK | 24 - 40 | 0.6763 | < 0.0001 |
| OAK | 40 + | 0.5577 | < 0.0001 |
| SPR | 9 - 24 | 0.8710 | < 0.0001 |
| SPR | 24 - 40 | 0.7403 | < 0.0001 |
| SPR | 40 + | 0.7776 | < 0.0001 |
| RMA | 9 - 24 | 0.9579 | < 0.0001 |
| RMA | 24 - 40 | 0.7559 | < 0.0001 |
| RMA | 40 + | 0.8596 | < 0.0001 |
| SMA | 9 - 24 | 0.9218 | < 0.0001 |
| SMA | 24 - 40 | 0.8907 | < 0.0001 |
| SMA | 40 + | 0.9123 | < 0.0001 |
| ABE | 9 - 24 | 0.9576 | < 0.0001 |
| ABE | 24 - 40 | 0.7457 | < 0.0001 |
| ABE | 40 + | 0.8258 | < 0.0001 |
| POP | 9 - 24 | 0.7932 | < 0.0001 |
| POP | 24 - 40 | 0.5851 | < 0.0001 |
| POP | 40 + | 0.3314 | < 0.0001 |
| PIN | 9 - 24 | 0.4807 | < 0.0001 |
| PIN | 24 - 40 | 0.2881 | < 0.0001 |
| PIN | 40 + | 0.1247 | < 0.0001 |
| HEM | 9 - 24 | 0.4491 | < 0.0001 |
| HEM | 24 - 40 | 0.7133 | < 0.0001 |
| HEM | 40 + | 0.6364 | < 0.0001 |
| BFI | 9 - 24 | 0.4877 | < 0.0001 |
| BFI | 24 - 40 | 0.9134 | < 0.0001 |
| BFI | 40 + | 0.7840 | < 0.0001 |

Table 10. R-square and p values for the prediction of mortality, by species and diameter class.

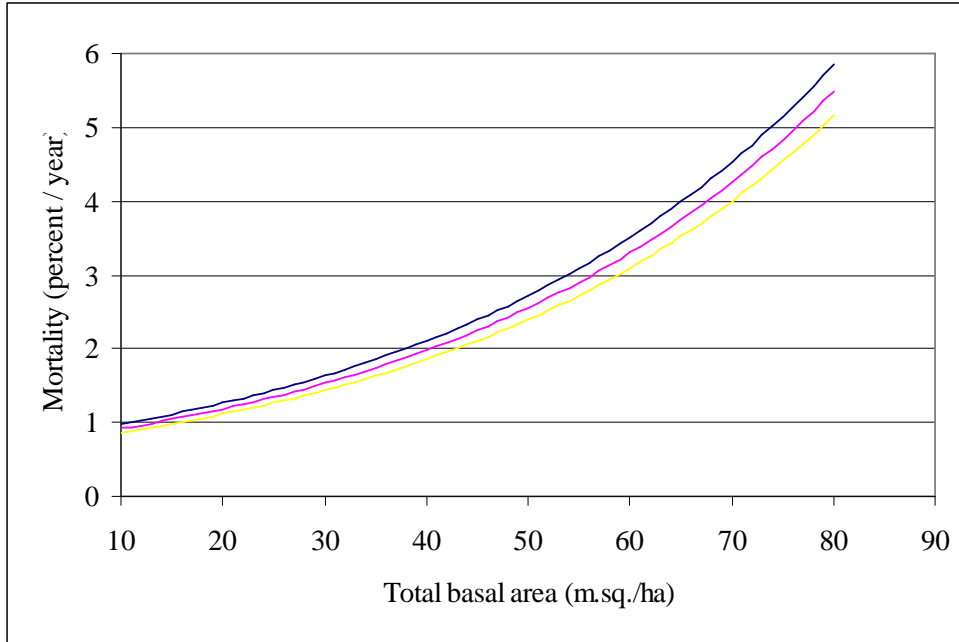


Fig. 17. Predicted values of the mortality of the 9-24cm diameter class of paper birch as a function of a stand's total basal area, for stands where this cohort represents 25% (in blue), 50% (in pink), and 75% (in yellow) of the stands' basal area.

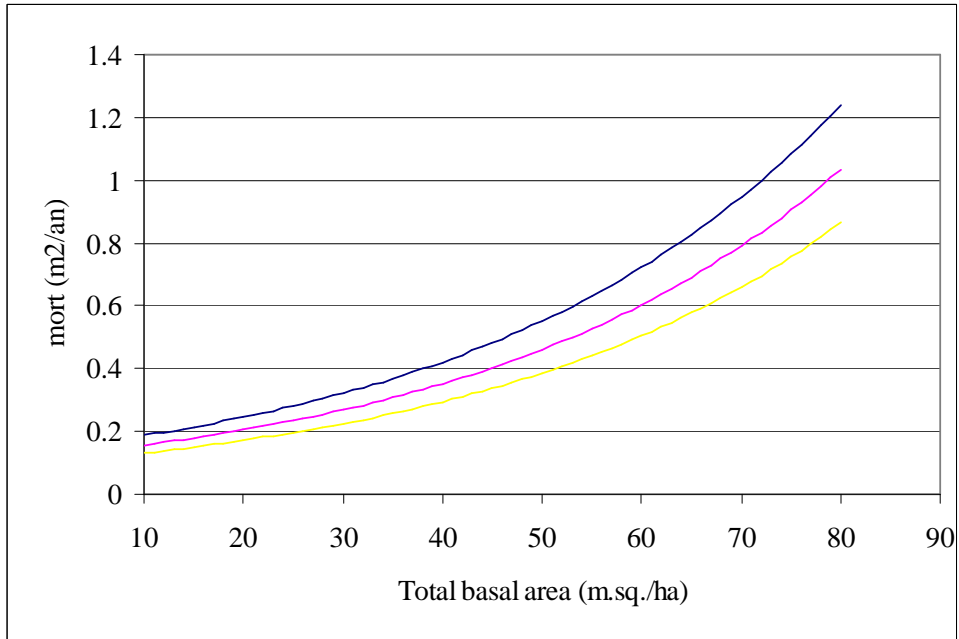


Fig. 18. Predicted values of the mortality of the 9-24cm diameter class of eastern hemlock as a function of a stand's total basal area, for stands where this cohort represents 25% (in blue), 50% (in pink), and 75% (in yellow) of the stands' basal area.

Although the analysis presented here is based on modeled output, the explanation of variability in this output data is not perfect (that is, the r-squares are not equal to 100%). There are three reasons why the explanation of the COHORTE data is not perfect : (i) the COHORTE model tracks

individual stems and thus maintains considerably more information than the data that was analyzed (where information on stems within a species and diameter class is lost), (ii) mortality within the COHORTE model is a stochastic process and it is distributed within a stand on a stem-by-stem basis, and (iii) there are more processes at work and more variables within the COHORTE model than those included in the statistical models (Eq. 1-5). Nonetheless, we feel that the parameters extracted from the COHORTE model for the prediction of recruitment, growth, transfer from one diameter class to the next, and mortality (Appendix A) are sufficiently reliable to be used in the context of the ImpaCC-1 landscape model.

Verification of ImpaCC-1

Succession only, no disturbance

The first simulations that were run with the ImpaCC-1 model (after debugging was completed) were carried out to look at the behaviour of the model under current climatic conditions, and in the absence of disturbance. Simulations show that at the landscape scale, total stand basal area increases significantly while composition changes very little (Fig. 19). Basal area increases most where hemlock, sugar maple, and red maple make up an important part of the stand's composition (Fig. 20). The basal area of the most shade tolerant species (HEM, ABE, SMA) can be seen to increase gradually, while the basal area of other species remains stable.

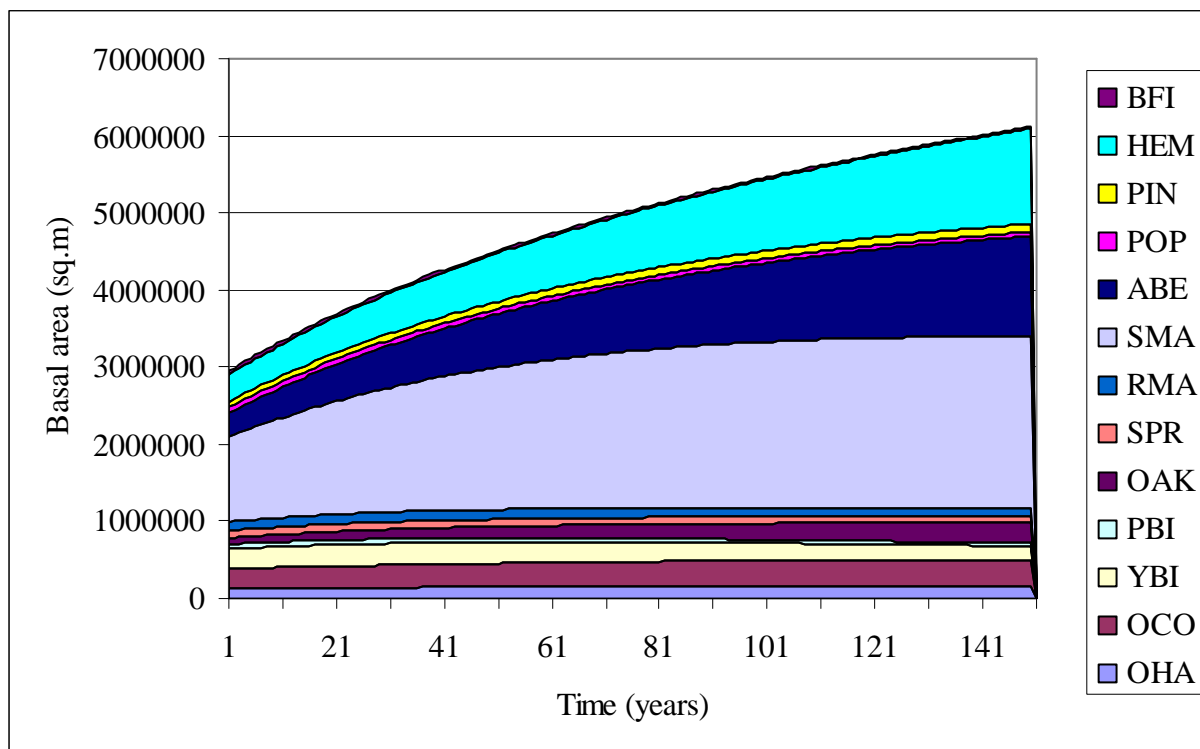


Fig. 19. Basal area by species over the course of a 150-year simulation with the ImpaCC-1 landscape model, simulating no disturbance and no climate change; abbreviations for species are provided in Table 3.

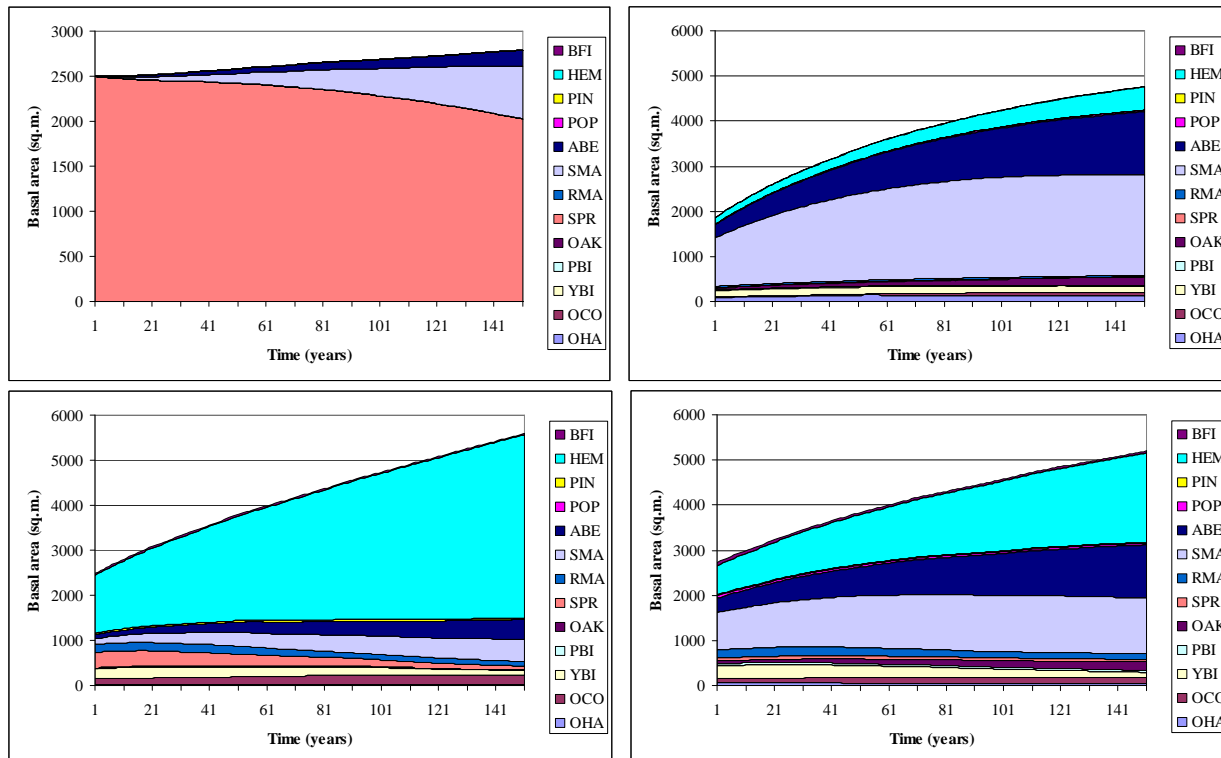


Fig. 19. Basal area by species over the course of a 150-year simulation, simulating no disturbance and no climate change, for four sample-plot cells in the model.

The natural disturbance regime

The next run sought to simulate forest dynamics under the current climate, so as to replicate the natural disturbance regime and historical trends of succession. Therefore, disturbance agents (defoliation and windthrow) were turned on for these simulations, and harvesting was turned off. These runs show that the model replicates current conditions with reasonable accuracy (Fig. 21). The graphs of natural disturbance show the 30-year periodicity of spruce defoliation by spruce budworm (Fig. 21, upper left). This graph also shows that spruce completely disappears from the cell after the second defoliation cycle, which suggests that mortality as a function of SBW defoliation was overestimated for spruce. The susceptibility of sugar maple to the 10-year defoliation cycle can also be observed (Fig 21, top right). Basal area accumulation remains within observed ranges, that is, above 40 m² / ha for sites dominated by hemlock (Fig. 21, bottom), and between 20 and 30 m² / ha for other sites (Fig. 21, top). At the landscape scale (Fig 22) we can clearly observe the 10-year defoliation cycle, as well as a gradual shift in composition from sugar maple to hemlock. This shift has been observed in the real world (Duchesne et al. 2005, Duchesne et al. 2006), and is not entirely understood. The output of the model suggests that this shift is natural and a result of the combined effects of all species' recruitment, growth, and mortality, and regeneration dynamics under a natural disturbance regime.

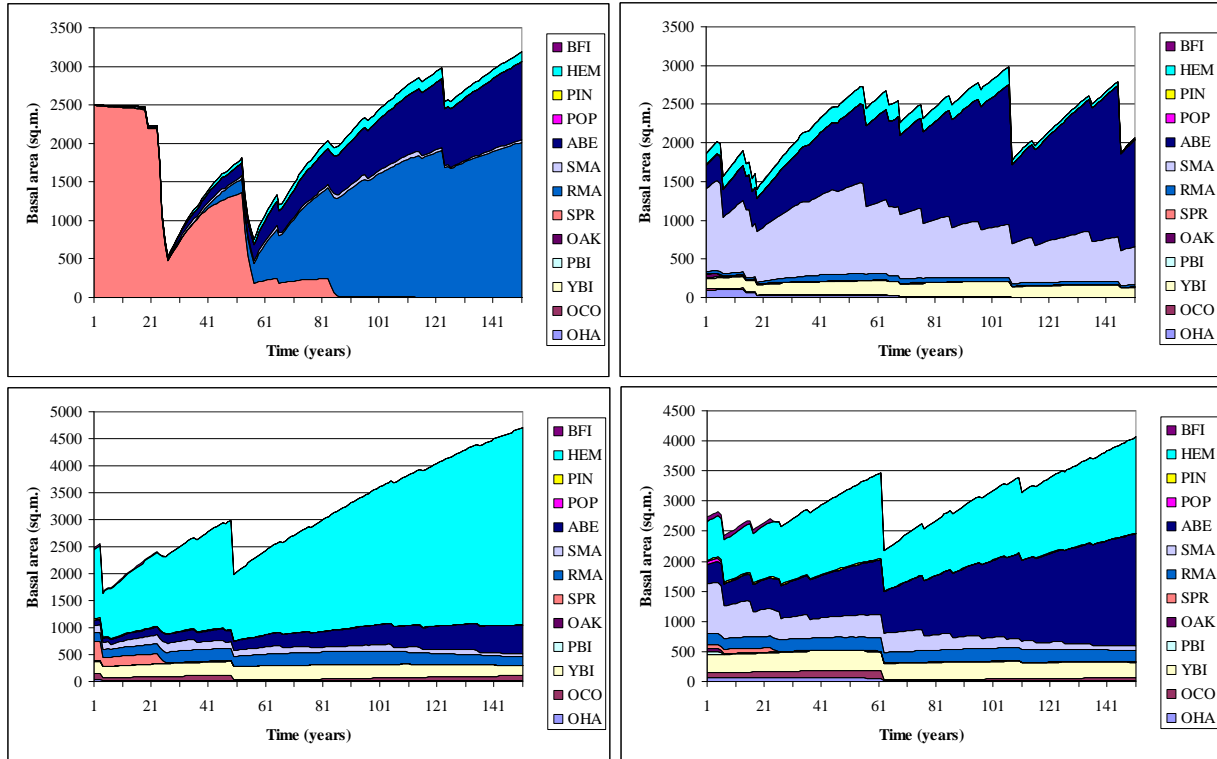


Fig. 21. Basal area by species over the course of a 150-year simulation, simulating natural disturbance and no climate change, for four sample-plot cells in the model.

