Using the LANDIS model to evaluate forest harvesting and planting strategies under possible warming climates in Northeastern China

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Abstract

The Small Khingan Mountains in northeastern China provide most of the timber and wood products in the country. Evaluating the long-term effects of harvesting and planting strategies is important especially as the climate changes. In this study, we evaluated the effects of the projected climate warming on potential changes in species’ coverage (percent cover), area harvested (percentage of the study area) and species harvested, using the LANDIS model. Our evaluation was based on the harvest and planting plans specified in Natural Forest Protection Project (NFPP). Our simulated results show that the coverage of southern species such as Korean pine (Pinus koraiensis) and ribbed birch (Betula costata) increases, whereas the coverage of northern species like larch (Larix gmelinii), Kingan fir (Abies nephrolepis), spruces (Picea koraiensis and P. jezoensis) and Dahur birch (Betula davurica) decreases under the warming climate in the region. The species harvested primarily consist of the southern species, especially deciduous species under the warming climate. The warming climate leads to 11.2% increase in area harvested compared to that under the current climate, when planting is not simulated. When planting is simulated, tradeoffs between planting and area harvested are complex. The area harvested only increases in places where moderate planting is implemented, and decreases in places with both low (≤5% area planted) and high (>30%) planting percentage. This is because when the planting percentage is low, the rate of increase of harvestable species due to planting is lower than the rate of decrease of warming-declining species. When the planting percentage is high, the rate of increase of planted species is higher than the rate of colonization of warming-adapted deciduous species, and the planted species delay the establishment of the warming-adaptable species that have short harvest rotations (due to lower harvestable ages). Our results suggest that the management strategy with planting area of 20% is the best among all the scenarios simulated. Under this warming climate, moderate planting area (e.g. 20%) increases the area harvested to about 43%, which is still less than that (58%) designated in the NFPP. These results have important implications for forest managers designing sustainable forest harvest and reforestation strategies for the landscape under the warming climate.

Keywords: Natural Forest Protection Project; LANDIS; Small Khingan Mountains; Climate change; Northeastern China

1. Introduction

The Small Khingan Mountains in northeastern China is one of the three largest forested areas in the country. It provides more timber and wood products than most other forested regions in China. The Small Khingan Mountains are located in the transitional zone between the boreal and temperate forests of China. This area has the highest tree species diversity (Zhou, 1994; Xu, 2001). Prior to 1900, forests in this region were regarded as a symbol of the ‘origin’ of the Manchurians who ruled in the Qing dynasties (1600–1900). This region was also believed to be protected from human emigration and timber harvesting. Only a very small population used the forest resource. Between 1900 and 1945, about 6 million ha of forest was harvested, totaling about 100 million m3 of timber. This decreased the forest volume by 60%. After World War II and the China’s civil war (1948–1949), the need for timber increased immensely in China especially as the population increased. Harvested timber increased from 6 million m3 in 1949 to over 50 million m3 in 1984. Most forests were harvested with clear-cutting management (removes all species and all ages) during this period (Xin, 1987). Furthermore, 75% of the harvested timber was burned as firewood. The availability of
log timber in northeastern China was much less than in other developed countries (Xin, 1987; Zhang, 2005).

Timber harvesting and other human activities have altered the forest composition, structure, ecosystem processes, and landscape pattern of this region (Burgess et al., 2005; D’eon and Glenn, 2005). Coniferous species, the dominant species in this region, have decreased by 42% (Lin and Li, 1989; Li and Li, 2003). Natural coniferous forests and mixed broadleaf Korean pine (*Pinus koraiensis*) forests have degenerated into secondary deciduous forests with non-timber species such as white birch (*Betula platyphylla*) and wild poplar (*Populus davidiana*) (Yi and Ye, 2004). Timber harvesting has also led to a fragmented forest landscape with many young forests (Dong, 2002; Wang, 2005).

Forest ecosystems in China have been altered so greatly that human intervention is probably needed for restoration (Zhang, 1999). Larch (*Larix gmelinii*) is the main species to regenerate forests after disturbances due to its rapid growth, allowing it to reach the harvesting size in a short time (Lin and Li, 1989; Zhang, 2005). The area reforested by human covers 1.8% of the forested area in this region (Lin and Li, 1989). Spruces (*Picea koraiensis* and *Picea jezoensis*) and Korean pine were planted in the region to recover species composition of the degenerated forest. Though this reforestation effort in recent years (Li et al., 2000), the timber harvesting in the previously over-logged areas have caused (1) environmental degeneration (e.g., soil erosion and decreasing water quality) and (2) decrease of forest resources, and economic problems in Northeastern China (Zhang, 2005).

Since 1998, national and local governments have instituted a sustainable forest development plan, called the Natural Forest Protection Project (NFPP) (Zhang, 1999; Shen, 2006). NFPP is a classified management strategy separating forests spatially into two types: commercial forest and non-commercial forest. The commercial forest is the source of timber and where the trees are planted. Timber harvest will be primarily restricted to the planted areas in the commercial forest from 2010 (Zhang, 1999, 2005). Non-commercial forest is protected from human intervention.