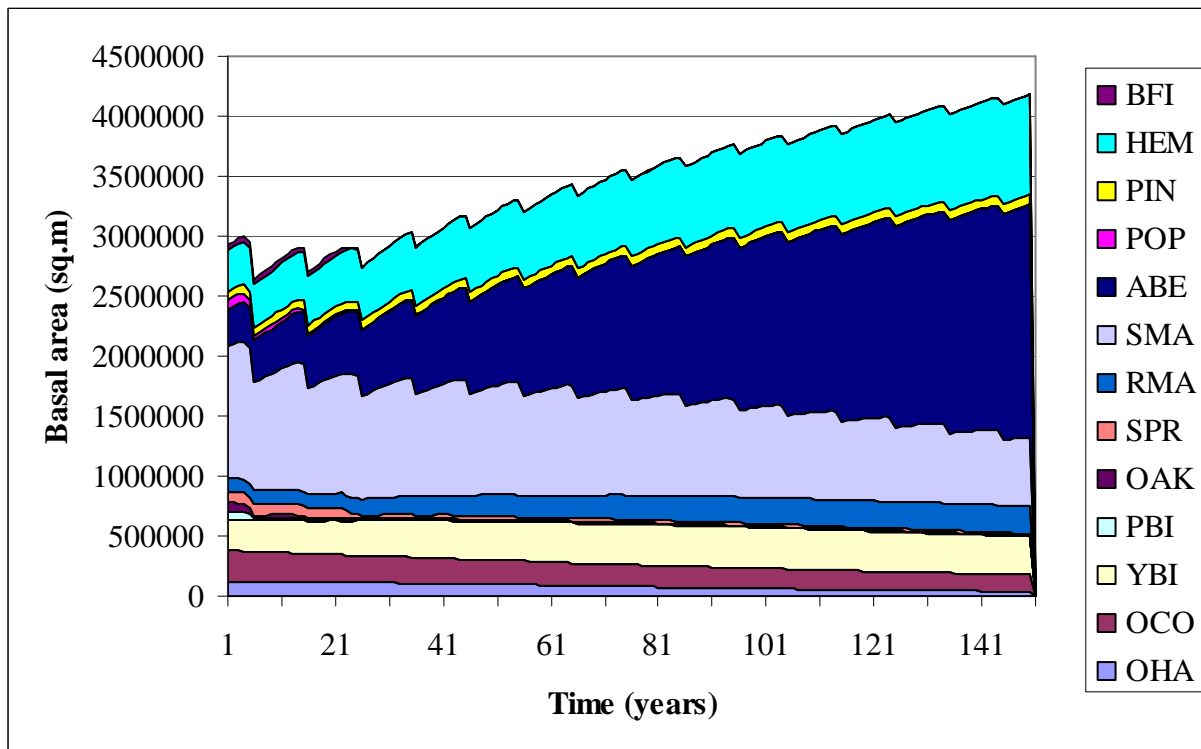


Fig. 22. Basal area by species over the course of a 150-year simulation, simulating natural disturbance and no climate change, for all forested cells in the model (approximately 129 000 ha).

Natural disturbance and harvesting

We then ran simulations with harvesting and natural disturbance, simulations which most closely simulated the current situation in the temperate hardwood forest in the region. Overall, results appear to suggest that partial harvesting over the entire landscape tends to simplify the composition of the most diverse stands among the four sample plot cells (Fig. 23, bottom). This result confirms previous suggestions that extensively and uniformly applied partial harvesting does not provide the range of conditions required to maintain a broad diversity of tree species over the landscape as Doyon (2000) has found in his study. Indeed, at the landscape scale, we can observe that the proportion of the landscape occupied by the less abundant species (all species other than SMA, RMA, ABE, and HEM) under the disturbance + harvesting scenario (Fig. 24) is lesser than that for the natural disturbance regime (Fig. 22).

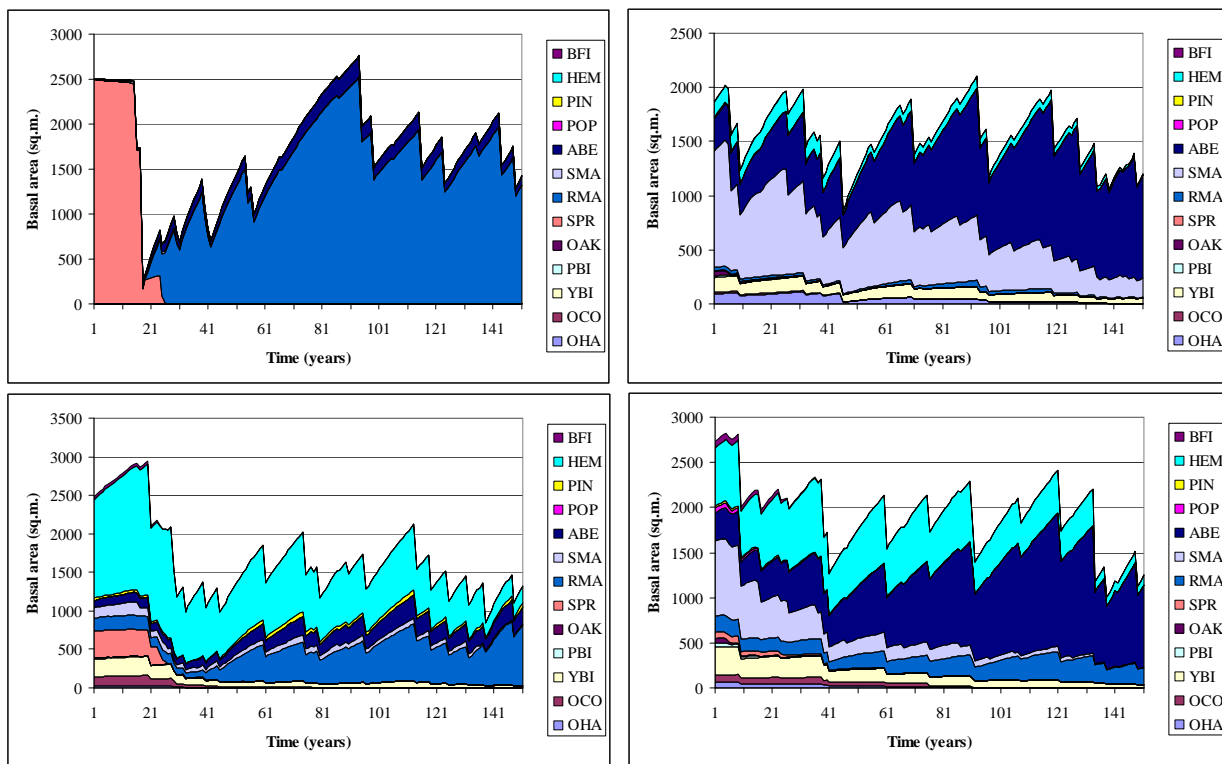


Fig. 23. Basal area by species over the course of a 150-year simulation, simulating natural disturbance, harvesting, and no climate change, for four sample-plot cells in the model.

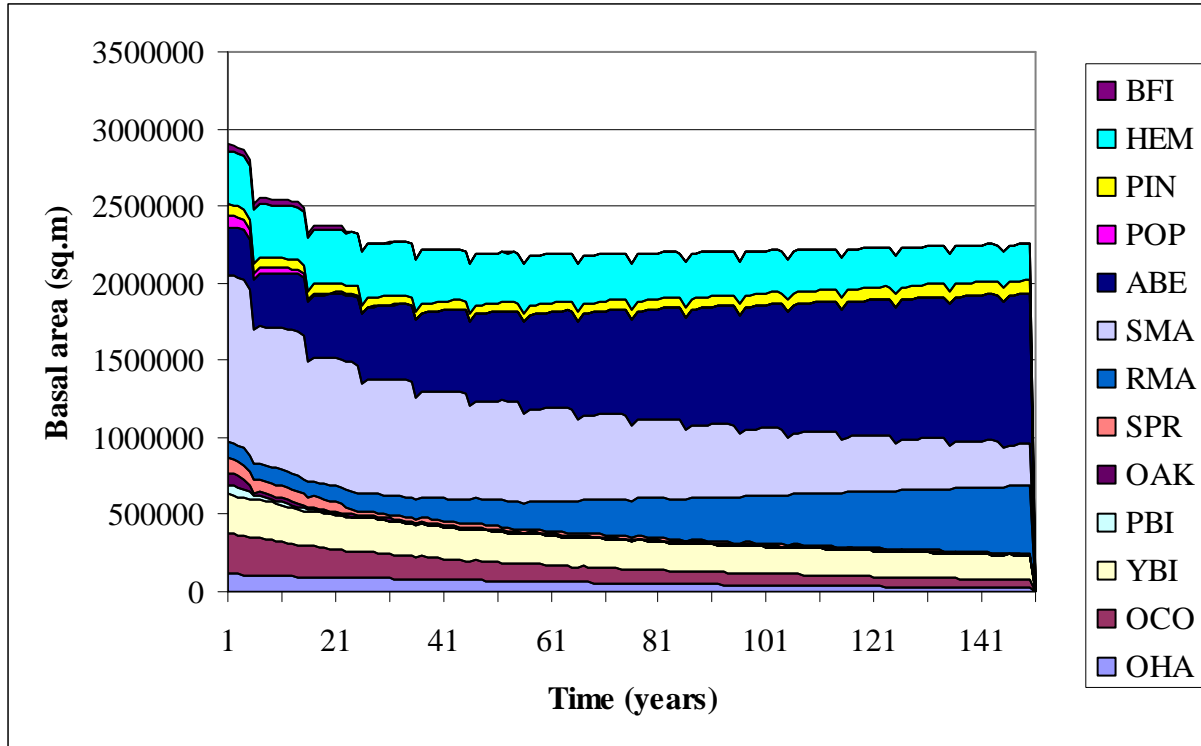


Fig. 24). Basal area by species over the course of a 150-year simulation, simulating natural disturbance, harvesting, and no climate change, for all forested cells in the model (approximately 129 000 ha).

Impacts of climate change

Impacts of climate change without CO₂

Before applying climate change to the simulations, we were interested in looking at the impacts of climate change impacts without the impact of CO₂. The point of this exercise was to compare results of stand dynamics without CO₂ change to dynamics of stands further south, where the temperature regime is equivalent to those in our climate change scenarios. Looking at the mean annual temperature for a transect reaching from Ottawa, Ontario (the closest location to the study area with complete weather records) south into the U.S.A., we can see a steady trend of increasing temperature (Fig. 25). The predicted maximum mean annual temperature change for the A1b scenario of the CGCM3 is 5.7 degrees Celsius. By interpolating the sum of the mean annual temperature for Ottawa to this temperature change on this graph, we obtain that the temperature analogue for Ottawa under the A1b-CGCM3 scenario is Richmond, Virginia. By comparing stand dynamics for our study area under the influence of climate change without CO₂ to stand dynamics in Richmond, Virginia, we can evaluate the performance of our model.

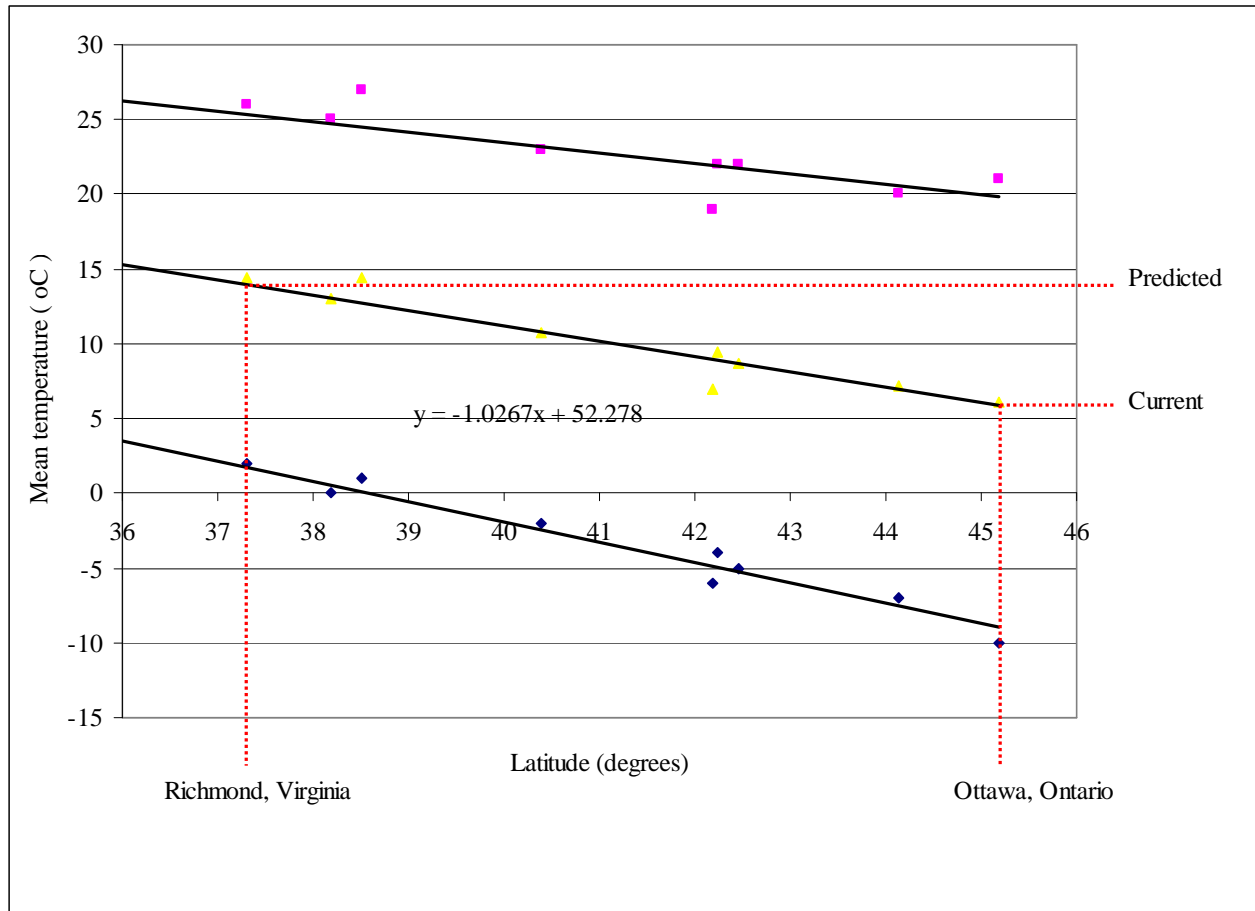


Fig. 25. Trends in temperature as a function of latitude on a transect reaching from Ottawa into the U.S.A., showing the mean annual temperature for Ottawa (°); mean annual temperature in yellow, mean July temperature in pink, and mean January temperature in blue.

Stand scale results of the simulation with the A1b scenario without CO₂ effects (Fig. 26) indicate that basal area reaches higher values than under current conditions (Fig. 21). While the landscape mean basal area per hectare under natural disturbance 31.9 m²/ha, it rises to 37.2 m²/ha under the A1b/no CO₂ scenario, a 16% increase. This corresponds reasonably well with estimates from the literature (Busing 1998, Beane 2007).

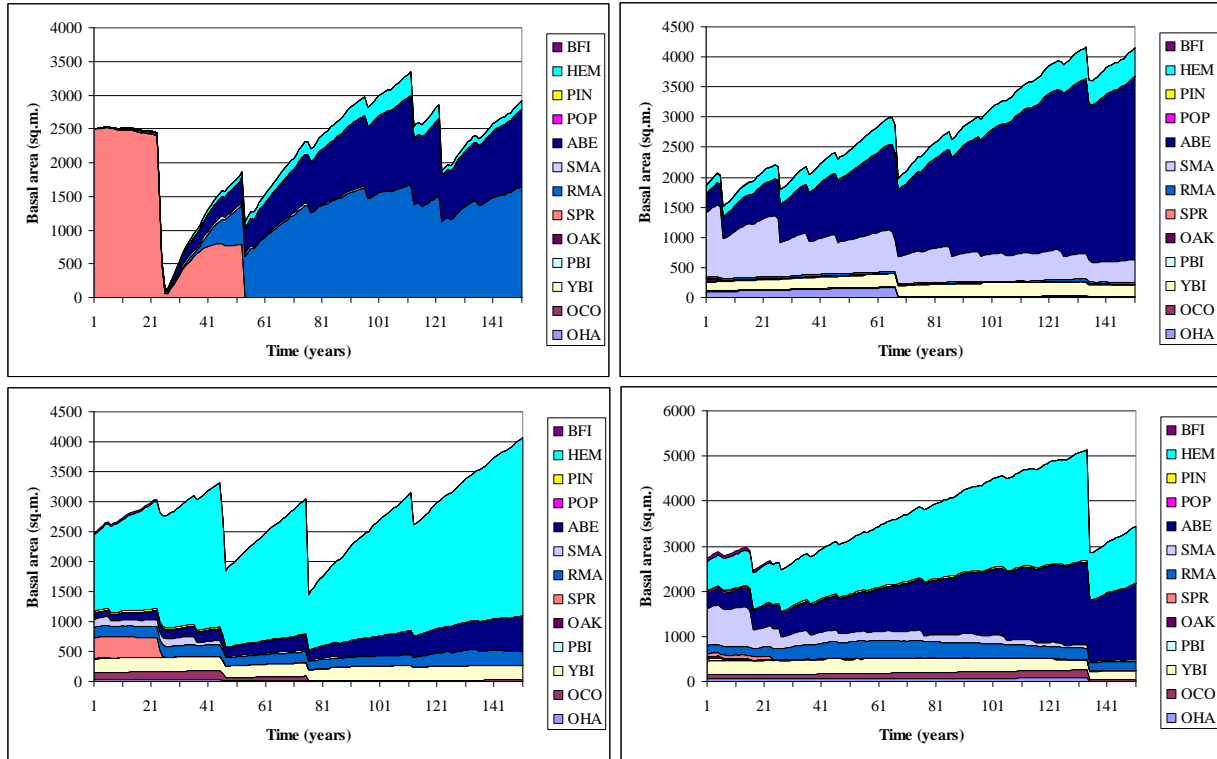


Fig. 26. Stand dynamics of the four virtual sample-plots under the influence of the A1b scenario (CGCM3) without the effect of CO₂.

Impact of climate change with CO₂

Simulations of landscape dynamics under climate change with CO₂ effects differ significantly from the results obtained without CO₂. The clearest difference is in the rate of basal area accumulation and the maximum amounts of basal area accumulated (Fig. 27). Whereas without the effect of CO₂, basal area barely reach maximum values of 50 m²/ha, with CO₂ effect basal areas reach values of over 60 m²/ha (Fig. 27). The results also show that there is a slight shift towards beech at the expense of hemlock.

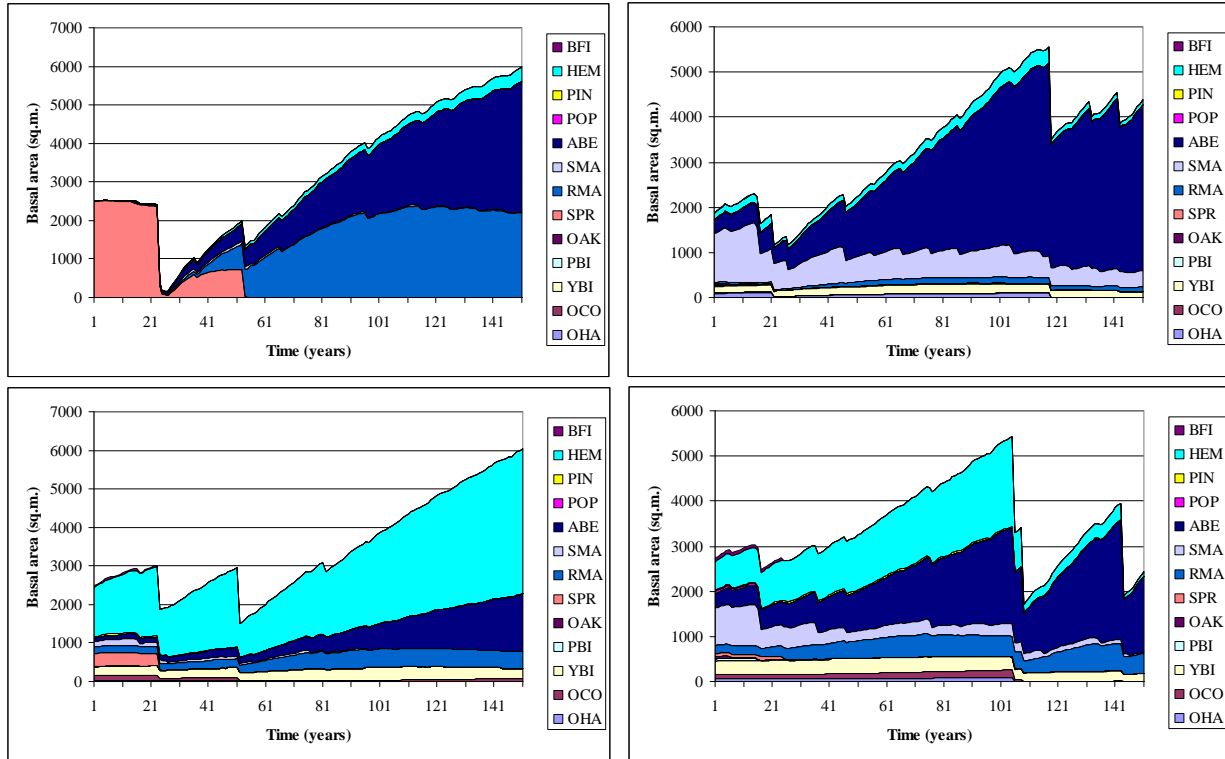


Fig. 27. Stand dynamics of the four virtual sample-plots under the influence of the A1b scenario (CGCM3) with the effect of CO₂.

Impacts of climate change and beech bark disease

Beech bark disease, which according to the expert panel will likely move into the study area over the coming years, had a very important impact on forest dynamics in the model. We can observe from the output at the stand scale (Fig. 28) that beech becomes much more important than under the climate change only scenario (Fig. 27). The same trend is evident at the landscape scale (Fig. 29). That beech becomes more important in stands when beech bark disease is present may seem counter intuitive. However, beech bark disease, while triggering increased mortality in older stems, causes an increase in the root sprouting of disturbed beech. This leads to a vicious circle of increased mortality and increased root sprouting in beech that can lead to the exclusion of other species. This trend has been observed further south where the disease is well established (Le Guerrier et al. 2001).

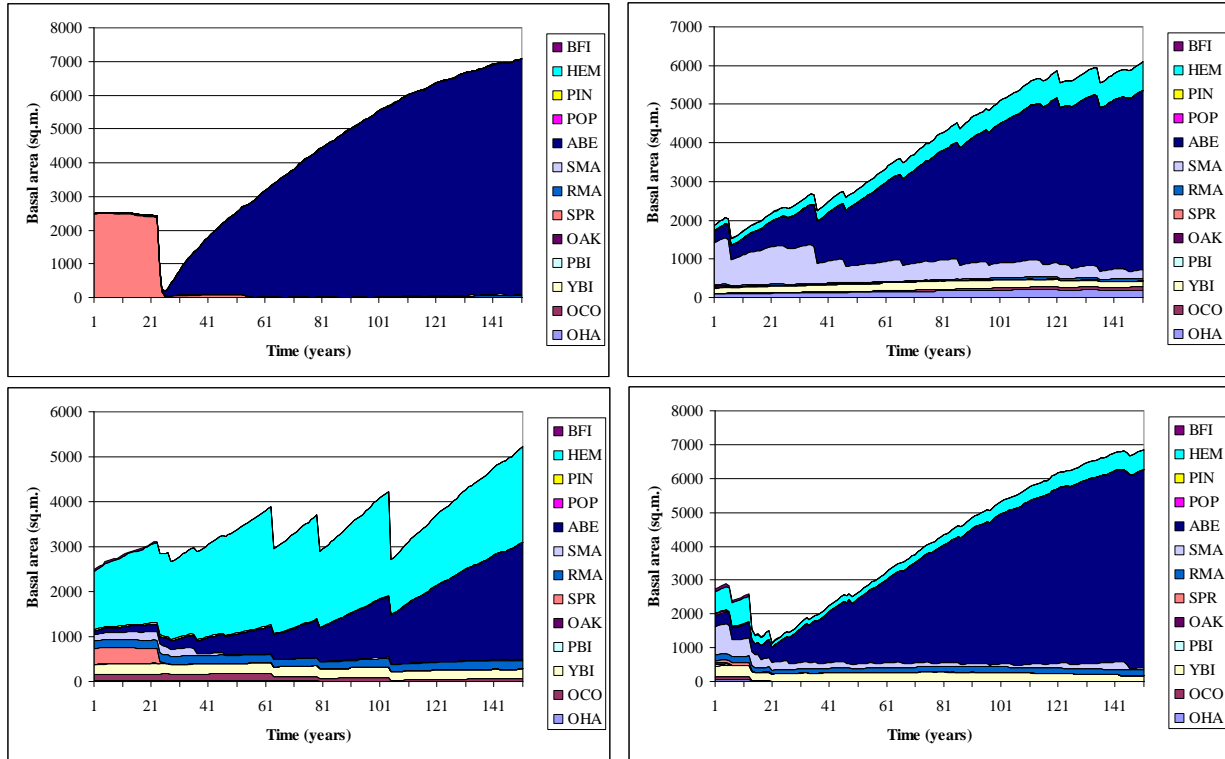


Fig. 28. Stand dynamics of the four virtual sample-plots with natural disturbance under the influence of the A1b scenario (CGCM3) with CO₂, and with the effect of beech bark disease.

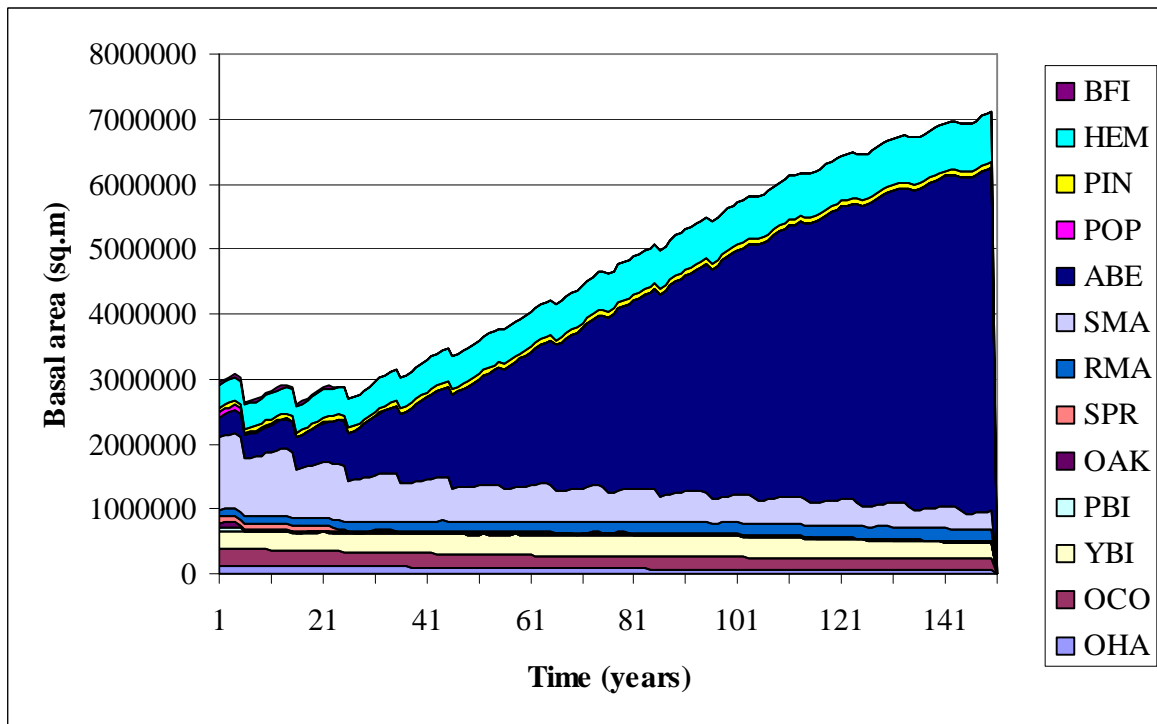


Fig. 29. Basal area by species over the course of a 150-year simulation, simulating natural disturbance, no harvesting, beech bark disease, and the A1b-CGCM3 climate, for all forested cells in the model.

The situation becomes considerably worse in terms of stand composition and landscape scale stand diversity when harvesting is turned on; with every disturbance within a stand, beech can be seen to become increasingly important (Fig. 30), and at the landscape scale, the species dominates almost entirely (Fig. 31). The combined disturbances due to defoliation, windthrow, and partial harvesting create conditions that promote the dominance of beech at the expense of all other species.

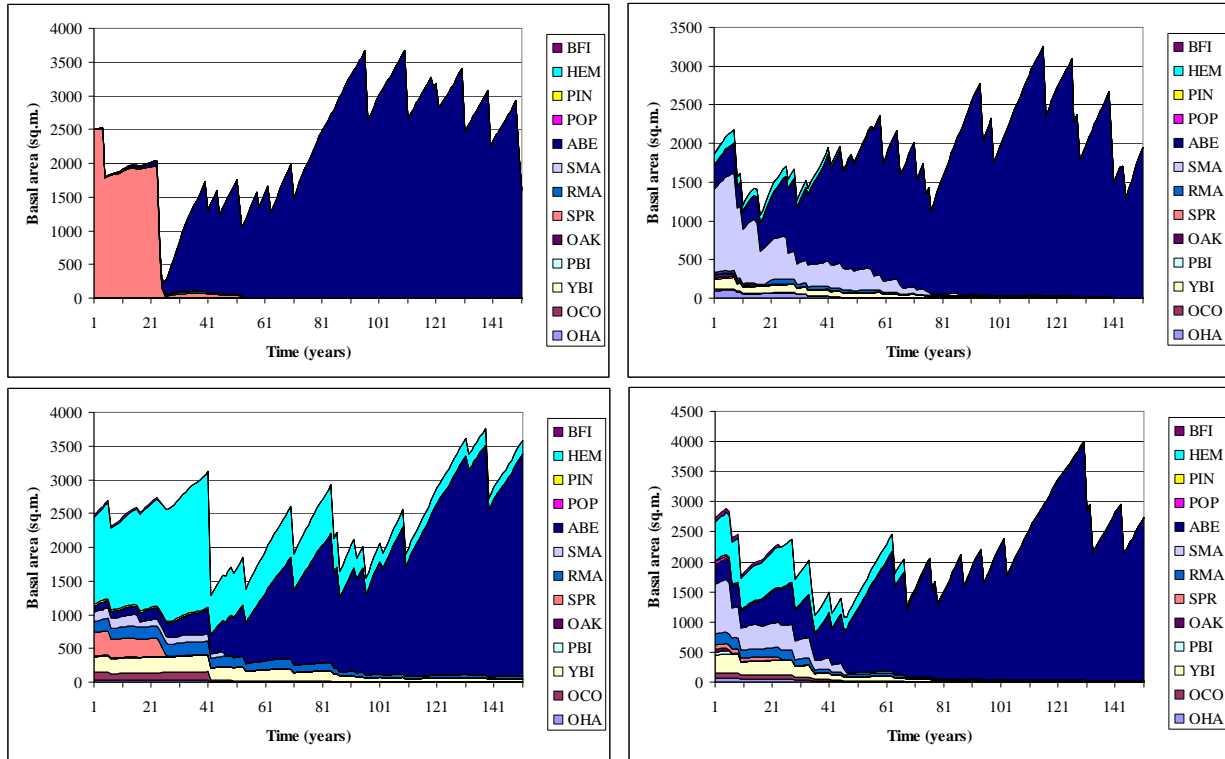


Fig. 30. Stand dynamics of the four virtual sample-plots with natural disturbance under the influence of the A1b scenario (CGCM3) with CO₂, and with the effect of beech bark disease.

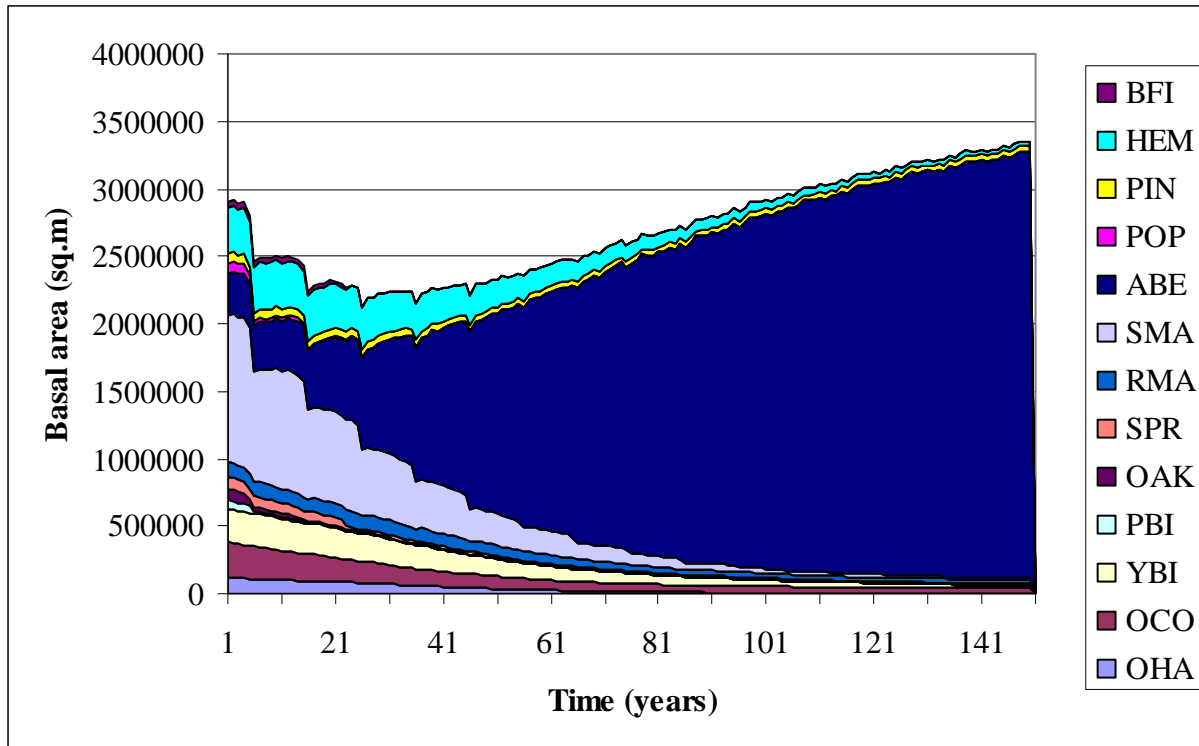


Fig. 31. Basal area by species over the course of a 150-year simulation, simulating natural disturbance, harvesting, beech bark disease, and the A1b-CGCM3 climate, for all forested cells in the model.

Development of adaptation strategies

Clearly, the situation presented by the simulations of climate change with beech bark disease (Fig. 31) is not acceptable according to the terms laid out by public participation group. The results of the simulations clearly show that the value of ecosystem diversity over the landscape is not respected. Therefore, adaptation strategies were developed.

From the trial and error process of adaptation strategy development, several adaptation strategies were put implemented in the model but were judged unsuccessful, based again on the standards established by the public participation group. However, from each failed adaptation something was learned that contributed to the development of the next adaptation. Here we present these unsuccessful strategies, along with their resulting landscape impacts.

Reduce harvest rate

The first strategy developed involved a reduction of the rate of harvest. Results had shown that increased disturbance rates aggravated the root suckering of beech and increased its dominance (Fig. 31). Therefore, two reduced harvest rates were tested: a 25% and 50% decreased from the standard rate (which is itself a 20% reduction of the maximum potential harvest rate, as described in the methods).

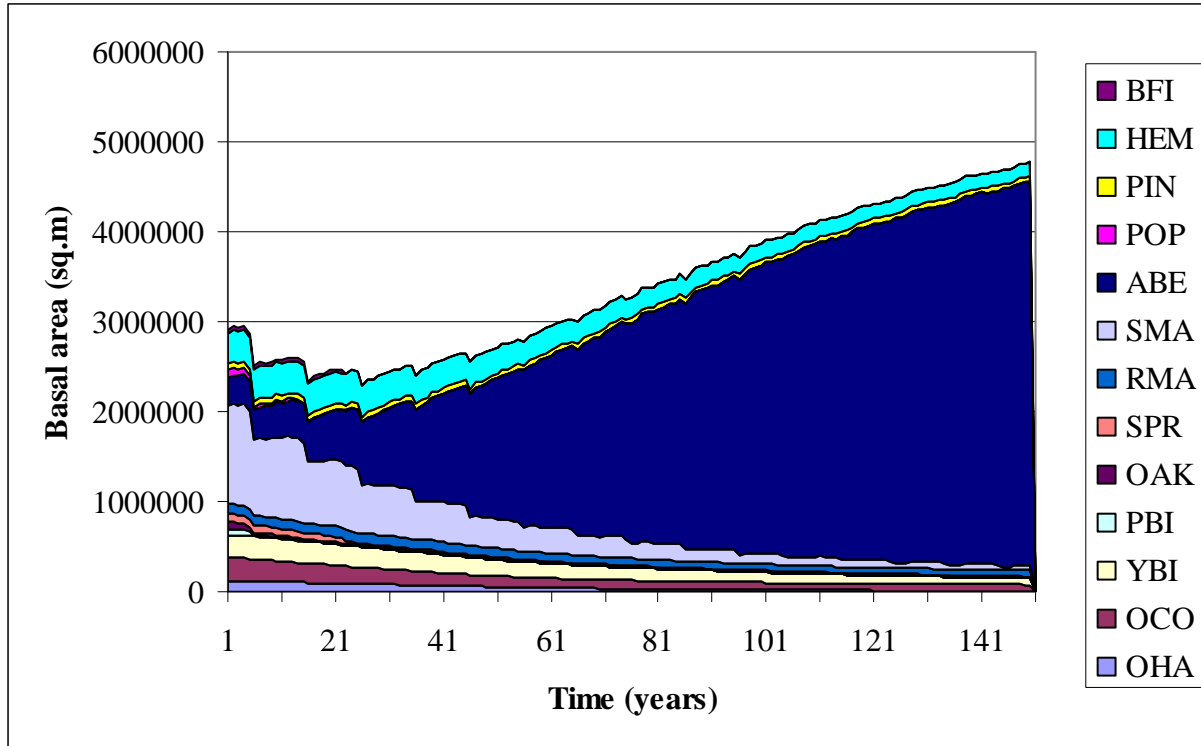


Fig. 32. Basal area by species over the course of a 150-year simulation, simulating reduced harvesting (25%) and the A1b-CGCM3 climate, for all forested cells in the model.