While the climate is warming, the quantitative evaluation of current harvest and percent of the area planted just become an ecologically and economically important issue in northeastern China. The average temperature in northeastern China has been increasing since the 1960s (Wang, 1995; Wang and Huang, 2006; Wang et al., 2002). Under the CGCM2 (Canadian Global Coupled Model) (Canadian Centre for Climate Modeling and Analysis, 2006), the annual average temperature will increase by 5.97 ± 0.14 °C and the precipitation will decrease by 16.2 ± 6.2 mm by the year 2100. Climate warming creates conditions for certain species that are adaptable (warming-adapted species) and unsuitable conditions for other species (warming-declining species). In addition, the conditions can be further affected by landscape fragmentation caused by natural disturbance, timber harvesting, and other human land uses (Pitelka, 1997; Scheller and Mladenoff, 2005; Iverson et al., 2005). The presence of declining species occupying the sites that would no longer be suitable under climate warming would cause the ‘emigration delay’ (Kirilenko and Solomon, 1998) of warming-adapted species (Davis, 1989; Walker et al., 2002). The planting of larch, the main species of boreal forests, may lengthen the migration lag of more suitable species under a warming climate. Larch planting may also affect timber harvesting and the emigration of southern species in the region under a warming climate.

Evaluating forest management strategies at large spatial (>10⁶ ha) and temporal (e.g., >100 years) scales is beyond the limit of traditional studies, which are often conducted at stand-level scales. Models have, therefore, become an important tool for evaluating the effects of alternative management strategies on forest landscapes (Gustafson et al., 2000). Landscape models were used in this study because other types of models, such as gap models and ecosystem process models, are often limited in spatial extent (He et al., 2002; Mladenoff, 2004). They are also limited in the capability of simulating species migration. LANDIS can be used to study the effects of natural and anthropogenic disturbances on forest landscapes on both long temporal and large spatial scales (He et al., 1999; Gustafson et al., 2000; Scheller and Mladenoff, 2005). Landscape models can also evaluate the feasibility of harvest and reforestation plans in the NFPP under a warming climate, which has not been explicitly studied for climate warming scenarios.

The objectives of this study include (1) What are the changes of species’ percent cover under the warming climate? (2) Would the warming climate affect percent area harvested and harvested species? and (3) Can forest planting be used to provide sufficient timber required for harvesting under the warming climate? Management scenarios will be designed, and then simulated, using LANDIS to investigate these questions. The evaluation of the feasibility of harvesting and reforestation will provide insights into the forest management under a warming climate in this region.

2. Methods

2.1. Study area

The study area is in the Small Khingan Mountains region (from 127°03′00″E to 129°54′40″E and from 47°45′14″N to 49°15′21″N), located in Heilongjiang Province of Northeastern China (Fig. 1). It encompasses 2.34 million ha, 110 forestry farms and 12 forestry bureaus with a forested area covering 1.83 million ha. The study area has a cold, continental climate with annual average temperatures decreasing gradually from 1.0 °C in the south to −3.6 °C in the north. The annual average precipitation decreases from 656 mm in the south to 490 mm in the north. Seventy-five percent of the precipitation occurs between June and August.

A mountain ridge, running from the southwest to the northeast, divides the region between boreal and temperate forests. In the temperate forests, common tree species include Korean pine, spruces, Khingan fir, Amur linden (*Tilia amurensis*), ribbon birch (*Betula costata*), mono maple (*Acer mono*), Amur corktree (*Phellodendron amurense*), Manchurian walnut (*Juglans mandshurica*), Mongol oak (*Quercus mon-
golica), Dahur birch (*Betula davurica*) and Manchur ash (*Fraxinus mandshurica*). Korean pine (*Pinus koraiensis*) is the dominant species. Fir (*Abies nephrolepis*) and spruces (*P. koraiensis* and *P. jezoensis*) only dominate in high elevation areas. The temperate forest areas are characterized with a rough topography of uplands and hills. The elevation ranges from 217 to 1045 m with a mean elevation around 420 m. Slopes are generally less than $5^\circ$. The maximum slope is $33^\circ$.

In the boreal forests, white birch (*Betula platyphylla*) often accompanies the dominant larch (*L. gmelinii*). The area is characterized by a relatively smooth topography with flatlands and some small hills. The elevation ranges from 150 to 790 m with a mean elevation around 710 m. Slopes are generally less than $3^\circ$. The maximum slope is $37^\circ$.

According to classified management of NFPP, the forest land in this region was classified into two types of management areas: non-commercial forest (NCF) and commercial forest (CF) (Fig. 1, CF sets). NCF covers 71% of forested areas in the study region and contains natural reserves, conservation areas, and water. Human activities are generally prohibited in NCF. CF covers 29% of forest in the study region. In the CF areas, mature sites are harvested and standard sets of species are planted. In the CF1 area, the Korean pine was planted; in the CF2 area, the Korean pine and spruces were planted; in the CF3 area, larch was planted; and in the CF4 area, no species were planted.

The current percent of the area harvested (in the CF areas) averages 5.8% per year, and in simulation with 10-year steps, the percent of the area harvested is 58%. The current percent of the area planted in the CF areas simulated using LANDIS with 10-year steps, is 5.1% for larch, 1.0% for spruces and it is 1.1% for Korean pine in the CF areas. The scenario designed in simulation (see Table 1, H58P01) is the initial status of simulation for the year 2000 in the Small Khingan Mountains.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Percent of the area harvested (H)</th>
<th>Percent of the area planted (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H00P00</td>
<td>0</td>
<td>0% for each planted species</td>
</tr>
<tr>
<td>H58P00</td>
<td>58</td>
<td>0% for each planted species</td>
</tr>
<tr>
<td>H58P01</td>
<td>58</td>
<td>5.1% for larch, 1.0% for spruces, and 1.1% for Korean pine</td>
</tr>
<tr>
<td>H58P05</td>
<td>58</td>
<td>5% for each planted species</td>
</tr>
<tr>
<td>H58P10</td>
<td>58</td>
<td>10% for each planted species</td>
</tr>
<tr>
<td>H58P20</td>
<td>58</td>
<td>20% for each planted species</td>
</tr>
<tr>
<td>H58P30</td>
<td>58</td>
<td>30% for each planted species</td>
</tr>
<tr>
<td>H58P40</td>
<td>58</td>
<td>40% for each planted species</td>
</tr>
<tr>
<td>H58P50</td>
<td>58</td>
<td>50% for each planted species</td>
</tr>
</tbody>
</table>
2.2. The LANDIS model

LANDIS is a spatially explicit, raster-based landscape model that is used to simulate ecological dynamics including forest succession, disturbance, seed dispersal, species establishment, as well as fire, wind disturbance, and timber harvesting (Mladenoff et al., 1996; Mladenoff and He, 1999; He et al., 1999; Gustafson et al., 2000). It simulates their interactions at long temporal (e.g. >100 years) and large spatial scales (e.g. >10^4 ha) where landscapes can be represented by cells of 10 m x 10 m to 500 m x 500 m.