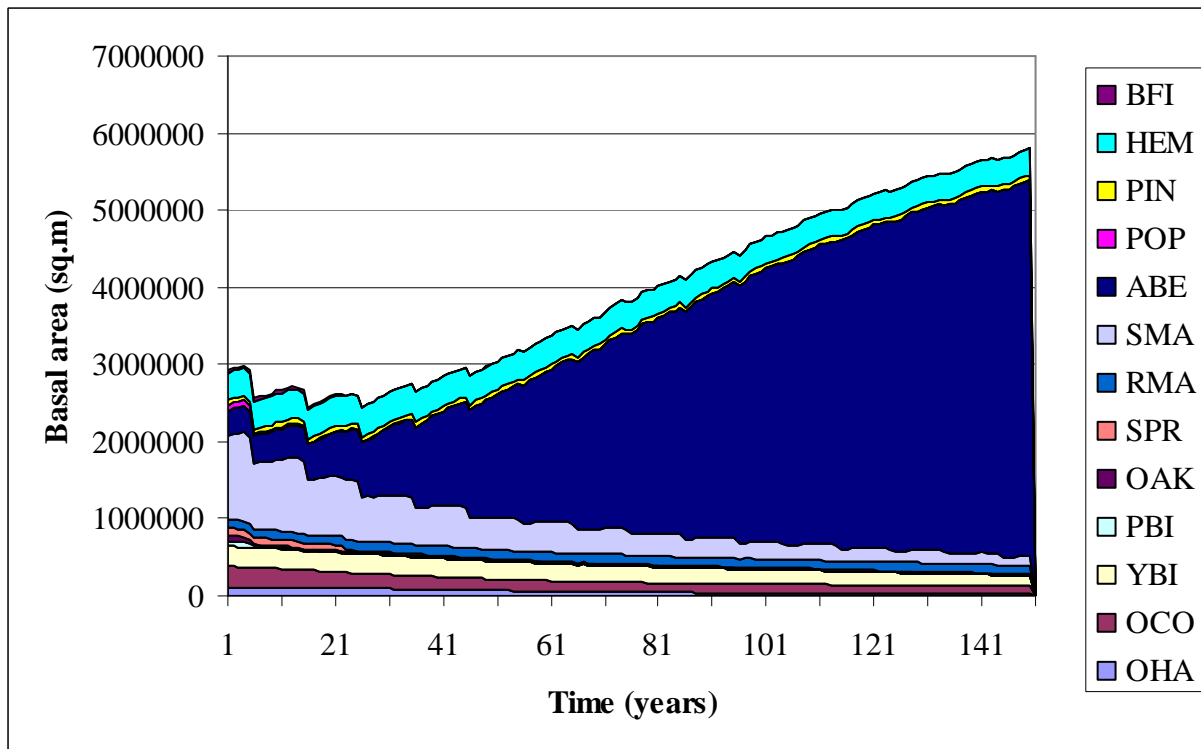


Fig. 32. Basal area by species over the course of a 150-year simulation, simulating reduced harvesting (50%) and the A1b-CGCM3 climate, for all forested cells in the model.

The reduced rates of harvest lead to a somewhat decreased dominance of beech, although beech clearly remained the dominant species at the landscape scale (Fig. 32, Fig. 33). The percentage of the landscape basal area as beech at the end of simulation for the baseline harvest rate is 97%, 91% for the middle rate scenario, and 85% for the lowest rate of harvesting. We considered that this was still too high, and chose to investigate other forms of adaptation.

Apply preference for beech when harvesting

Since the problem with the outcome of previous adaptations was an over-abundance of beech, we developed an adaptation strategy that preferentially targeted beech for partial harvesting. This led to very little change from the baseline strategy (partial harvesting at base rate) decreasing the proportion of landscape basal area by only 1% (data not shown).

Clear-cut, plant pine and oak

In an attempt to re-establish species other than beech, a strategy was developed according to which stands would be clear-cut (again targeting beech dominated stands), and planting would be carried out. Clear-cutting was only applied in the model if beech was present. Given that we had expected pine and oak to become better competitors under climate change conditions (since they are the species that tolerate moisture stress most among simulated species), we chose to plant these species.

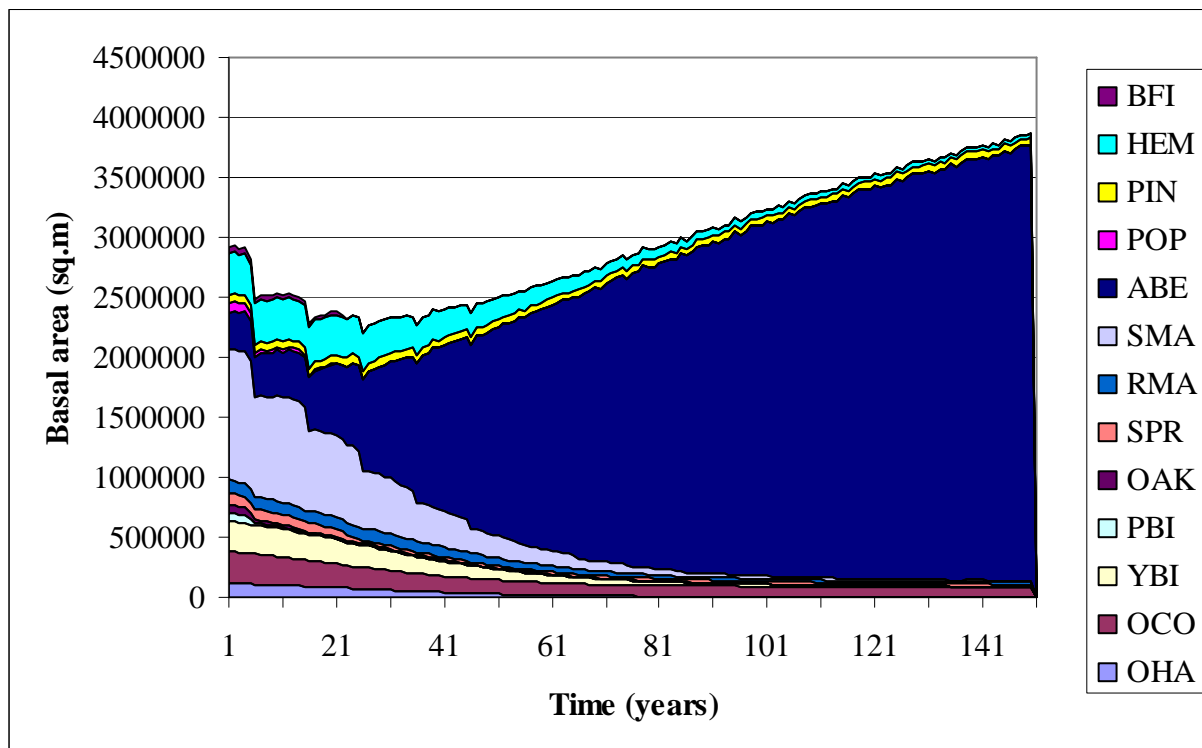


Fig. 34. Basal area by species over the course of a 150-year simulation, simulating clear-cut/plant oak and pine adaptation and the A1b-CGCM3 climate with beech bark disease, for all forested cells in the model.

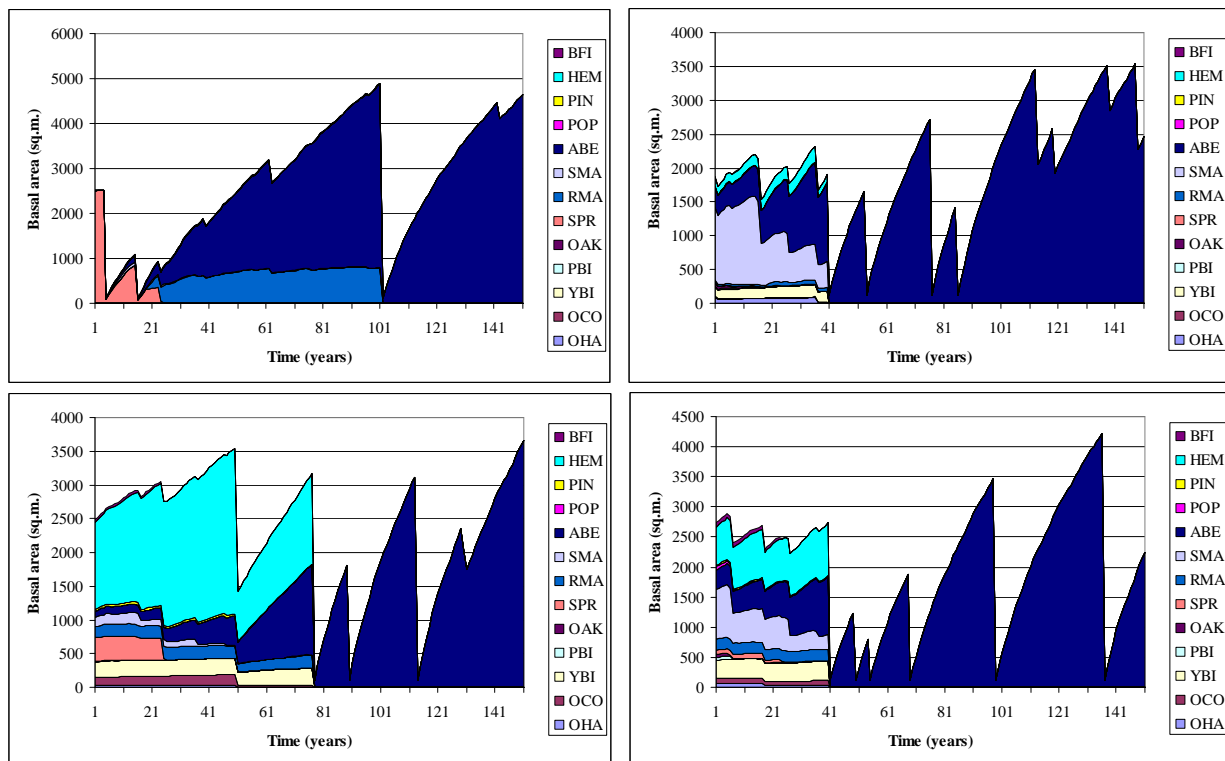


Fig. 35. Stand dynamics of the four virtual sample-plots with natural disturbance under the influence of the A1b scenario (CGCM3) with CO₂, with the effect of beech bark disease, and with the clear-cut/plant oak and pine adaptation.

This adaptation lead to exactly the same end-point as the baseline strategy (97% of the landscape basal area as beech) at the landscape scale (Fig. 34). In certain respects it was worse, since dominance increased at a faster rate. Thus, by the year of simulation 50 under this adaptation, beech had reached 72% of the total landscape basal area, while under the baseline treatment beech occupied 66% of the landscape basal area by the same time. Evidence of this can be seen at the stand scale (Fig. 35). For this adaptation, planting had no effect since established regeneration in the 20-40 year regeneration bank was already dominated by beech by the time clear-cutting and planting occurred.

Clear-cut, plant pine and oak, clear competing vegetation

Given the result of the previous adaptation, we simulated the control of vegetation in the 20-40 year regeneration bank by changing the composition of this bank to that of the planted seedlings. As outlined in the methods section, this does not imply that 20 year old seedlings are planted, but simply that when recruitment occurs, it is the planted seedlings that are recruited. This is partly justified by the fact that seedlings in an open setting evolve much more rapidly than seedlings established under a closed canopy. Results from this simulation show important change from the baseline strategy.

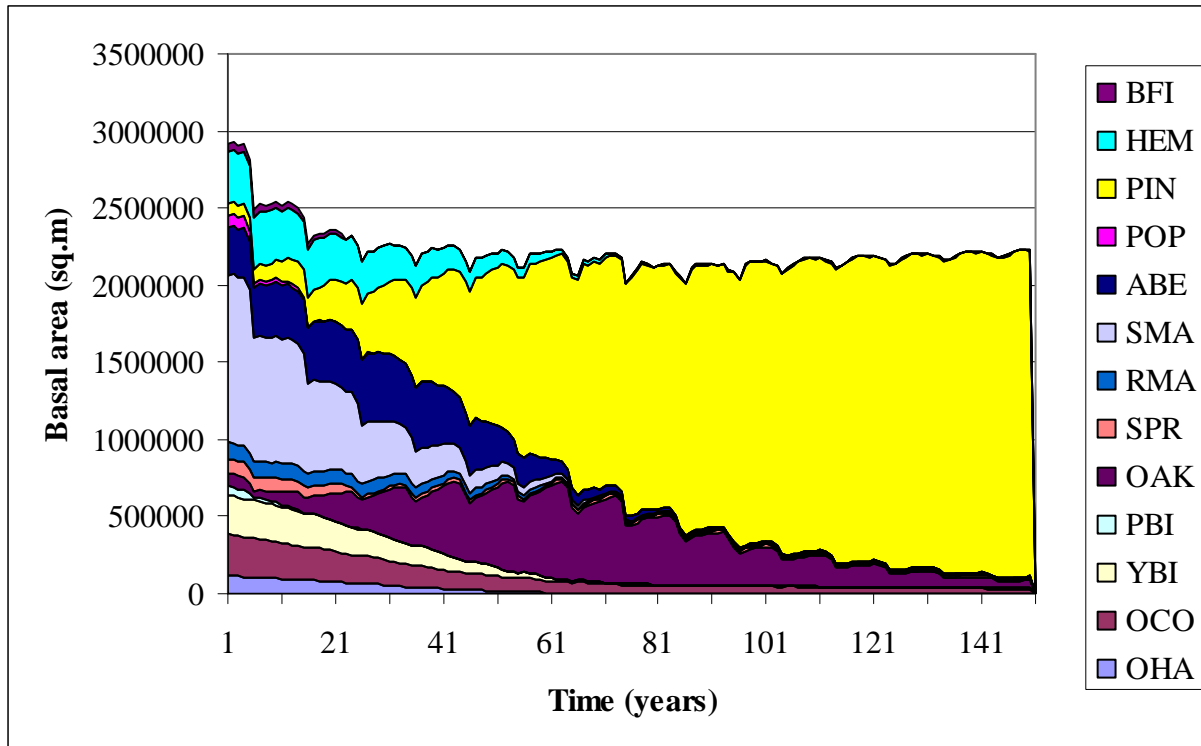


Fig. 36. Basal area by species over the course of a 150-year simulation, simulating the clear-cut/plant oak and pine adaptation and the A1b-CGCM3 climate with beech bark disease, for all forested cells in the model.

The results show that beech is no longer a problem (Fig. 36). However, such a uniformly applied strategy results in a landscape composition that is equally problematic in terms of ecosystem diversity. Also, the oak component of the planted stock does not seem able to compete with pine under climate change conditions. It appears that the oak component is greatly affected by the 10 year cycle of gypsy moth (Fig. 36). While this adaptation showed us that the beech component can be displaced, it did not offer an interesting outcome in terms of ecosystem diversity.

Clear-cut, plant by site type, clear competing vegetation

In order to create landscape scale compositional diversity through a strategy involving extensive tree planting, a system was developed whereby species composition of the planted stock for a given site was determined based on the surficial geology of the site. An analysis was carried out to determine the species composition of stands on the various surficial geology types in the study area. For each surficial geology type, the two most common composition types (among the 116 total for the area) were identified (Table 11). For a site of a given geology type then, a virtual coin toss was carried out to determine which of the two most common compositions was to be applied.

| Surficial geology | Common composition types | |
|-------------------|--------------------------|--------|
| | First | Second |
| 1A | 38 | 22 |
| 1AA | 38 | 38 |
| 1AM | 1 | 2 |
| 1AR | 1 | 2 |
| 1AY | 1 | 2 |
| 2A | 2 | 34 |
| 2BD | 115 | 115 |
| 2BE | 38 | 116 |
| 3 | 84 | 57 |
| 5A | 1 | 2 |
| 5S | 22 | 115 |
| 7 | 115 | 89 |
| 9 | 115 | 115 |
| R | 2 | 1 |

Table 11. The 14 surficial geology types of the study area, and the corresponding most common and second most common composition types found on those geology types; the species composition of these types is provided in Appendix B.

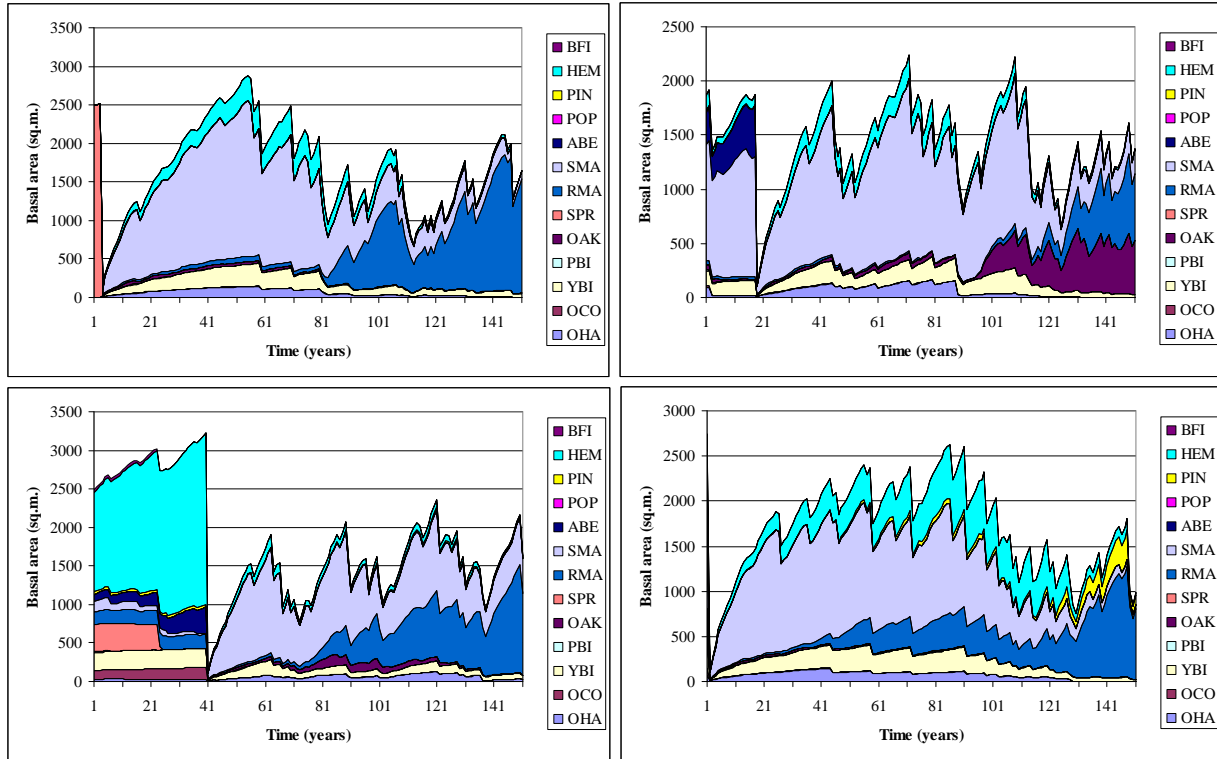


Fig. 37. Stand dynamics of the four virtual sample-plots with natural disturbance under the influence of the A1b scenario (CGCM3) with CO₂, with the effect of beech bark disease, and with the clear-cut/plant by surficial geology adaptation.

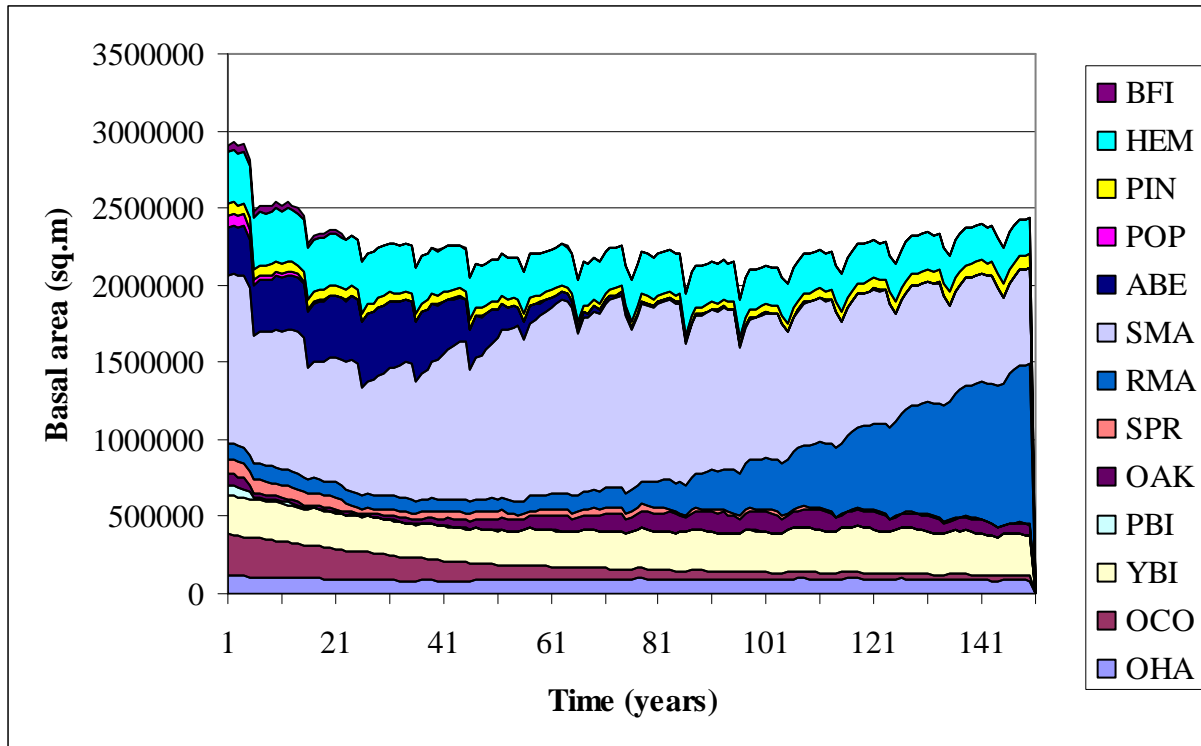


Fig. 38. Basal area by species over the course of a 150-year simulation, simulating the clear-cut/plant by surficial geology adaptation and the A1b-CGCM3 climate with beech bark disease, for all forested cells in the model.

Results from this adaptation indicate that beech can be removed from the landscape and replaced by other species (Fig. 37), to create a landscape that is more diverse (Fig. 38) than without any adaptation (Fig. 31). It can be observed in the stand scale evolution of stands that clear-cutting was only applied if beech was present in the stand (Fig. 37). Under this adaptation, more rare species such as yellow birch and other hardwoods occupy a significant proportion of the landscape. Indeed, the pattern of stand diversity under this adaptation (Fig. 39) is quite similar to the pattern under the assumption of no climate change for the same period (Fig. 40). These two maps differ in terms of species composition, with red maple being favoured under the climate change assumption (Fig. 39) rather than sugar maple (Fig. 40). This is largely due to the high susceptibility and vulnerability of sugar maple to defoliation, particularly under the climate change scenario.

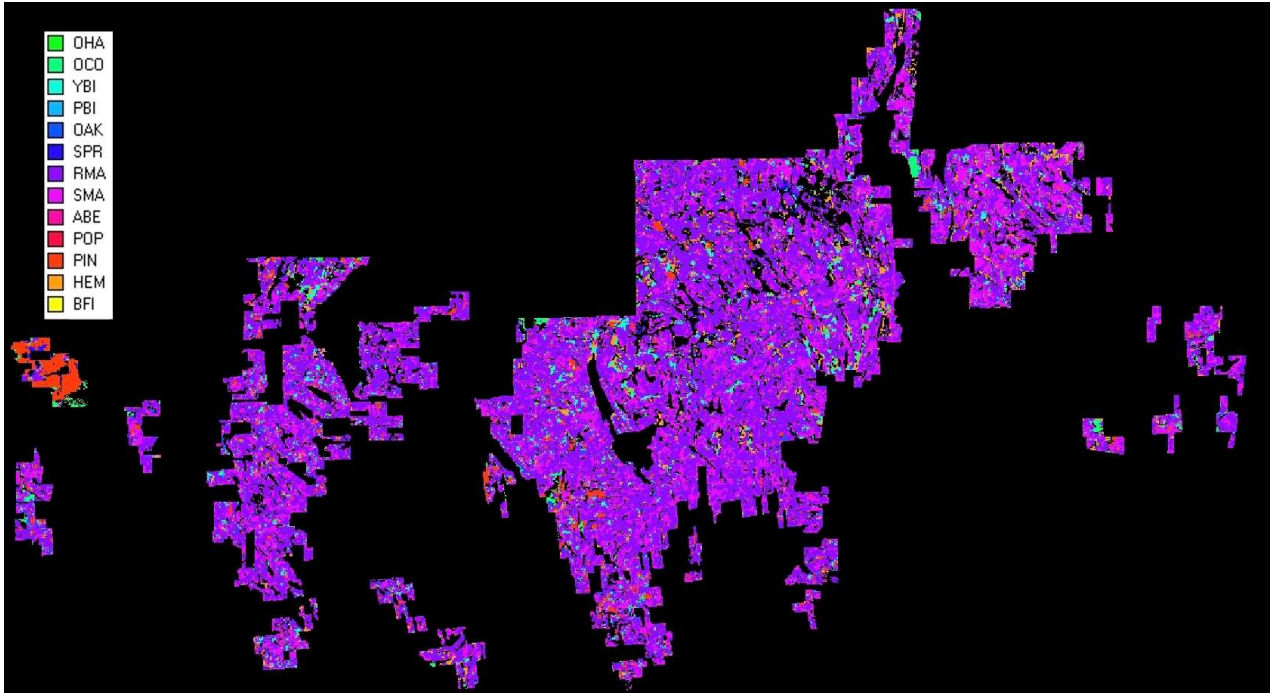


Fig. 39. Map of the study area showing the most abundant species for each cell at the end of a 150-year simulation of the A1b-CGCM3 scenario, with the planting by surficial geology adaptation; species names are provided in Table 3.

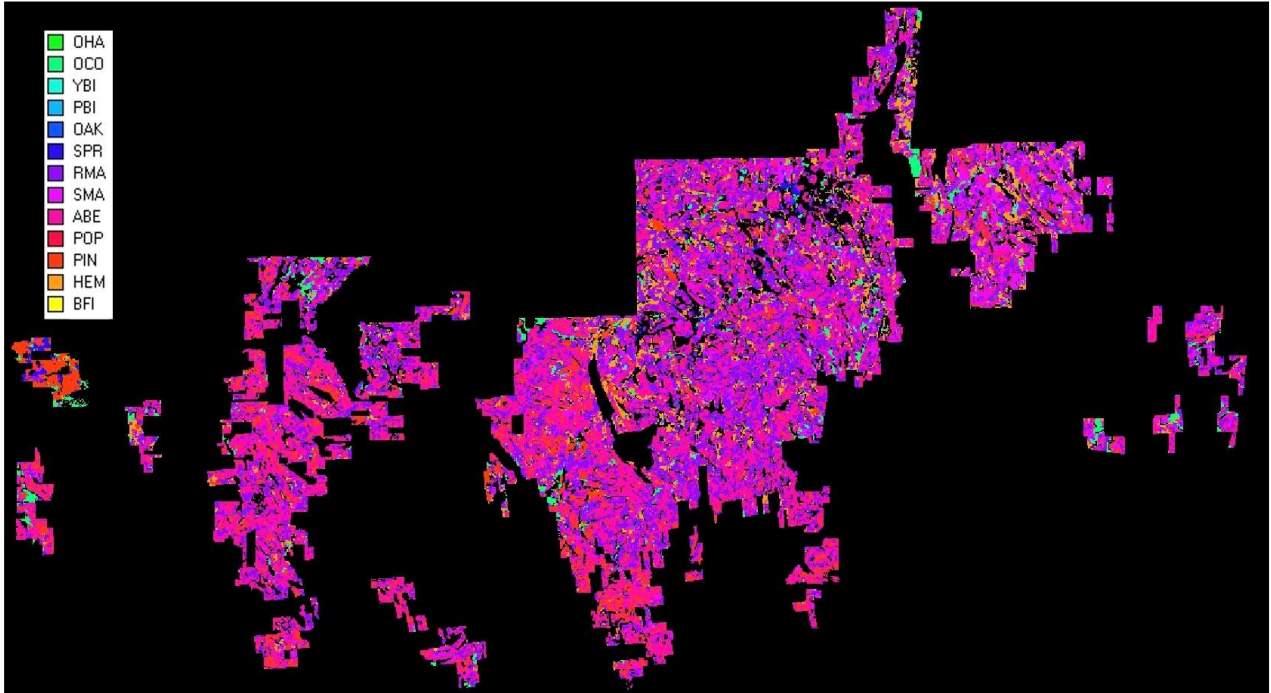


Fig. 40. Map of the study area showing the most abundant species for each cell at the end of a 150-year simulation under the no climate change assumption.

The productivity of virtual sample plots (Fig. 37) is not as high as the productivity under climate change without beech bark disease (Fig. 27), again principally due to the 10-year defoliation cycle. Fine tuning of the species composition could lead to increases in productivity. However, based on the input from the public participation process, the productivity of forest ecosystems per se is not a priority. Therefore, we feel that this adaptation meets all established requirements.

Adaptations under several potential futures

The final step of the analysis was to look at the most promising adaptations under the full range of climate scenarios available. To this end, we ran 3 adaptations: do nothing; clear-cut, plant by geology, and control vegetation over all forested area (adapt all); and the latter applied to only one zone of the study area (adapt zone) representing roughly 70% of the total forested area. These were run under the influence of no climate change and 12 climate change scenarios (Table 1), and in the presence and absence of beech bark disease. This set of analysis thus resulted in 78 runs of 150 years.

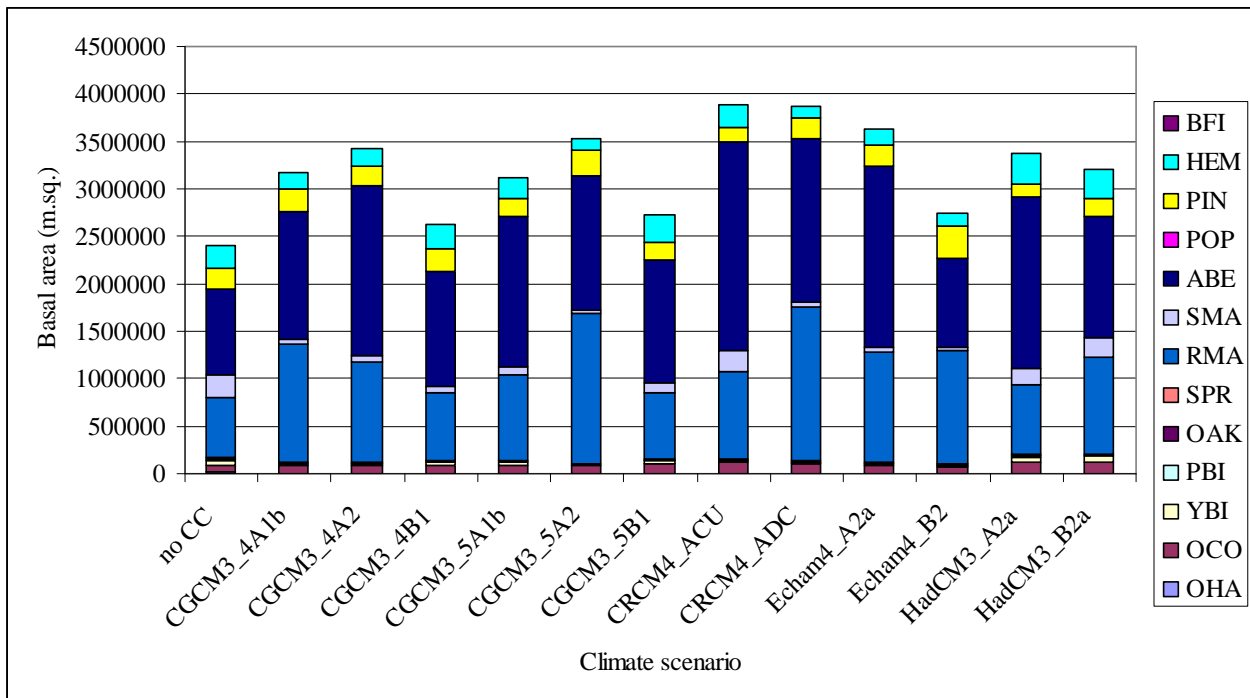


Fig. 41. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, without adaptation and in the absence of beech bark disease (do nothing); the GCM names and emissions scenario are provided.

Results from the do nothing adaptation in the absence of beech bark disease indicate that the total basal area of the landscape is quite variable over the range of climate scenarios (Fig. 41). The highest total basal areas are obtained under the A2 scenarios, followed by the A1b scenario, while the B1 and B2 scenarios result in the lowest quantities of basal area. Composition is also quite variable. In particular, the balance between red maple and beech varies greatly among scenarios. It is also interesting to note that the two CRCM scenarios result in considerably different outcomes,

despite that fact that they are based on the same emissions scenario and GCM (CGCM3). This illustrates that the variability among replicates of the same climate scenario can be of significance.

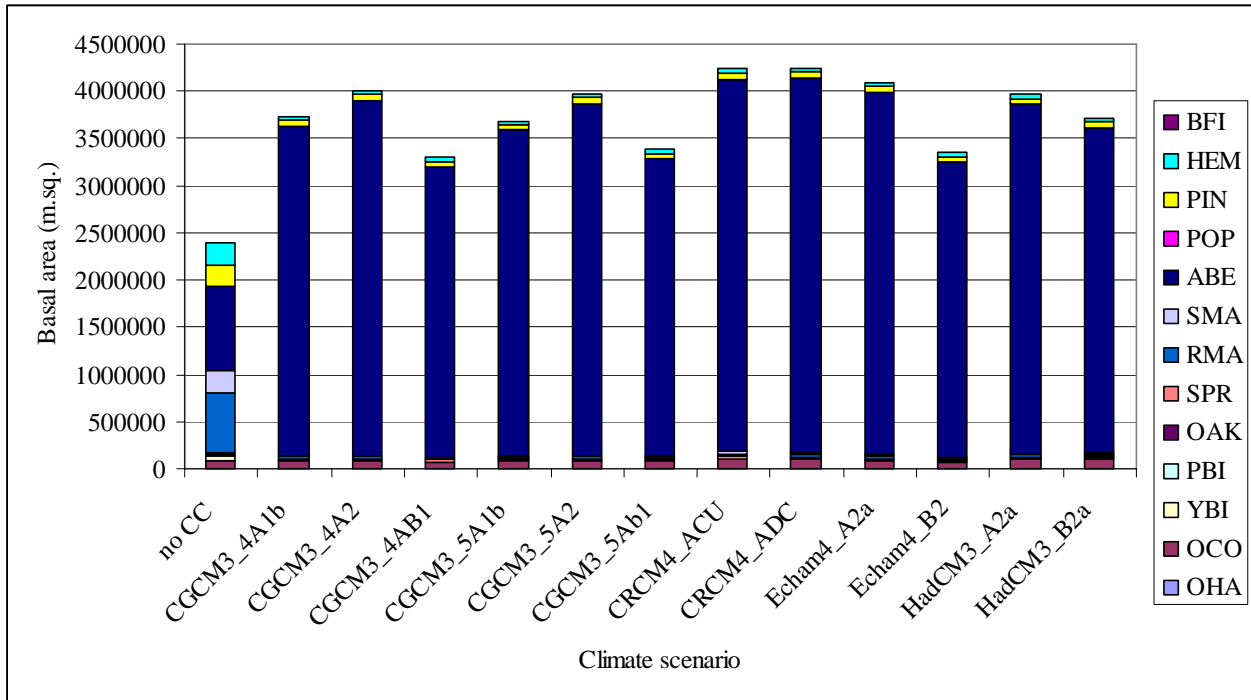


Fig. 42. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, without adaptation and in the presence of beech bark disease (do nothing); the GCM names and emissions scenario are provided.

The simulations under climate change and beech bark disease illustrate the potential significance of the disease for the hardwood forests of eastern Canada (Fig. 42). Regardless of the GCM model and emissions scenario, and despite the fact that total landscape basal area varies, the outcome of simulation is essentially the same in all cases. Beech comes to dominate the landscape at the expense of all other species. In certain cases, hemlock, pine, and other conifers can maintain a limited presence, but in quantities far inferior to the no climate change scenario. Landscape total basal is greater under these assumptions, though the lack of ecosystem diversity makes these outcomes undesirable in terms of the criteria established by the public participation process.