In LANDIS, a heterogeneous landscape is delineated into various homogeneous forest land types where the environmental conditions such as climate, terrain attributes (e.g. slope, aspect, and slope position) and soils are assumed to be homogeneous. Therefore, a single land type has similar species establishment coefficients (SEC) (ranging from 0 to 1.0) that quantify how different land types favor or inhibit the establishment of a particular species (Mladenoff and He, 1999). Each cell of a land type map contains a matrix that consists of a species list and 10-year age cohorts.

At the cell scale, LANDIS simulates species birth, growth, death, regeneration, random mortality, and vegetative reproduction based on species establishment coefficients and species vital attributes for each cell on the grid (He et al., 2005). At the landscape scale, LANDIS simulates spatial processes. Seed dispersals simulate the seed travel based on species’ effective and maximum seeding distance. When seed successfully arrives at a given site, seedling establishment algorithm decides whether the seed can establish based on species that occur on the site and the shade tolerance rank of the seeding species relative to the species occupying the site. Seed establishment is a random process based on the comparing species’ SEC with a uniform random number from 0 to 1 is drawn (e.g. if its SEC is greater than the random number, the species establish) (He et al., 1999, 2005). Fire is stochastically simulated based on distribution of fire intensity, burn size, and fuel load based on the fire-tolerance of species, fire regime and fuel regime (He et al., 1999; Yang et al., 2004). Windthrow is also stochastically simulated based on the distribution of windthrow, and windthrow mortality increases with tree age and size. Harvesting and planting is simulated based on the management area, stand boundaries and management strategy (Gustafson et al., 2000). Cell- and landscape-scale processes interact during the simulation. For example, windthrow causes the death of trees and further increases the potential fire intensity class at a site due to increased fuel load (He et al., 1999).

2.3. Parameterization of LANDIS

LANDIS inputs include species life history attributes, disturbance and management parameters (harvesting, planting, and fire), species composition maps with associated species presence/absence and age information, land type maps and the species establishment coefficients for each land type (Mladenoff, 2004; He et al., 2005). Seventeen common tree species in the study area were included in our LANDIS simulation (Table 2). Species life history attributes were derived by previous LANDIS parameterization of the region and consultations with local experts.

An initial species composition map, including species and age information, was derived from a forest stand inventory map and database developed in 2000 (provided by the Forestry Planning and Design Bureau of Heilongjiang Province, 2003). The database provided information on stand boundaries and the relative abundance of canopy species, average age of dominant canopy species and timber production for each stand. The stand map in vector format was converted into a grid format with a

<table>
<thead>
<tr>
<th>Species</th>
<th>LONG</th>
<th>MTR</th>
<th>ST</th>
<th>FT</th>
<th>ED</th>
<th>MD</th>
<th>VP</th>
<th>MVP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korean pine (P. koraiensis)</td>
<td>400</td>
<td>80</td>
<td>4</td>
<td>3</td>
<td>200</td>
<td>600</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spruces (P. koraiensis and P. jezoensis)</td>
<td>300</td>
<td>30</td>
<td>4</td>
<td>3</td>
<td>80</td>
<td>150</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Khingan fir (A. nephrolepis)</td>
<td>250</td>
<td>40</td>
<td>5</td>
<td>3</td>
<td>80</td>
<td>150</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Larch (L. gmelinii)</td>
<td>300</td>
<td>20</td>
<td>3</td>
<td>4</td>
<td>150</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mongol Scotch pine (P. sylvestris var. mongolica)</td>
<td>210</td>
<td>40</td>
<td>1</td>
<td>3</td>
<td>100</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Manchurian ash (Fraxinus mandshurica)</td>
<td>250</td>
<td>40</td>
<td>2</td>
<td>5</td>
<td>120</td>
<td>400</td>
<td>0.9</td>
<td>50</td>
</tr>
<tr>
<td>Manchurian walnut (J. mandshurica)</td>
<td>250</td>
<td>15</td>
<td>2</td>
<td>4</td>
<td>50</td>
<td>100</td>
<td>0.9</td>
<td>60</td>
</tr>
<tr>
<td>Amur corktree (P. amurense)</td>
<td>250</td>
<td>15</td>
<td>2</td>
<td>4</td>
<td>60</td>
<td>300</td>
<td>0.8</td>
<td>60</td>
</tr>
<tr>
<td>Mongol oak (Q. mongolica)</td>
<td>350</td>
<td>20</td>
<td>1</td>
<td>5</td>
<td>50</td>
<td>100</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Black elm (Ulmus japonica)</td>
<td>250</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>400</td>
<td>600</td>
<td>0.5</td>
<td>60</td>
</tr>
<tr>
<td>Mono maple (A. mono)</td>
<td>200</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>120</td>
<td>350</td>
<td>0.5</td>
<td>50</td>
</tr>
<tr>
<td>Ribbed birch (B. costata)</td>
<td>250</td>
<td>15</td>
<td>2</td>
<td>3</td>
<td>200</td>
<td>350</td>
<td>0.9</td>
<td>40</td>
</tr>
<tr>
<td>Dahur birch (B. davurica)</td>
<td>150</td>
<td>15</td>
<td>2</td>
<td>5</td>
<td>150</td>
<td>300</td>
<td>0.9</td>
<td>30</td>
</tr>
<tr>
<td>Amur linden (T. amurenensis)</td>
<td>300</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>80</td>
<td>250</td>
<td>0.8</td>
<td>30</td>
</tr>
<tr>
<td>White birch (B. platyphylla)</td>
<td>150</td>
<td>15</td>
<td>1</td>
<td>3</td>
<td>250</td>
<td>600</td>
<td>0.8</td>
<td>30</td>
</tr>
<tr>
<td>Wild poplar (P. davidiana)</td>
<td>150</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>400</td>
<td>800</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td>Ussuri poplar (Populous ussuriensis)</td>
<td>180</td>
<td>10</td>
<td>2</td>
<td>4</td>
<td>300</td>
<td>500</td>
<td>0.8</td>
<td>10</td>
</tr>
</tbody>
</table>