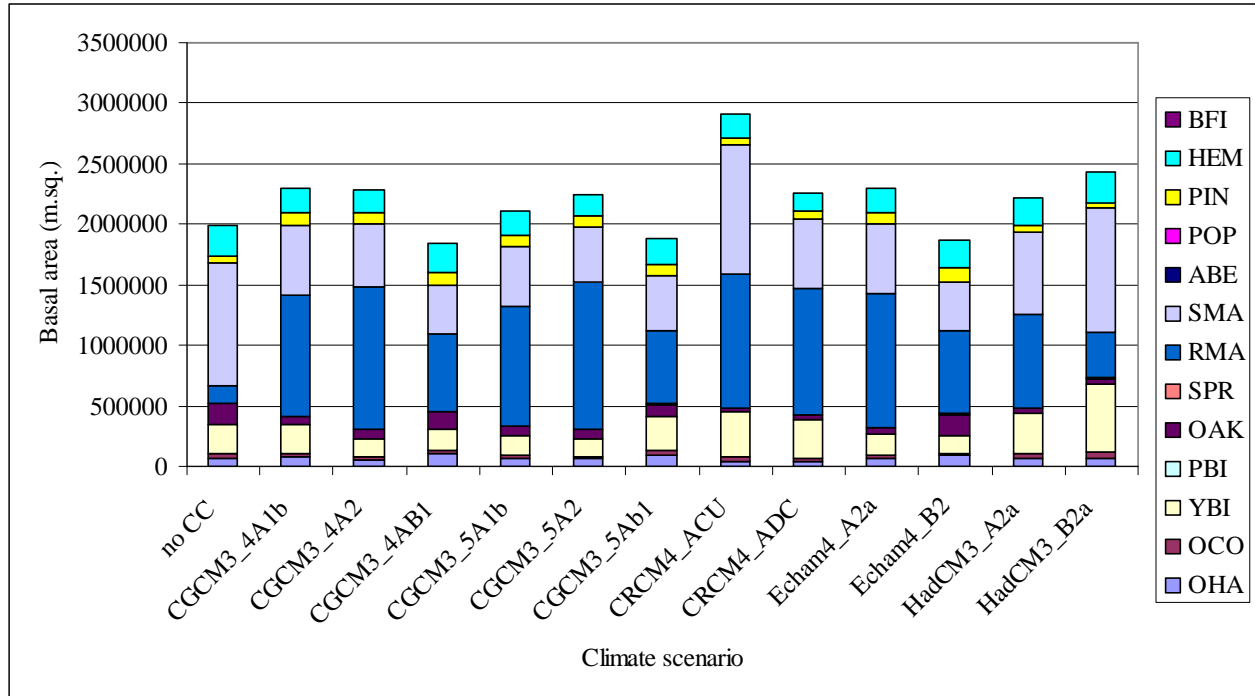


Fig. 43. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, with adaptation (adapt all) and in the absence of beech bark disease; the GCM names and emissions scenario are provided.

The clear-cut, plant, and vegetation control adaptation applied to all forested area (adapt all) simulations show outcomes that are promising in terms of values laid out by the public participation process. Under these adaptations and climate assumptions, the landscape is able to maintain a balanced diversity of species (Fig. 43). The balance between sugar maple and ref maple varies considerably among scenarios, but this element though currently of economic interest, was judged unimportant by the public participation group.

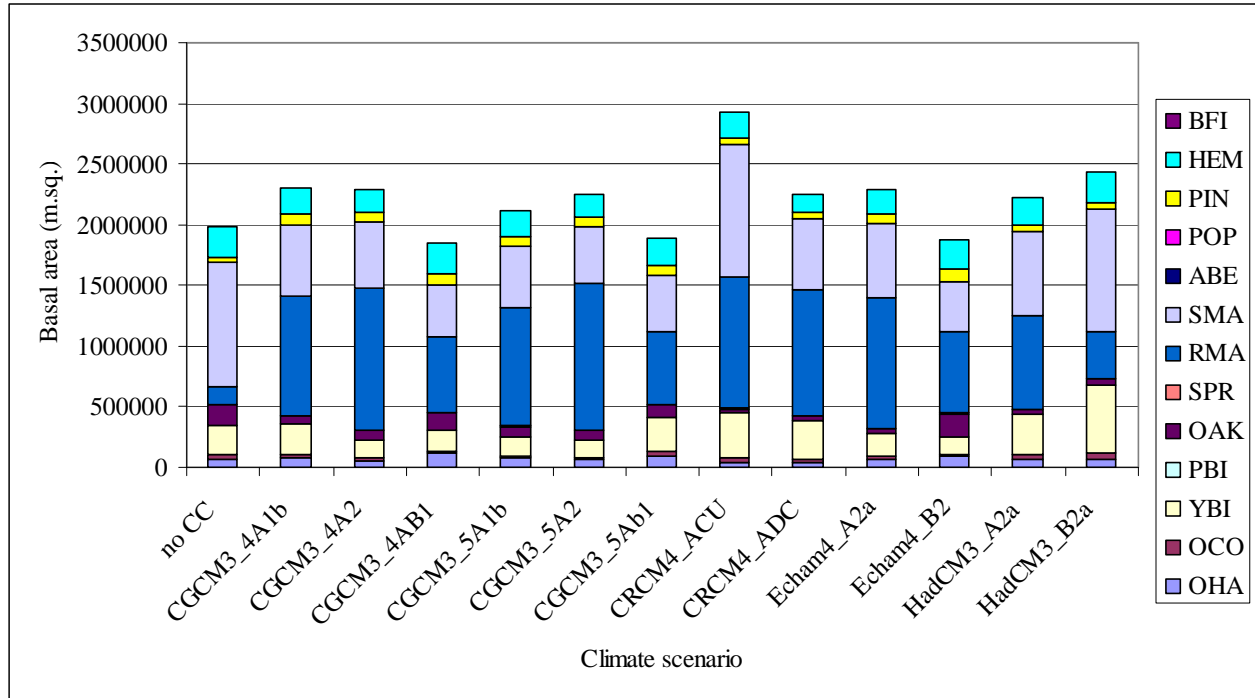


Fig. 44. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, with adaptation and in the presence of beech bark disease (adapt all); the GCM names and emissions scenario are provided.

As anticipated, the simulations of adaptation with beech bark disease (Fig. 44) do not differ greatly from the simulations without beech bark disease (Fig. 43) in terms of composition and total landscape basal area, since beech has been completely removed from the landscape. This shows that the adaptation strategy is robust with regards to beech bark disease. That is, regardless of whether or not beech bark disease moves into the study area in the future, the adaptation strategy will lead to the same result, given the assumptions made here.

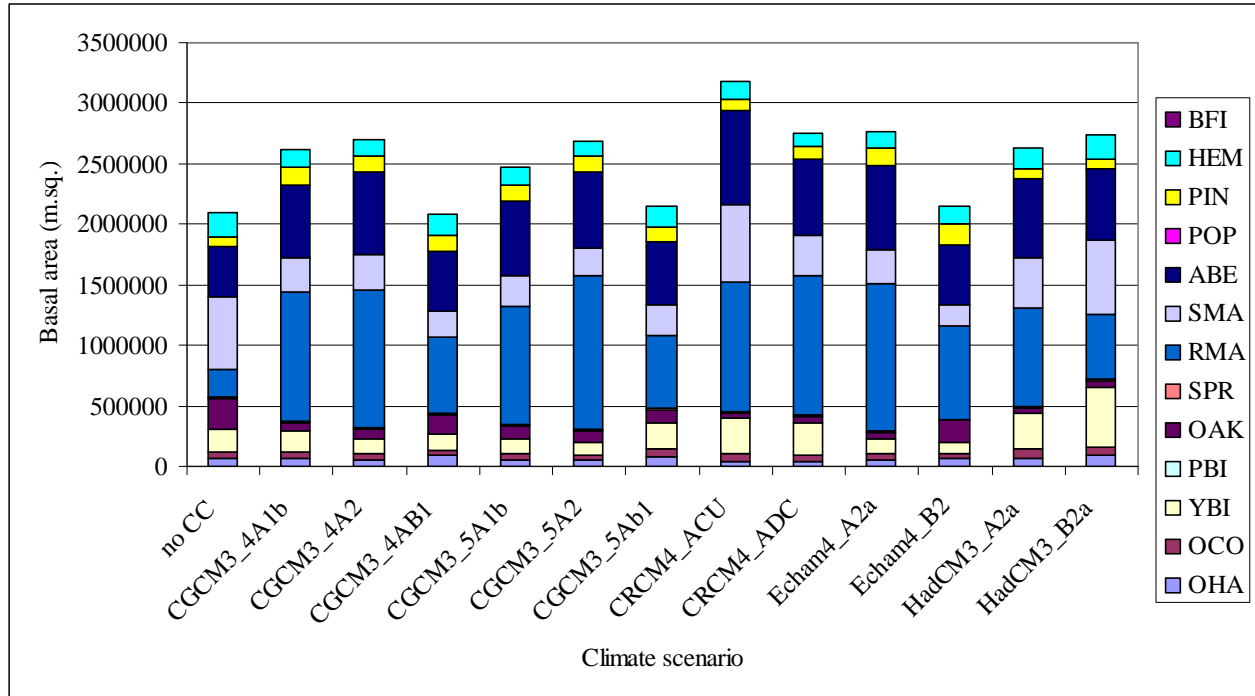


Fig. 45. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, with adaptation over one zone of the forested area (adapt zone) and in the absence of beech bark disease; the GCM names and emissions scenario are provided.

The aspatial results of the simulation of adaptation over only one zone of the study area show promise (Fig. 45). Output from the model demonstrates that regardless of the climate scenario applied, results are quite similar to the base case of no climate impacts on the forest. While total landscape basal area is quite variable, the proportion of the basal area as each species is surprisingly stable over all climate scenarios. However, if the spatial result of the adaptation are examined (Fig. 46), it becomes clear that the dominance of beech is quite widespread outside the treated area. In our opinion, this adaptation strategy will be of interest if there is a societal desire to diversify approaches, or if the costs of such an adaptation are prohibitive (this issue is addressed in the following section (Costs and benefits of adaptations)).

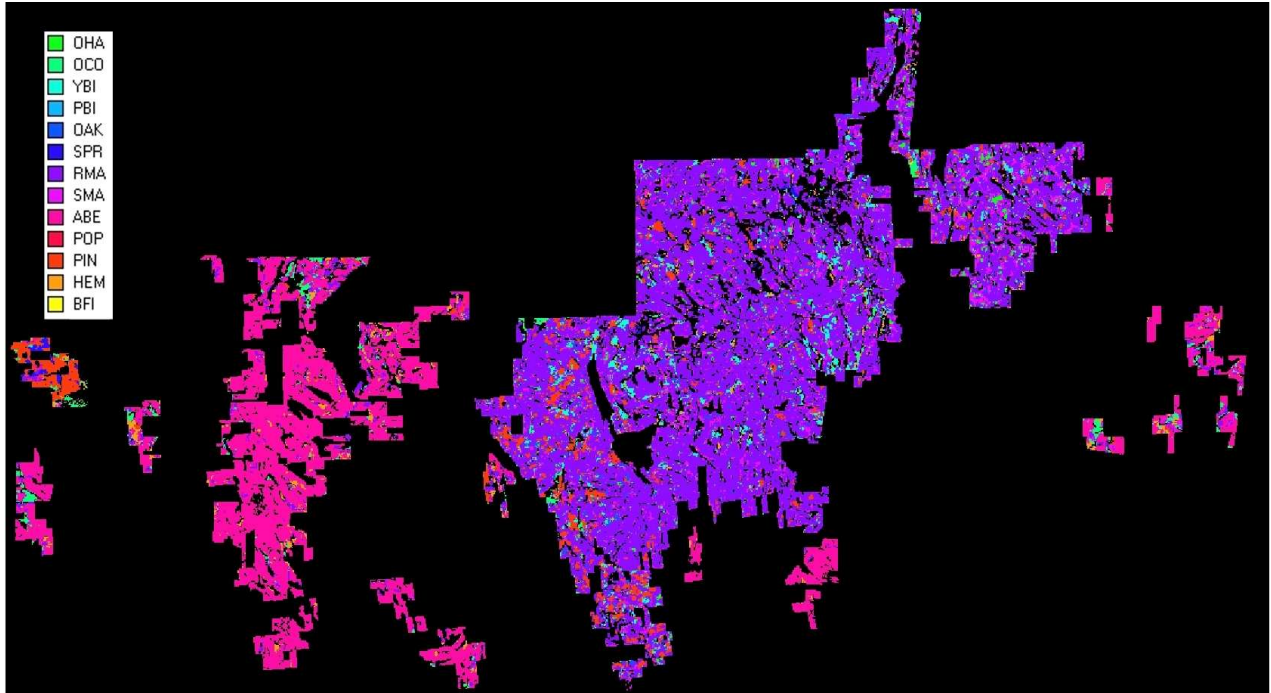


Fig. 46. Map of the study area showing the most abundant species for each cell at the end of a 150-year simulation of the A1b-CGCM3 scenario without beech bark disease, with the planting by surficial geology adaptation applied to one zone of the forest area (adapt zone).

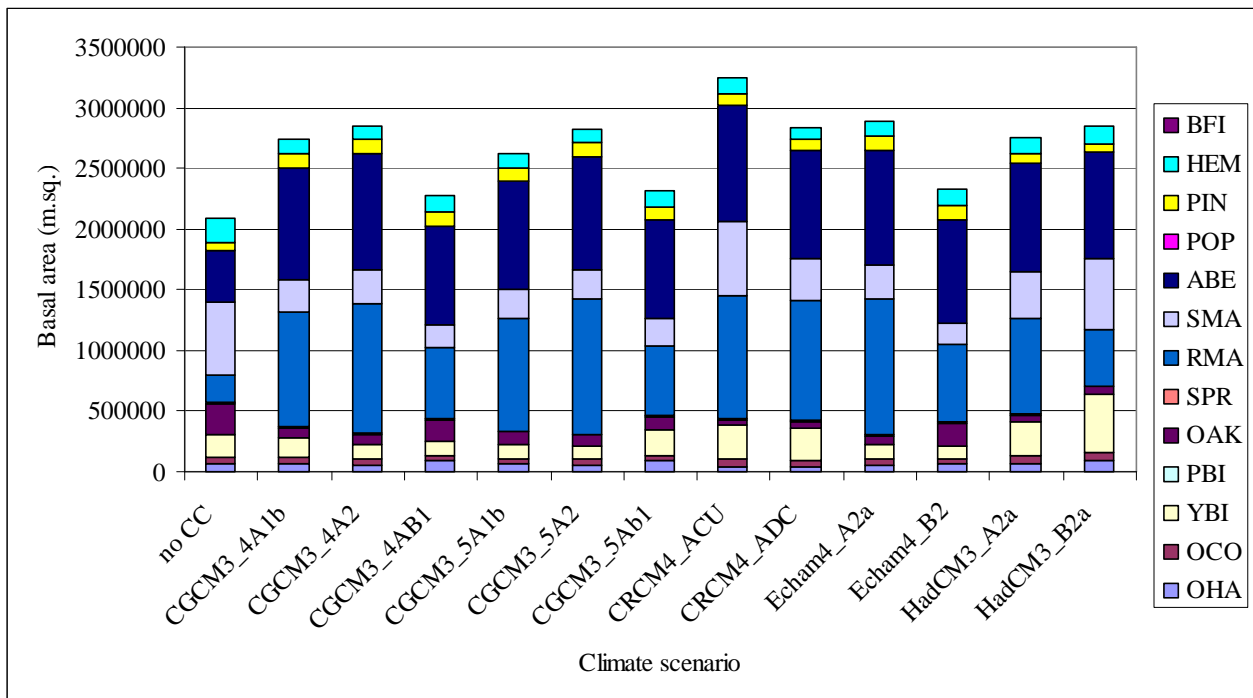


Fig. 47. The distribution of basal area among species for the landscape at the end point of 150 year simulations, under 13 different climate change assumptions, with adaptation over one zone of the forested area (adapt zone) and in the presence of beech bark disease; the GCM names and emissions scenario are provided.

Simulation of adaptation strategies over only one zone, in the presence of climate change and beech bark disease, is quite similar to the same simulations without beech bark disease (Fig. 47). The important difference being that outside the treated area and in the presence of beech bark disease, beech forms an almost continuous cover of dominance (Fig. 48). Again, we feel that this adaptation will only be useful as a form of compromise between doing nothing and implementing adaptation over the entire study area.

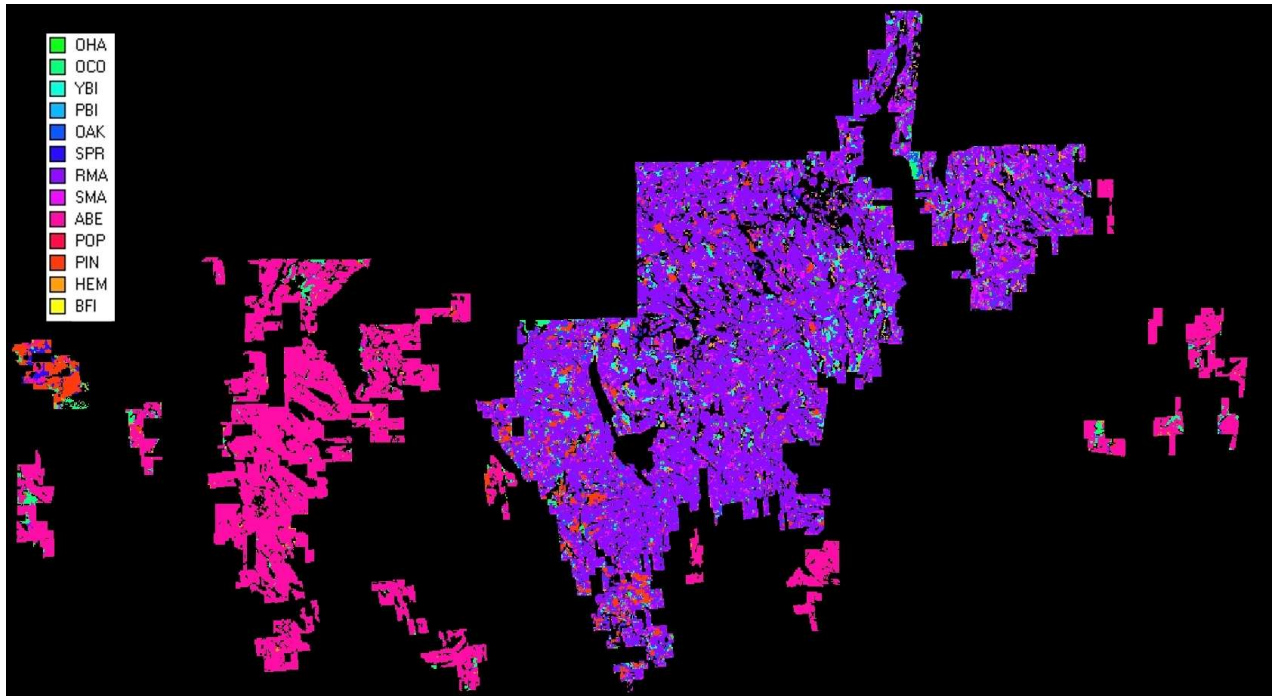


Fig. 48. Map of the study area showing the most abundant species for each cell at the end of a 150-year simulation of the A1b-CGCM3 scenario with beech bark disease, with the planting by surficial geology adaptation applied to one zone of the forest area (adapt zone).

Costs and benefits of adaptations

The patchworks modeling work allowed us to establish the medium term (25 years) costs and benefits of adaptation strategies for the study area. We implemented the three adaptations described above (do nothing, adapt all, and adapt zone). Results are shown in Table 12. There were certain surprises in the results of this modeling analysis. For example, the implementation of adaptation strategies resulted in fewer jobs, and lesser costs and greater benefits than the status quo. The important thing to note here is that the status quo, the application of partial harvesting over the whole study area, is a costly (principally due to the cost of road building and maintenance) and labour intensive practice. The implementation of clear-cutting, which is more cost effective than partial cutting for a given amount of harvested volume, over the study area is the key to greater profit (although still negative) by the industry. The cost of planting and vegetation control in Quebec is covered by the Province, and this is the cause of decreased net benefits by the state. However, given the seriousness of potential impacts (especially under the assumption of beech bark disease) we feel it would be justifiable for the state to invest in adaptation strategies for the benefit of society in the long-run. It is essential to note that the costs

and benefits to not integrate the impacts of climate change, but reflect only the costs and benefits involved in the implementation only.

| | | Area treated with adaptation | | |
|------------|--------------|------------------------------|----------|------------|
| | | 0% | 50% | 100% |
| Societal | Jobs | 236 | 206 | 168 |
| Industrial | Costs | 15 M\$ | 15 M\$ | 13 M\$ |
| | Benefits | 11 M\$ | 11.5 M\$ | 10 M\$ |
| | Net benefits | -4 M\$ | -3.5 M\$ | -3 M\$ |
| State | Net benefits | 0.3 M\$ | 0.15 M\$ | -0.125 M\$ |

Table 12. A summary of the costs and benefits for each of the adaptation strategies applied to the study area.

Return to the public participation group

As had been planned at the outset, a second meeting was organized with the public participation group. Unfortunately, some key players were absent from this meeting, stating that more pressing matters had priority over the presentation of the findings of this study. This may be due to several factors, not the least of which is the ever increasing number of responsibilities being transferred from the Province to the regional planners, our absentee participants. We cannot know for certain if different actions or communications on our behalf would have led to a different outcome. We can only express the impression that, while climate change and its potential impacts generate widespread concern, planning and action in response to these concerns is still regarded as premature and speculative.

RECOMMENDATIONS FOR FOREST MANAGEMENT AND POLICY

The role of public participation

While the public participation exercise was of limited scope, this component contributed greatly to the development of adaptation strategies. The exercise provided criteria according to which adaptation strategies could be developed and refined. Without such input, it would have been impossible for us to judge of the relative value of each of the adaptation strategies and their outcome. This underlines the importance of public input for the development of adaptation strategies. Since the desirableness of an adaptation strategy depends entirely on what forest values are considered essential to maintain over the very long run, the development of such strategies should always be founded in some manner of public input.

The need to act now

It was clear from our discussions with experts, and subsequently from the projections produced by the ImpaCC-1 model, that there are important changes in store for the tolerant hardwood forest of eastern Canada. Results suggest that inaction or business as usual may lead to forest conditions that are unacceptable according to the terms put forward by the public participation group. The demonstration that our current climate is significantly different from the historical climate has already been made (Vincent and Mekis 2006, Vincent et al. 2007). Thus, it is only a matter of time for changes to the forest, such as those we have shown here, to become obvious. In fact, some changes may already be evident. For example, the balance between sugar maple and beech, which is expected to change as a result of climate change, has already begun to be drifting (Duchesne et al. 2005, Duchesne et al. 2006). While there is considerable uncertainty about the details of future climates and their impacts on the forest, changes are clearly imminent. Given the lag times between forest management and their results, action must be taken immediately.

The need for a better understanding of future impacts

While it has been important for us to explore adaptation strategies, we feel that there are still significant gaps in our knowledge of the future impacts of climate change on forests. There has been a considerable amount of work on the potential impacts of climate change, but we feel strongly that there is still a need for fundamental research in this field. Relationships between changing climate and regeneration, defoliation, and disease in particular require attention. Also, in our work and in much of the other work on climate change impacts, the assumption is made that soil fertility will not limit the growth triggered by increased concentrations of CO₂. However, we can expect the relationship of atmospheric CO₂ and soil fertility to change both productivity and leaf chemistry, which could in turn influence the susceptibility and vulnerability of trees to defoliation. Thus, while the exploration, development, and implementation of adaptation strategies should be undertaken immediately, fundamental research on climate change impacts should by no means be abandoned.

Adaptation strategies

The adaptations presented in this study, while a first attempt, point the way to certain strategies that are both realizable and financially interesting for the forest industry. There are greater costs involved in the adaptation strategies than with status quo management from the point of view of the Province, but we believe that these costs are justified given the potential magnitude of impacts of climate change on the forest. Since many of the adaptation strategies we have proposed go against standard forestry practices for the hardwood forest (e.g., clear-cutting is generally not permitted), forest management guidelines will need to be modified in order to permit forest managers to implement entirely new management strategies. Also, it is important to underline that, although our adaptation strategies were successful in the context of the model, we have no means of determining what the impact of adaptation strategies will be on the ecosystem components that were not modeled (wildlife, understory plants, etc.) Finally, a certain amount of public education should be undertaken in order to prepare the public to unconventional forestry practices.

Adaptive management

Ecosystem modeling presents many benefits. One of these is that it can generate a benchmark of our understanding in terms of future forest conditions, which can be compared to the future forest conditions. By comparing model outcome with the actual behaviour of forests under the influence of climate change, we will be able to judge whether our not our understanding was sufficient to allow a prediction of climate change impacts. Adaptive management is therefore highly relevant in the field of climate change impacts, since it allows us to move forward with imperfect knowledge and, over time, to refine that knowledge by comparing predicted and obtained forest conditions (Yamasaki et al. 2001).

The continuing role of mitigation

While we present adaptation strategies to future climate change, we must state here that there are factors not considered in this study that may greatly influence the hardwood forest in the future. Disease, insects, and invasive exotics may surprise all those currently working on climate change impacts. Also, the response of wildlife species to climate change is wholly misunderstood. Since many of these species play essential roles in forest ecosystems, there is clearly a gap in our understanding of climate change impacts. Therefore, we strongly suggest that the mitigation of climate change impacts through carbon sequestration and emissions reduction should be maintained and indeed enhanced. In our view, if our objective is to maintain viable forest ecosystems for future generations, mitigation (or the avoidance of change) is a more reliable undertaking than adaptation.

CONCLUSION

We have been generally successful in reaching our objectives. We have identified key forest values for the long run. A cumulative impacts landscape model has been developed for the study area. We have derived the expected impacts of climate change for the hardwood forest, and from these, adaptation strategies. Cost and benefit analysis was carried out and the results discussed with the public participation group.

We have demonstrated that, to the best of our knowledge, there are important changes in store for the hardwood forest of eastern Canada. While we expect an increase in productivity of the hardwood forest, we also fear that disease, in particular beech bark disease, may shift the composition of forest significantly. The potential outcomes of this shift clearly go against the values outlined by the public participation group that was consulted at the outset. Based on the best science available to us, we have proposed adaptation strategies that may correct some of the shift in species composition. We have suggested that adaptive management is especially relevant where climate change is concerned, given the uncertainty surrounding climate projections and the state of our knowledge. We also suggest that mitigation (climate change avoidance) should be maintained and enhanced in order to ensure viable forests for future generations.

ACKNOWLEDGEMENTS

The authors acknowledge the Commission Régionale pour la Protection de l'Environnement, Aménagement du territoire et Transport of the Conférence régionale des Élus for their invaluable contribution to the public participation process. The authors would like to thank Régis Pouliot, Pascal Rochon, and Vincent McCullough for their assistance in data preparation and Patchworks modeling. We thank Daniel Houle of the Ouranos Consortium for his participation in the panel of experts. We acknowledge the funding of the Climate Change Impacts and Adaptations Program of Natural Resources Canada, Ouranos, and IQAFF. CRCM4 data has been generated and supplied by Ouranos. For the CGCM3 and ECHAM4 data, we acknowledge the following international modeling groups: the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. This work, including access to the data and technical assistance, is provided by the Model and Data Group (M&D) at the Max-Planck-Institute for Meteorology, with funding from the Federal Ministry for Education and Research and by the German Climate Computing Centre (DKRZ). HADCM3 Data (c) Crown copyright 2005, provided by the Met Office Hadley Centre.

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APPENDICES

Appendix A

This appendix presents the parameters that served to calculate the modifiers for the rate of growth and mortality as a function of climate, defoliation, and beech bark disease. The order indicated is the order of the polynomial to calculate the modifier, where the independent variable is the value of the amount of change in the corresponding climatic variable. The methods used to obtain these parameters are described in the text.

| Diameter class | Parameter | OHA | OCO | YBI | PBI | OAK | SPR | RMA | SMA | ABE | POP | PIN | HEM | BFI |
|--|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| CO2 effect on growth : 2nd order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 0.844 | 1.0825 | 0.844 | 1.0753 | 1.0825 | 0.9283 | 1.0409 | 0.844 | 1.0409 | 0.844 | 1.0825 | 1.0825 | 1.0969 |
| 9 - 24 | b1 | -0.083 | -0.325 | -0.083 | -0.34 | -0.325 | -0.154 | -0.477 | -0.083 | -0.477 | -0.083 | -0.325 | -0.325 | -0.294 |
| 9 - 24 | b2 | 0.2311 | 0.2418 | 0.2311 | 0.2638 | 0.2418 | 0.22 | 0.42 | 0.2311 | 0.42 | 0.2311 | 0.2418 | 0.2418 | 0.1978 |
| 24 - 40 | b0 | 1.0825 | 1.174 | 1.0825 | 1.0969 | 1.174 | 1.0969 | 0.9283 | 1.0825 | 0.844 | 1.0825 | 1.174 | 1.174 | 1.1811 |
| 24 - 40 | b1 | -0.325 | -0.38 | -0.325 | -0.294 | -0.38 | -0.294 | -0.154 | -0.325 | -0.083 | -0.325 | -0.38 | -0.38 | -0.364 |
| 24 - 40 | b2 | 0.2418 | 0.2087 | 0.2418 | 0.1978 | 0.2087 | 0.1978 | 0.22 | 0.2418 | 0.2311 | 0.2418 | 0.2087 | 0.2087 | 0.1867 |
| 40 + | b0 | 1.1811 | 1.1255 | 1.1811 | 1.1883 | 1.1883 | 1.1883 | 1.0969 | 1.1811 | 1.0825 | 1.1811 | 1.1255 | 1.1255 | 1.0691 |
| 40 + | b1 | -0.364 | -0.233 | -0.364 | -0.349 | -0.349 | -0.349 | -0.294 | -0.364 | -0.325 | -0.364 | -0.233 | -0.233 | -0.128 |
| 40 + | b2 | 0.1867 | 0.1098 | 0.1867 | 0.1647 | 0.1647 | 0.1647 | 0.1978 | 0.1867 | 0.2418 | 0.1867 | 0.1098 | 0.1098 | 0.0593 |
| Temperature effect on growth : 1st order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 |
| 9 - 24 | b1 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 |
| 24 - 40 | b0 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 |
| 24 - 40 | b1 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| 40 + | b0 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 | 0.9933 |
| 40 + | b1 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 |
| Precipitation effect on growth : 4th order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 2.149 | 1.6792 | 3.0885 | 3.0885 | 1.6792 | 1.6792 | 1.6792 | 2.149 | 1.6792 | 3.0885 | 1.2094 | 1.6792 | 2.149 |
| 9 - 24 | b1 | -8.693 | -5.831 | -14.42 | -14.42 | -5.831 | -5.831 | -5.831 | -8.693 | -5.831 | -14.42 | -2.968 | -5.831 | -8.693 |
| 9 - 24 | b2 | 14.661 | 10.113 | 23.757 | 23.757 | 10.113 | 10.113 | 10.113 | 14.661 | 10.113 | 23.757 | 5.5655 | 10.113 | 14.661 |
| 9 - 24 | b3 | -8.989 | -6.291 | -14.39 | -14.39 | -6.291 | -6.291 | -6.291 | -8.989 | -6.291 | -14.39 | -3.592 | -6.291 | -8.989 |
| 9 - 24 | b4 | 1.8817 | 1.3373 | 2.9707 | 2.9707 | 1.3373 | 1.3373 | 1.3373 | 1.8817 | 1.3373 | 2.9707 | 0.7928 | 1.3373 | 1.8817 |
| 24 - 40 | b0 | 2.149 | 1.6792 | 3.0885 | 3.0885 | 1.6792 | 1.2094 | 1.6792 | 2.149 | 1.6792 | 3.0885 | 1.2094 | 1.2094 | 1.6792 |
| 24 - 40 | b1 | -8.693 | -5.831 | -14.42 | -14.42 | -5.831 | -2.968 | -5.831 | -8.693 | -5.831 | -14.42 | -2.968 | -2.968 | -5.831 |
| 24 - 40 | b2 | 14.661 | 10.113 | 23.757 | 23.757 | 10.113 | 5.5655 | 10.113 | 14.661 | 10.113 | 23.757 | 5.5655 | 5.5655 | 10.113 |
| 24 - 40 | b3 | -8.989 | -6.291 | -14.39 | -14.39 | -6.291 | -3.592 | -6.291 | -8.989 | -6.291 | -14.39 | -3.592 | -3.592 | -6.291 |
| 24 - 40 | b4 | 1.8817 | 1.3373 | 2.9707 | 2.9707 | 1.3373 | 0.7928 | 1.3373 | 1.8817 | 1.3373 | 2.9707 | 0.7928 | 0.7928 | 1.3373 |
| 40 + | b0 | 1.6792 | 1.6792 | 2.149 | 2.149 | 1.6792 | 1.2094 | 1.6792 | 2.149 | 1.6792 | 3.0885 | 1.2094 | 1.2094 | 1.6792 |
| 40 + | b1 | -5.831 | -5.831 | -8.693 | -8.693 | -5.831 | -2.968 | -5.831 | -8.693 | -5.831 | -14.42 | -2.968 | -2.968 | -5.831 |
| 40 + | b2 | 10.113 | 10.113 | 14.661 | 14.661 | 10.113 | 5.5655 | 10.113 | 14.661 | 10.113 | 23.757 | 5.5655 | 5.5655 | 10.113 |
| 40 + | b3 | -6.291 | -6.291 | -8.989 | -8.989 | -6.291 | -3.592 | -6.291 | -8.989 | -6.291 | -14.39 | -3.592 | -3.592 | -6.291 |
| 40 + | b4 | 1.3373 | 1.3373 | 1.8817 | 1.8817 | 1.3373 | 0.7928 | 1.3373 | 1.8817 | 1.3373 | 2.9707 | 0.7928 | 0.7928 | 1.3373 |
| Moisture stress effect on growth : 3rd order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 1.9857 | 1.6775 | 2.6021 | 2.6021 | 1.6775 | 1.6775 | 1.6775 | 1.9857 | 1.6775 | 2.6021 | 1.3693 | 1.6775 | 1.9857 |
| 9 - 24 | b1 | -1.807 | -1.205 | -3.011 | -3.011 | -1.205 | -1.205 | -1.205 | -1.807 | -1.205 | -3.011 | -0.604 | -1.205 | -1.807 |
| 9 - 24 | b2 | 1.0515 | 0.6745 | 1.8057 | 1.8057 | 0.6745 | 0.6745 | 0.6745 | 1.0515 | 0.6745 | 1.8057 | 0.2974 | 0.6745 | 1.0515 |
| 9 - 24 | b3 | -0.23 | -0.144 | -0.4 | -0.4 | -0.144 | -0.144 | -0.144 | -0.23 | -0.144 | -0.4 | -0.059 | -0.144 | -0.23 |
| 24 - 40 | b0 | 1.9857 | 1.6775 | 2.6021 | 2.6021 | 1.6775 | 1.3693 | 1.6775 | 1.9857 | 1.6775 | 2.6021 | 1.3693 | 1.3693 | 1.6775 |
| 24 - 40 | b1 | -1.807 | -1.205 | -3.011 | -3.011 | -1.205 | -0.604 | -1.205 | -1.807 | -1.205 | -3.011 | -0.604 | -0.604 | -1.205 |
| 24 - 40 | b2 | 1.0515 | 0.6745 | 1.8057 | 1.8057 | 0.6745 | 0.2974 | 0.6745 | 1.0515 | 0.6745 | 1.8057 | 0.2974 | 0.2974 | 0.6745 |
| 24 - 40 | b3 | -0.23 | -0.144 | -0.4 | -0.4 | -0.144 | -0.059 | -0.144 | -0.23 | -0.144 | -0.4 | -0.059 | -0.059 | -0.144 |
| 40 + | b0 | 1.6775 | 1.6775 | 1.9857 | 2.6021 | 1.6775 | 1.3693 | 1.6775 | 1.9857 | 1.6775 | 2.6021 | 1.3693 | 1.3693 | 1.6775 |
| 40 + | b1 | -1.205 | -1.205 | -1.807 | -3.011 | -1.205 | -0.604 | -1.205 | -1.807 | -1.205 | -3.011 | -0.604 | -0.604 | -1.205 |
| 40 + | b2 | 0.6745 | 0.6745 | 1.0515 | 1.8057 | 0.6745 | 0.2974 | 0.6745 | 1.0515 | 0.6745 | 1.8057 | 0.2974 | 0.2974 | 0.6745 |
| 40 + | b3 | -0.144 | -0.144 | -0.23 | -0.4 | -0.144 | -0.059 | -0.144 | -0.23 | -0.144 | -0.4 | -0.059 | -0.059 | -0.144 |
| Growing season length effect on growth : 1st order | | | | | | | | | | | | | | |
| all | b0 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 | 1.0003 |
| all | b1 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 | 0.6386 |

Table A1. Parameters for the calculation of modifiers on growth rates from climate data.