LONG: life span (years); MTR: age of maturity (years); ST: shade tolerance (1–5); FT: fire tolerance (1–5); ED: effective seeding distance (m); MD: maximum seeding distance (m); VP: vegetative production probability (0–1); MVP: minimum age of vegetative reproduction (years). The attributes were derived from the previous studies (Yan and Zhao, 1996; Yan et al., 2000; He et al., 2002, 2005) and consultations with local experts.
90 m × 90 m resolution to reduce computational loads during model simulations. This yielded 1845 rows × 2365 columns. A stand-based assignation (SBA) approach developed by Xu et al. (2004) was used to assign species and age cohorts based on a forest inventory map and stand attribute database for each cell on the species composition map ignoring species co-existence. According to the field studies in this area (e.g. Ge et al., 1990; Zhou, 1994; Xu, 2001), single species occur only in early successional stands (e.g. white birch or aspen). Usually, more than one species exists in mid to late successional stands. Therefore, at the pixel size of 90 m × 90 m, many species may occur in one pixel.

We developed a new species and age cohort assignment method that takes this species coexistence into account. The new assignment method assumes that trees of all species are distributed homogeneously in the stand (Wang, 2003) and the minimum size that an individual tree covers is 1 m × 1 m. Under those assumptions, we created a species distribution map stochastically at a pixel size of 1 m × 1 m based on the proportion of each species in the inventory map and database. The maps of individual tree distribution with a pixel size of 1 m × 1 m was aggregated into a species composition map with a pixel size of 90 m × 90 m by using ArcGIS (9.1). Each pixel on the species composition map reported the presence/absence of each species.

In addition, the age structure for a species in a stand showed a parabolic-curve from the average age of species, with the youngest and the oldest trees having lower proportions than average aged trees in each species (Chen et al., 1994; Ge et al., 1990; Zhou, 1994; Xu, 2001). In a natural stand of mixed Korean pine and hardwoods with an average age of 220, 85% of Korean pines ranged from 120 to 280 years old (Xu, 2001). In the past, harvesting used even-aged management, meaning that the average age of species in a stand would be the same for all species. However, some over-matured trees were left as seed trees to accelerate forest recruitment in harvested stands (Li and Li, 2003). There is a variation that can be expressed as the standard deviation for all ages of species in the stand. Therefore, to parameterize the age of species in a pixel realistically, we created a distribution map for the species age classes. The map is used to assign the ages classes for the species composition map in ArcGIS (9.1). The parameters also included intervals for replacement of generation, average age of a species and standard deviation in a previous study (Chen et al., 1994; Ge et al., 1990; Zhou, 1994; Xu, 2001). In a natural stand of mixed Korean pine and hardwoods with an average age of 220, 85% of Korean pines ranged from 120 to 280 years old (Xu, 2001). In the past, harvesting used even-aged management, meaning that the average age of species in a stand would be the same for all species. However, some over-matured trees were left as seed trees to accelerate forest recruitment in harvested stands (Li and Li, 2003). There is a variation that can be expressed as the standard deviation for all ages of species in the stand. Therefore, to parameterize the age of species in a pixel realistically, we created a distribution map for the species age classes. The map is used to assign the ages classes for the species composition map in ArcGIS (9.1). The parameters also included intervals for replacement of generation, average age of a species and standard deviation in a previous study (Chen et al., 1994; Ge et al., 1990; Zhou, 1994; Xu, 2001), as well as consultations with local experts. In the composition map, 68% of the pixels fell within one standard deviation and 95% of pixels fell within two standard deviations. The standard deviation varied among species. The standard deviation of white birch in a stand, for example, was 5 years, according to previous studies (Chen et al., 1994).

We conducted a supervised classification on four scenes of satellite imagery taken in 2000, and used delineated non-forested areas (NF) to map human land use. Non-forested areas were not simulated in the study. Satellite images at 30 m × 30 m resolution were resampled to 90 m × 90 m to match the resolution of the species composition map. Road, rivers, and railroads (in the stand map) that are wider than minimum effective seeding distance (50 m) were converted into non-forested areas.

We divided the study region into 92 land types using elevation, aspect, topographical position and boundaries between southern and northern areas. Each land type has relatively homogeneous environmental conditions. Aspects were classified into southern and northern. The elevation was divided into four classes (50–350, 350–500, 500–650, and 650–1050 m) according to the vertical variation of species distribution (Zhou, 1994; Xu, 2001). Topographical position was classified into ridge, upper slope, lower slope, middle slope and flat, using a program from Jenness (2006).