| Diameter class | Parameter | OHA | OCO | YBI | PBI | OAK | SPR | RMA | SMA | ABE | POP | PIN | HEM | BFI |
|--|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Precipitation effect on mortality: 3rd order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 0.3100 | 0.3100 | 0.2822 | 0.2822 | 0.5859 | 0.3100 | 0.2822 | 0.2822 | 0.3100 | 0.2822 | 0.5859 | 0.3100 | 0.3100 |
| 9 - 24 | b1 | 3.2357 | 3.2357 | 3.3100 | 3.3100 | 1.9396 | 3.2357 | 3.3100 | 3.3100 | 3.2357 | 3.3100 | 1.9396 | 3.2357 | 3.2357 |
| 9 - 24 | b2 | -3.7190 | -3.7190 | -3.7415 | -3.7415 | -2.2199 | -3.7190 | -3.7415 | -3.7415 | -3.7190 | -3.7415 | -2.2199 | -3.7190 | -3.7190 |
| 9 - 24 | b3 | 1.1635 | 1.1635 | 1.1310 | 1.1310 | 0.6862 | 1.1635 | 1.1310 | 1.1310 | 1.1635 | 1.1310 | 0.6862 | 1.1635 | 1.1635 |
| 24 - 40 | b0 | 0.5859 | 0.5859 | 0.3100 | 0.3100 | 0.5420 | 0.5859 | 0.3100 | 0.3100 | 0.5859 | 0.2822 | 0.5420 | 0.5859 | 0.5859 |
| 24 - 40 | b1 | 1.9396 | 1.9396 | 3.2357 | 3.2357 | 2.1405 | 1.9396 | 3.2357 | 3.2357 | 1.9396 | 3.3100 | 2.1405 | 1.9396 | 1.9396 |
| 24 - 40 | b2 | -2.2199 | -2.2199 | -3.7190 | -3.7190 | -2.4499 | -2.2199 | -3.7190 | -3.7190 | -2.2199 | -3.7415 | -2.4499 | -2.2199 | -2.2199 |
| 24 - 40 | b3 | 0.6862 | 0.6862 | 1.1635 | 1.1635 | 0.7730 | 0.6862 | 1.1635 | 1.1635 | 0.6862 | 1.1310 | 0.7730 | 0.6862 | 0.6862 |
| 40 + | b0 | 0.5859 | 0.5859 | 0.5859 | 0.3100 | 0.5420 | 0.5420 | 0.5859 | 0.5859 | 0.5420 | 0.3100 | 0.5420 | 0.5420 | 0.5859 |
| 40 + | b1 | 1.9396 | 1.9396 | 1.9396 | 3.2357 | 2.1405 | 2.1405 | 1.9396 | 1.9396 | 2.1405 | 3.2357 | 2.1405 | 2.1405 | 1.9396 |
| 40 + | b2 | -2.2199 | -2.2199 | -2.2199 | -3.7190 | -2.4499 | -2.4499 | -2.2199 | -2.2199 | -2.4499 | -3.7190 | -2.4499 | -2.4499 | -2.2199 |
| 40 + | b3 | 0.6862 | 0.6862 | 0.6862 | 1.1635 | 0.7730 | 0.7730 | 0.6862 | 0.6862 | 0.7730 | 1.1635 | 0.7730 | 0.7730 | 0.6862 |
| Moisture stress effect on mortality: 3rd order | | | | | | | | | | | | | | |
| 9 - 24 | b0 | 0.0143 | 0.3225 | -0.6021 | -0.6021 | 0.3225 | 0.3225 | 0.3225 | 0.0143 | 0.3225 | -0.6021 | 0.6307 | 0.3225 | 0.0143 |
| 9 - 24 | b1 | 1.8071 | 1.2054 | 3.0105 | 3.0105 | 1.2054 | 1.2054 | 1.2054 | 1.8071 | 1.2054 | 3.0105 | 0.6036 | 1.2054 | 1.8071 |
| 9 - 24 | b2 | -1.0515 | -0.6745 | -1.8057 | -1.8057 | -0.6745 | -0.6745 | -0.6745 | -1.0515 | -0.6745 | -1.8057 | -0.2974 | -0.6745 | -1.0515 |
| 9 - 24 | b3 | 0.2297 | 0.1444 | 0.4004 | 0.4004 | 0.1444 | 0.1444 | 0.1444 | 0.2297 | 0.1444 | 0.4004 | 0.0591 | 0.1444 | 0.2297 |
| 24 - 40 | b0 | 0.0143 | 0.3225 | -0.6021 | -0.6021 | 0.3225 | 0.6307 | 0.3225 | 0.0143 | 0.3225 | -0.6021 | 0.6307 | 0.6307 | 0.3225 |
| 24 - 40 | b1 | 1.8071 | 1.2054 | 3.0105 | 3.0105 | 1.2054 | 0.6036 | 1.2054 | 1.8071 | 1.2054 | 3.0105 | 0.6036 | 0.6036 | 1.2054 |
| 24 - 40 | b2 | -1.0515 | -0.6745 | -1.8057 | -1.8057 | -0.6745 | -0.2974 | -0.6745 | -1.0515 | -0.6745 | -1.8057 | -0.2974 | -0.2974 | -0.6745 |
| 24 - 40 | b3 | 0.2297 | 0.1444 | 0.4004 | 0.4004 | 0.1444 | 0.0591 | 0.1444 | 0.2297 | 0.1444 | 0.4004 | 0.0591 | 0.0591 | 0.1444 |
| 40 + | b0 | 0.3225 | 0.3225 | 0.0143 | -0.6021 | 0.3225 | 0.6307 | 0.3225 | 0.0143 | 0.3225 | -0.6021 | 0.6307 | 0.6307 | 0.3225 |
| 40 + | b1 | 1.2054 | 1.2054 | 1.8071 | 3.0105 | 1.2054 | 0.6036 | 1.2054 | 1.8071 | 1.2054 | 3.0105 | 0.6036 | 0.6036 | 1.2054 |
| 40 + | b2 | -0.6745 | -0.6745 | -1.0515 | -1.8057 | -0.6745 | -0.2974 | -0.6745 | -1.0515 | -0.6745 | -1.8057 | -0.2974 | -0.2974 | -0.6745 |
| 40 + | b3 | 0.1444 | 0.1444 | 0.2297 | 0.4004 | 0.1444 | 0.0591 | 0.1444 | 0.2297 | 0.1444 | 0.4004 | 0.0591 | 0.0591 | 0.1444 |

Table A2. Parameters for the calculation of modifiers on mortality rates from climate data.

| Parameter | 9 - 24 | 24 - 40 | 40 + |
|--|---------|---------|--------|
| Temperature effect on recruitment: 2nd order | | | |
| b0 | 0.9977 | | |
| b1 | 0.0397 | | |
| b2 | 0.0033 | | |
| Temperature effect on growth: exponential | | | |
| b0 | 0.9963 | 0.996 | 0.9919 |
| b1 | -0.0261 | -0.0302 | -0.046 |
| Temperature effect on mortality: 2nd order | | | |
| b0 | 1.0006 | 0.9993 | 0.9989 |
| b1 | 0.0187 | 0.0383 | 0.0534 |
| b2 | 0.0002 | 0.0015 | 0.0027 |

Table A3. Parameters for the calculation of beech bark disease modifiers for recruitment, growth, and mortality rates, for the effect of temperature; these parameters are only applied if beech bark disease is present in the cell.

| Parameter | 9 - 24 | 24 - 40 | 40 + |
|--|---------|---------|---------|
| Precipitation effect on recruitment: 3rd order | | | |
| b0 | 0.6017 | | |
| b1 | 2.3633 | | |
| b2 | -2.9474 | | |
| b3 | 0.9825 | | |
| Precipitation effect on growth: 3rd order | | | |
| b0 | 0.6017 | 0.6017 | 0.6017 |
| b1 | 2.3633 | 2.3633 | 2.3633 |
| b2 | -2.9474 | -2.9474 | -2.9474 |
| b3 | 0.9825 | 0.9825 | 0.9825 |
| Precipitation effect on mortality: 3rd order | | | |
| b0 | 1.3983 | 1.3983 | 1.3983 |
| b1 | -2.3633 | -2.3633 | -2.3633 |
| b2 | 2.9474 | 2.9474 | 2.9474 |
| b3 | -0.9825 | -0.9825 | -0.9825 |

Table A4. Parameters for the calculation of beech bark disease modifiers for recruitment, growth, and mortality rates, for the effect of precipitation; these parameters are only applied if beech bark disease is present in the cell.

| Temperature | PBI | | OAK | | SPR | | RMA | | SMA | | POP | | PIN | | BFI | |
|-------------|-------|--------|-------|---------|-------|---------|-------|---------|-------|---------|-------|-------|-------|---------|-------|---------|
| | alpha | beta | alpha | beta | alpha | beta | alpha | beta | alpha | beta | alpha | beta | alpha | beta | alpha | beta |
| 0 | 99 | 0.4 | 99 | 0.4 | 70 | 0.9 | 25 | 0.9 | 99 | 0.9 | 99 | 0.55 | 25 | 0.9 | 99 | 0.8 |
| 0.5 | 99 | 0.3972 | 99 | 0.39925 | 70 | 0.89948 | 25 | 0.89948 | 99 | 0.89498 | 99 | 0.547 | 25 | 0.89948 | 99 | 0.79925 |
| 1 | 99 | 0.3938 | 99 | 0.398 | 70 | 0.8989 | 25 | 0.8989 | 99 | 0.8899 | 99 | 0.543 | 25 | 0.8989 | 99 | 0.798 |
| 1.5 | 99 | 0.3898 | 99 | 0.39625 | 70 | 0.89828 | 25 | 0.89828 | 99 | 0.88478 | 99 | 0.538 | 25 | 0.89828 | 99 | 0.79625 |
| 2 | 99 | 0.3852 | 99 | 0.394 | 70 | 0.8976 | 25 | 0.8976 | 99 | 0.8796 | 99 | 0.532 | 25 | 0.8976 | 99 | 0.794 |
| 2.5 | 99 | 0.38 | 99 | 0.39125 | 70 | 0.89688 | 25 | 0.89688 | 99 | 0.87438 | 99 | 0.525 | 25 | 0.89688 | 99 | 0.79125 |
| 3 | 99 | 0.3742 | 99 | 0.388 | 70 | 0.8961 | 25 | 0.8961 | 99 | 0.8691 | 99 | 0.517 | 25 | 0.8961 | 99 | 0.788 |
| 3.5 | 99 | 0.3678 | 99 | 0.38425 | 70 | 0.89528 | 25 | 0.89528 | 99 | 0.86378 | 99 | 0.508 | 25 | 0.89528 | 99 | 0.78425 |
| 4 | 99 | 0.3608 | 99 | 0.38 | 70 | 0.8944 | 25 | 0.8944 | 99 | 0.8584 | 99 | 0.498 | 25 | 0.8944 | 99 | 0.78 |
| 4.5 | 99 | 0.3532 | 99 | 0.37525 | 70 | 0.89348 | 25 | 0.89348 | 99 | 0.85298 | 99 | 0.487 | 25 | 0.89348 | 99 | 0.77525 |
| 5 | 99 | 0.345 | 99 | 0.37 | 70 | 0.8925 | 25 | 0.8925 | 99 | 0.8475 | 99 | 0.475 | 25 | 0.8925 | 99 | 0.77 |
| 5.5 | 99 | 0.3362 | 99 | 0.36425 | 70 | 0.89148 | 25 | 0.89148 | 99 | 0.84198 | 99 | 0.462 | 25 | 0.89148 | 99 | 0.76425 |
| 6 | 99 | 0.3268 | 99 | 0.358 | 70 | 0.8904 | 25 | 0.8904 | 99 | 0.8364 | 99 | 0.448 | 25 | 0.8904 | 99 | 0.758 |
| 6.5 | 99 | 0.3168 | 99 | 0.35125 | 70 | 0.88928 | 25 | 0.88928 | 99 | 0.83078 | 99 | 0.433 | 25 | 0.88928 | 99 | 0.75125 |
| 7 | 99 | 0.3062 | 99 | 0.344 | 70 | 0.8881 | 25 | 0.8881 | 99 | 0.8251 | 99 | 0.417 | 25 | 0.8881 | 99 | 0.744 |
| 7.5 | 99 | 0.295 | 99 | 0.33625 | 70 | 0.88688 | 25 | 0.88688 | 99 | 0.81938 | 99 | 0.4 | 25 | 0.88688 | 99 | 0.73625 |
| 8 | 99 | 0.2832 | 99 | 0.328 | 70 | 0.8856 | 25 | 0.8856 | 99 | 0.8136 | 99 | 0.382 | 25 | 0.8856 | 99 | 0.728 |

Table A5. Parameters for the calculation of the modifier for growth due to defoliation by insects, as a function of change in temperature from the reference period; the equation is given in the main body of the text.

| Temperature | PBI | | | OAK | | | SPR | | | RMA | | | SMA | | | POP | | | PIN | | |
|-------------|-------|------|-----|-------|------|-----|-------|------|-----|-------|-------|-----|-------|------|-----|-------|------|-----|-------|------|-----|
| | alpha | beta | k | alpha | beta | k | alpha | beta | k | alpha | beta | k | alpha | beta | k | alpha | beta | k | alpha | beta | k |
| 0 | 3.5 | -12 | 100 | 2 | -6 | 100 | 0.75 | -8 | 100 | 2.4 | -12.5 | 100 | 3 | -12 | 100 | 3 | -11 | 100 | 2.2 | -12 | 100 |
| 0.5 | 3.574 | -12 | 100 | 2.074 | -6 | 100 | 0.799 | -8 | 100 | 2.449 | -12.5 | 100 | 3.059 | -12 | 100 | 3.074 | -11 | 100 | 2.249 | -12 | 100 |
| 1 | 3.646 | -12 | 100 | 2.146 | -6 | 100 | 0.846 | -8 | 100 | 2.496 | -12.5 | 100 | 3.116 | -12 | 100 | 3.146 | -11 | 100 | 2.296 | -12 | 100 |
| 1.5 | 3.716 | -12 | 100 | 2.216 | -6 | 100 | 0.891 | -8 | 100 | 2.541 | -12.5 | 100 | 3.171 | -12 | 100 | 3.216 | -11 | 100 | 2.341 | -12 | 100 |
| 2 | 3.784 | -12 | 100 | 2.284 | -6 | 100 | 0.934 | -8 | 100 | 2.584 | -12.5 | 100 | 3.224 | -12 | 100 | 3.284 | -11 | 100 | 2.384 | -12 | 100 |
| 2.5 | 3.85 | -12 | 100 | 2.35 | -6 | 100 | 0.975 | -8 | 100 | 2.625 | -12.5 | 100 | 3.275 | -12 | 100 | 3.35 | -11 | 100 | 2.425 | -12 | 100 |
| 3 | 3.914 | -12 | 100 | 2.414 | -6 | 100 | 1.014 | -8 | 100 | 2.664 | -12.5 | 100 | 3.324 | -12 | 100 | 3.414 | -11 | 100 | 2.464 | -12 | 100 |
| 3.5 | 3.976 | -12 | 100 | 2.476 | -6 | 100 | 1.051 | -8 | 100 | 2.701 | -12.5 | 100 | 3.371 | -12 | 100 | 3.476 | -11 | 100 | 2.501 | -12 | 100 |
| 4 | 4.036 | -12 | 100 | 2.536 | -6 | 100 | 1.086 | -8 | 100 | 2.736 | -12.5 | 100 | 3.416 | -12 | 100 | 3.536 | -11 | 100 | 2.536 | -12 | 100 |
| 4.5 | 4.094 | -12 | 100 | 2.594 | -6 | 100 | 1.119 | -8 | 100 | 2.769 | -12.5 | 100 | 3.459 | -12 | 100 | 3.594 | -11 | 100 | 2.569 | -12 | 100 |
| 5 | 4.15 | -12 | 100 | 2.65 | -6 | 100 | 1.15 | -8 | 100 | 2.8 | -12.5 | 100 | 3.5 | -12 | 100 | 3.65 | -11 | 100 | 2.6 | -12 | 100 |
| 5.5 | 4.204 | -12 | 100 | 2.704 | -6 | 100 | 1.179 | -8 | 100 | 2.829 | -12.5 | 100 | 3.539 | -12 | 100 | 3.704 | -11 | 100 | 2.629 | -12 | 100 |
| 6 | 4.256 | -12 | 100 | 2.756 | -6 | 100 | 1.206 | -8 | 100 | 2.856 | -12.5 | 100 | 3.576 | -12 | 100 | 3.756 | -11 | 100 | 2.656 | -12 | 100 |
| 6.5 | 4.306 | -12 | 100 | 2.806 | -6 | 100 | 1.231 | -8 | 100 | 2.881 | -12.5 | 100 | 3.611 | -12 | 100 | 3.806 | -11 | 100 | 2.681 | -12 | 100 |
| 7 | 4.354 | -12 | 100 | 2.854 | -6 | 100 | 1.254 | -8 | 100 | 2.904 | -12.5 | 100 | 3.644 | -12 | 100 | 3.854 | -11 | 100 | 2.704 | -12 | 100 |
| 7.5 | 4.4 | -12 | 100 | 2.9 | -6 | 100 | 1.275 | -8 | 100 | 2.925 | -12.5 | 100 | 3.675 | -12 | 100 | 3.9 | -11 | 100 | 2.725 | -12 | 100 |
| 8 | 4.444 | -12 | 100 | 2.944 | -6 | 100 | 1.294 | -8 | 100 | 2.944 | -12.5 | 100 | 3.704 | -12 | 100 | 3.944 | -11 | 100 | 2.744 | -12 | 100 |

Table A6. Parameters for the calculation of the modifier for mortality due to defoliation by insects, as a function of change in temperature from the reference period; the equation is given in the main body of the text.

Appendix B

This appendix presents the species composition of the most common composition types within the study area.

| Composition type | OHA | OCO | YBI | PBI | OAK | SPR | RMA | SMA | ABE | POP | PIN | HEM | BFI |
|------------------|-----|-------|------|-----|-----|-------|-----|------|------|-----|-----|------|-----|
| 1 | 4.3 | 0.7 | 6.5 | 1.3 | 2.8 | 0.4 | 1.9 | 56.0 | 17.8 | 1.2 | 0.3 | 6.0 | 0.6 |
| 2 | 5.1 | 1.0 | 7.1 | 1.0 | 2.1 | 0.5 | 1.8 | 56.8 | 15.8 | 0.7 | 0.3 | 7.6 | 0.3 |
| 22 | 2.6 | 2.9 | 11.2 | 1.7 | 1.9 | 2.7 | 6.6 | 29.9 | 11.5 | 2.0 | 0.9 | 23.2 | 2.9 |
| 34 | 2.6 | 2.9 | 11.2 | 1.7 | 1.9 | 2.7 | 6.6 | 29.9 | 11.5 | 2.0 | 0.9 | 23.2 | 2.9 |
| 38 | 2.4 | 9.7 | 18.8 | 1.6 | 0.9 | 6.8 | 6.8 | 15.4 | 4.0 | 0.8 | 0.3 | 29.2 | 3.2 |
| 57 | 4.3 | 0.7 | 6.5 | 1.3 | 2.8 | 0.4 | 1.9 | 56.0 | 17.8 | 1.2 | 0.3 | 6.0 | 0.6 |
| 84 | 2.4 | 9.7 | 18.8 | 1.6 | 0.9 | 6.8 | 6.8 | 15.4 | 4.0 | 0.8 | 0.3 | 29.2 | 3.2 |
| 89 | 0.9 | 33.4 | 12.2 | 0.0 | 0.0 | 14.6 | 0.0 | 8.7 | 6.5 | 0.0 | 0.0 | 19.3 | 4.4 |
| 115 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 116 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table B1. The species composition of the most common composition types for the study area; this data (with the proportion occupied by beech removed) is used to determine the species composition of planted stock.