We assumed that the species life history attributes will not change due to the warming climate, and recognized the species establishment coefficients on each land type as the most important parameters in responding to climate change. SEC for each species within a land type is relatively homogenous and reflects the mean probability of species occurrence in that land type. SEC for each species was derived from the logistic models based on slope, aspect, elevation, annual average temperature and precipitation, topographical position index and compound topographical index (Bu, 2006). The resulting maps and logistic models were generated for each decade from 2000 to 2100 with warming climate data in 10-year increments. The SEC for the species on the land type in the corresponding decade was the mean value of probabilities of species occurrence (resultant map of logistic model) on all cells within the land type. The initial SEC in 2000 was unchanged throughout simulation under the current climate, and the SEC under a warming climate was incorporated into models sequentially in 10-year increments from 2000 to 2100, and after 2100 the SEC was the same for remaining simulation years.

2.4. Climate warming scenarios

The climate data was obtained from the Northeastern Institute of Weather in China and was complied for 1961–2005 from 78 weather stations. Average annual temperature and precipitation was calculated based on the daily temperature and precipitation included in the climate data.

We used predictions generated by the second version of the Canadian Global Coupled Model (CGCM2), which has a surface grid resolution of 3.7° × 3.7° and has been revised to a 0.5° × 0.5° grid resolution (Flato and Boer, 2001). We acquired the prediction on all of Northeastern China from the Canadian Centre for Climate Modelling and Analysis. The average annual temperature increase predicted by CGCM2 over the next 100 years (from 2000s to 2100s) is 5.97 ± 0.14 °C, and the average annual precipitation decrease is 16.2 ± 6.2 mm over the next 100 years.

To process temperature data for the current and warming scenarios, we first used data from 78 weather stations distributed throughout Northeastern China to linearly interpolate temperature and precipitation gradients over the region. The results were converted into Arc/Info grids with 90 m × 90 m resolution, representing current temperature distributions. These grids captured average annual temperature
and precipitation variations with altitude. However, because only the average annual temperature and precipitation were used in logistic models, we did not process monthly and seasonal climate data variations. We first calculated the annual temperature differences between the warming and current climate, as predicted by CGCM2, using the following method to derive the warming climate data:

$$\Delta T_{i,j} = \frac{T_{w,i,j} - T_{c,i,j}}{10}$$

where $T_w$ represents warming climate data, $T_c$ represents current climate data from CGCM2, $i$ represents the year (2000 $\leq i \leq 2100$) and $j$ is the decade (2010 $\leq j \leq 2100$ with a 10-year increment). $\Delta T_{i,j}$ is, therefore, the climate change for year 1 and decade $j$. $\Delta T_{i,j}$ was added to the average annual temperature grids of current climate data to derive the warmed average annual temperature and precipitation grids for the decades from 2000 to 2100.

The predicted temperature and precipitation changes between 2000 and 2100 are linear and indicate that warming will occur gradually over the next 100 years as previous studies suggest (Flato and Boer, 2001). The resulting warmed conditions will persist for the simulation years after 2100. Average annual temperature and precipitation from the 10-year average for 2100 was used for simulation years after 2100. The predictions were processed to 2400 for Korean pine due to the longevity and current age cohorts of the species.

2.5. Simulation scenarios

We began with the parameterized forest composition and land type maps created from current conditions, including species age classes and species establishment coefficients that represent the initial status in 2000.

Eight simulation scenarios were designed, including no harvest and no planting scenarios (H00P00) for comparison (Table 1). The other scenarios include a combination of current designated harvest intensity and increasing percentage of the area planted to the current intensity (P01) to 5% (P05), 10% (P10), 20% (P20), 30% (P30), 40% (P40) and 50% (P50) of the study area. In addition, planting is simulated every 10 years (equal to the temporal step of LANDIS).

All scenarios were simulated under both the current and warming climate conditions. Five replicas were simulated for each scenario to assess model stochasticity. The average percent cover over the study area for each species and average percentage of the area harvested of the five replications had a standard error of less than 0.001%. The percent of the area harvested is the total pixels (sites) harvested, divided by the total number of pixels in the CF areas at a given 10-year interval. The average percentage of the area harvested is the average of the 40 iterations (400 years with 10-year increments). The proportion of a species harvested is the percent of cells where it was harvested in the sum of harvested cells for each species, and the summation of proportion is 100%. The average proportion of harvested species is the average proportion of a species harvested in the 400-year simulation. The percent of the area harvested was derived from the LANDIS harvest log file for each simulation scenario. We analyzed the changes in the percent of the area harvested and proportion of harvested species under different percent of the area planted. This tested the hypothesis that a warming climate and planting will affect the average percent of the area harvested using a paired-sample test (SPSS 10.0).

Other disturbances, such as fire and windthrow, were not included in all scenarios, because timber harvesting is thought to be the key disturbance for the region (Zhou, 1994). In the region, fire has been suppressed most intensively from 1990 by increasing population, and the fire does not obviously affect the forest composition and regeneration (Zhou, 1994). In addition, we have not seen any report about the windthrow for the region.

3. Results

3.1. Effects of climate warming on species percentage cover of the study area

Under the no planting and no harvesting scenario (H00P00) and warming climate, the warming-adapted species, Korean pine and ribbed birch, had small increases, 2.9 and 5.7%, respectively, at year 2100. The predictions are 5.1 and 7.4%, for the year 2200 (Fig. 2a and e). These warming-adapted species will have large increases after 2200 compared to results from the current climate. At year 2300, the Korean pine and ribbed birch have 12.8 and 21.9% increases, respectively, and at year 2400, they should be at a 16.7 and 30.8% increase (Fig. 2a and e).

The declining species, including spruces, Khingan fir, larch and Dahur birch have small decreases at year 2200, 10.8% for larch (Fig. 2d), 3.24% for spruces (Fig. 2b), 8.8% for Khingan fir (Fig. 2c), and 2.8% for Dahur birch (Fig. 2f). Under the warming climate, declining species have large decreases after 2200 compared to the results from the current climate. At year 2300, spruces decrease by 6.1%, Khingan fir by 20.2%, larch by 25.2% and Dahur birch by 4.9%. At year 2400, they decrease 7.6, 26.5, 32.7 and 6.6%, respectively. The drastic decrease of declining species between 2200 and 2300 releases the areas that they occupied, making it possible for warming-adapted species to establish in these areas. During this period, Korean pine and ribbed birch have larger increases (13.5 and 12.3%, respectively) (Fig. 2a and e) than those from 2000 to 2200 (increases by 5.1 and 7.4%) and those from 2300 to 2400 (increases by 7.3 and 10.9%).

3.2. Effects of climate warming on percent of the area harvested and proportions of harvested species

The percent of the area harvested fluctuates until 2080, and ranges from 22.0 to 55.1% under the warming climate, and from 22.4 to 52.1% under the current climate (Fig. 3). A cycle of 50 years of variation in timber harvesting is seen under the warming climate, during which the percentage of the area harvested increases from the lowest to the highest point in the cycle. In comparison, the results from the H58P00 scenario under both the current and warming climates show the average
percent of the area harvested throughout the simulation years increases 11.2% more under a warming climate than under the current climate.

Overall, the average harvested proportion of spruces, Khingan fir, larch and Dahur birch throughout the simulation years decreases by 5.3 ± 1.9%, 8.9 ± 3.2%, 9.8 ± 2.9% and 11.6 ± 3.0%, under the warming climate, compared to the current climate (Fig. 4). The average proportion of Korean pine and ribbed birch increases by 1.8 ± 1.1% and 8.1 ± 5.8%, under the warming climate compared to the current climate (Fig. 4). However, harvested proportions of various species vary with simulation stages. The proportions of spruces, Khingan fir, larch and Dahur birch decrease substantially from 2040 to 2080 in the harvested species under the warming climate, compared to the current climate. The proportion of Korean pine and ribbed birch among harvested species also increases beginning around 2040 under the warming climate.

Under the current climate, the proportions of coniferous species account for about 35% of the harvested species from 2100 and remain almost unchanged afterward. Under the warming climate, the proportions of coniferous species harvested decreases from about 33% in the initial decades to about 13% of the harvested species at the end of simulation (Fig. 4).

3.3. Effects of planting on percent of the area harvested and proportions of harvested species under the warming climate

Under the warming climate, the average percent of the area harvested is slightly higher throughout the simulation years,
0.7% \( (t_{39} = 6.4, p < 0.001) \) under the scenarios of 10% (H58P10) and 1.5% \( (t_{39} = 5.4, p < 0.001) \) under the 20% (H58P20) of area planted than that under the no planting scenario (Fig. 5 a). However, the average percent of the area harvested decreases by 0.1% \( (t_{39} = 17.5, p < 0.001) \), 0.1% \( (t_{39} = 1.9, p = 0.07) \), 0.1% \( (t_{39} = 0.2, p = 0.8) \), 4.6% \( (t_{39} = 4.1, p < 0.001) \) and 8.5% \( (t_{39} = 5.6, p < 0.001) \) in the H58P01, H58P05, H58P30, H58P40 and H58P50 scenarios, respectively (Fig. 5b).

The percent of the area harvested is not affected by planting and almost unchanged among all scenarios (Fig. 5) from 2010 to 2040. When comparing results among scenarios from 2070 to 2100 (H58P10, H58P20, H58P30, H58P40 and H58P50), the percent of the area harvested increases more under the high percentage of the areas planted than that under the areas with lower planted percentages. The maximal percent of the area harvested occurs at 2070 for the H58P50, H58P40, H58P30 and H58P20 and H58P10 scenarios and increases by 4.1, 3.5, 2.8 and 1.8% than in the H58P10 scenario (Fig. 5).

Percent of the area harvested tends to fluctuate in the initial decades under all scenarios, ranging from 28.4 to 54.4%. The fluctuations for percent of the areas harvested decrease in the H58P10 and H58P20 scenarios of increasing simulation years compared to the H58P00 scenario (Fig. 5a). The standard deviations for the percent of the area harvested are 5.7, 5.7 and 5.5% throughout the simulation years in the H58P00, H58P10 and H58P20 scenarios.

The proportions among harvest species remains similar until about 2060, while planting is simulated (Fig. 6). After 2060 the harvested species in the planting scenario are mainly the planted species. The proportion of harvested Korean pine, spruces, and larch increases from 10.3 to 23.9%, 2.2 to 12.5%, and 0.1 to 30.5%, at the end of the simulation years from the scenario that has 1% of area planted (H58P01) to scenario that has 50% of area planted (H58P50). Additionally, the proportion of the coniferous species in the harvest increases from 14.3% in the H58P01 scenario to 60.6% in the H58P50 scenario. The percent cover of planted species increases with the percent of the area planted (Fig. 7).

4. Discussion

4.1. Changes of species percent cover under the warming climate and their ecological impacts

The climate in the region has become dryer and warmer in recent decades (Sun et al., 2003, 2005), and the CGCM2 scenario is similar to the current warming trend in the study region. Our results show that the percent coverage of warming-adapted species such as Korean pine and ribbed birch increases under the warming climate. The percent cover of declining species such as larch, Khingan fir and Dahur birch decreases under the warming climate. The increases in Korean pine and other southern species under the warming climate should
increase the distribution of temperate forests. It is likely to increase the overall distribution of rare and precious species such as ginseng (Panax ginseng) and animals suitable to survive in the temperate forest understory (Zhou, 1994). It should also increase the overall biomass and productivity in the region (Feng et al., 1999) as compared to the current climate.

4.2. Percent of the area harvested and the shift of harvested species

Our results show that under the warming climate, the percent of the area harvested may increase by 11.2–42.4%. This suggests that the designated 58% of the area harvested could not be achieved. Reducing the percent of the area harvested or planting (see Section 4) is needed. In addition, our results show a shift in harvests from the current coniferous species to broadleaf species. This may have profound ecological and economical impact.

Timber harvesting would accelerate the regeneration of temperate forests (e.g. Korean pine mixed forest) and accelerate the decrease of species in the boreal forests (e.g. larch) from the ecological perspective. It will assist the northern boundary of the temperate forest as it moves north and accelerates the extinction of the larch under a warming climate (Fig. 7). Furthermore, timber harvesting under a warming climate accelerates the increase of rare and precious understory species. It also contributes to increases in overall biomass and productivity in the region (Feng et al., 1999). The shift of harvested species in the region would increase the diversity of the harvested species, a consideration from the economic perspective. The timbers from the coniferous species currently harvested are typically used as building materials. Timbers from broadleaf species are typically used in furniture and interior decorating materials. The ratio for timber imports from foreign countries to exports of timber from China will probably change with the potential change in harvested species under a warming climate. Wood products made from the debris of broadleaf species have increasingly replaced those from log timber (Youhao Forest Bureau, 2006). The forestry industry would benefit from a shift in harvest species caused by the warming climate because of the rising prices of broadleaf species in the recent years.

4.3. Tradeoffs between forest planting and timber harvesting

Our results show that the percent of the area harvested does not necessarily increase as the percent of the area planted increases. In fact, high percentage of the area planted (e.g. 30, 40 and 50%) results in decreases in the percent of the area harvested. Planting larch creates competitive environments that...
are unfavorable to fast growing, harvestable broadleaf species, like ribbed birch. These species lose sites when they are harvested. They did not seed into the new sites where larch was planted. The decrease of broadleaf species due to coniferous plantings suggests that the overall percent of the area harvested decreases with a higher percentage of the areas planted.

Low percent of the area planted (\(\leq 5\%\)) could not increase the percent of the area harvested under the warming climate either. This is because when the planting percentage is low, the rate of increase of harvestable species due to planting is lower than the rate of decrease of warming-declining species (Fig. 7). Only the moderate planting scenarios (e.g. H58P10 and H5820), actually increase the percent of the area harvested and the planted species cover 30–35% in the harvested species (Fig. 6). We believe 20% planting (H58P20) is the best among all the scenarios simulated to balance percent both of the area harvested and percent of the area planted. This is because (1) the average percent of the area harvested under H58P20 is the highest (43%) among all scenarios (Fig. 4); (2) the proportion of coniferous species (35%) in the harvested area is almost equal to harvest under the current climate with no planting (Fig. 5), suggesting relatively stable proportions of harvested species under a warming climate; (3) the percent of the area harvested has low fluctuation (Fig. 5), suggesting a sustainable timber harvest; (4) the percent cover of ribbed birch in the region increases (Fig. 7d), suggesting less impact of planting on the effects of the warming climate on species distribution.

Temporally, planting does not affect the percent of the area harvested. However, the percent of the area harvested under planting scenarios would increase after 2040 compared to scenarios with no planting (Fig. 5). The timeline extends to 2040 because the harvesting ages of planted species are longer (90 years for Korean pine, 60 years for spruces and 40 years for larch) than for the ribbed birch and other deciduous species (about 30 years). The harvest rotations for the sites where such species are planted would be lengthened.

4.4. Effects of warming climate on NFPP

NFPP requires that the timber harvested after 2010 be primarily restricted to planted forests (Zhang, 1999). In this plan, an increase in percent of the area planted is used to ensure that the harvest source is planted forests in the region. However, our results show that percentage of the area harvested with planting does not meet the percent of the area harvested under the warming climate (58%) designated in the NFPP plan for the region. The percent of the area harvested only reaches about 43%, far less than the designated 58% for the most planting scenarios. Planting increases the percent of the areas harvested after 2040, not after 2010.

These findings show that the current classified management of NFPP on the forest of the region needs to be revisited, or adjusted for the warming climate. We suggested that decision makers consider that (1) planting the warming adapted and fast growing species (e.g. ribbed birch) instead of larch since larch would not adapt to the warming climate, (2) increasing the percentage of the area planted to about 20% in a 10-year interval to achieve the highest percent of the area harvested, and (3) alternate the non-commercial forest and commercial forest in several decades (e.g. in about 50 years, change CF area to NCF area and NCF area to CF area) to increase the percent of the area harvested.

4.5. Result validation

Strict validation of long-term predictions of landscape simulation models is not possible (Rastetter, 1996; Gardner and Urban, 2003), since long-time series vegetation data does not exist for the warming climate. It is unfeasible to conduct model validation in the traditional sense that involves acquiring independent data at a particular time and place to compare with model predictions (Rykiel, 1996). Therefore, verifying the simulation results by comparing them with other results (e.g. other model simulations, palaeoecological and palaeoclimatic studies) is one feasible way to increase confidence in our simulation results (Bugmann, 2001; He et al., 2005).

Guo et al. (1998) found that the northern boundary of Korean pine’s distribution may shift 33.3–55.5 km northward. Yan et al. (2000) reported that larch would decrease or even disappear, and that the deciduous forests would become the dominant forest in the region in warmer and dryer conditions. Our results are consistent with these studies conducted in the region using gap models.

Pollen data from 65 Holocene sites was mapped into eight pollen taxa and seven time periods for northeast China (Ren and Zhang, 1998). These maps showed significant vegetation changes during the last 10,000 years in the current forest areas. This data showed that dominant forests follow climate dynamics. The deciduous species (Quercus and Ulmus) were the dominant species with warmer Holocene, and coniferous species (Pinus and Larix) increased in cooler Holocene. These recordings are not completely consistent with our simulation results, since our results show that Korean pine would increase under the warming climate. However, this is because the pollen study was conducted over all of northeastern China and did not consider the shift of distribution boundaries for all species, such as Korean pine. The Small Khingan Mountains is at the northernmost ecotone of temperate Korean pine mixed forests. Korean pine would increase under the warming climate since the northern boundary of Korean pine would shift toward the north. However, the decrease of larch and spruces is larger than the increase of Korean pine (Fig. 7). Therefore, the total percent cover of coniferous species would decrease under the warming climate, which is consistent with the pollen study (Ren and Zhang, 1998). In addition, the spore and pollen records from peat deposits and the paleoenvironmental reconstruction showed that the coniferous and mixed forests were the dominant forests when the climate became warmer and dryer in our region (Yang, 2003).

The qualitative comparisons such as those discussed above show that the trends and direction of forest responses to climate warming simulated in this study generally agree with the results derived from gap models, palaeoecological and palaeoclimatic studies.
4.6. Limitations

Our simulations of forest management strategy may be affected by the projections of a warming climate and limitations of LANDIS. The different climate projections may produce different species distributions and compositions in a study landscape (Adams and Kolb, 2004; Scheller and Mladenoff, 2005). Climate change predictions from the older generation of General Circulation Models (e.g. OSU and GFDL) have been used in previous studies in China. No predictions from HadRM3 are currently available for China. In our simulation, these predictions were not used because they either lacked the monthly data or used approaches (equilibrium or static) that are not comparable with those used in the new generation of GCM. CGCM2 scenario is similar to the current warming trend in the study region (Sun et al., 2003; 2005), and average annual temperate and precipitation, with a 10-year increment was used to project the warming climate. Annual average temperature and precipitation with a 10-year increment could not reflect the variability of climate between adjacent years and within given a year. The variability of climate affects the tree growth, mortality of trees and species establishment (Adams and Kolb, 2004; Guarin and Taylor, 2005). However, average annual temperature and precipitation with a 10-year increment could reflect the trend of climate change in the region, as well as mean effect of warming climate on species distribution, percent of the area harvested and planted in the region.

Detailed sensitivity analyses of LANDIS showed that long-term model projections are relatively insensitive to cell size, habitat heterogeneity, initial forest conditions, species establishment coefficient, harvesting and planting (Mladenoff and He, 1999; Gustafson et al., 2000; Syphard and Franklin, 2004; Wimberly, 2004; Xu et al., 2004; He et al., 2005). Model results are the most sensitive to differences in seed dispersal (Scheller and Mladenoff, 2005; He et al., 2005). Therefore, the most important attribute of species that would be affected by the warming climate seems to be the seed dispersal. Extreme climate would create nonstandard dispersal (long distance dispersal) and hold drastic deviation from the mean or standard trend (Nathan, 2006). In our simulation, the long distance dispersal is completely considered. Seed dispersal is limited by long distance dispersal (maximum dispersal distance) with deviations (5%) for each species. Five percent of seeds would fall in the sites within maximum dispersal distance and standard distance stochastically from the seeding tree. In the simulation process, the deviation (5%) would accelerate the migration of warming adapted species, and seems to make the nearly impossible long distance dispersal a reality. When the deviation is larger than 5%, our prediction may underestimate the abundance of Korean pine and ribbed birch. The prediction for declining species (larch, Khingan fir and spruces) is not affected by the long distance dispersal since they only emigrate from the region.

In addition, other studies have showed that warming climate affects the species attributes not included in simulation (e.g. water usage efficiency), and that drought affects the tree growth (Adams and Kolb, 2004), causes mortality of trees (Guarin and Taylor, 2005), and decreases the establishment of the tree species. However, variations of the vital attributes for species are reflected in the variation of species establishment coefficient under the warming climate in our simulations. When climate is becoming warmer and dryer, the SEC of Korean pine would increase and the SEC of larch decrease in the region. Korean pine could establish on sites that larch relinquish under the warming climate.

In our simulation, political and economic responses to warming climate are not considered because they area difficult to parameterize in LANDIS. However, evaluation on the NFPP showed that only 43% of the area harvested at the maximum, and 43% does not meet the percent of the area harvested (58%) designated in NFPP. This result reveals that the economic structure must change under the warming climate in the region. The economic structure has changed recently. While percent of the area harvested also remains at the over-harvested level, the percent of income from timber becomes less than that from other products (e.g. wild fruit of Vaccinium vitis-idaea and farms for cultivating wild animals) in the region (Youhao Forest Bureau, 2006). Therefore, the increase of temperate forest under warming climate indicates that wild fruits production such as Vaccinium vitis-idaea could increase in the northern part of the region and the higher price of these wild fruit and animals encourage the local people to cultivate them to keep pace with national economic development.

Except harvesting and planting, exotic species may affect the forest dynamics (Scheller and Mladenoff, 2005). However, this may not be a problem in our study. In the northern part of the region, the Korean pine is an exotic species and larch forests can resists its invasion from the south because the patch size of larch is much greater than the seeding distance of Korean pine (He et al., 1999; Lyford et al., 2003). The established larch and spruce can use shade, and other features, to compete effectively against Korean pine (Xu, 1992). The resistance of larch and spruce to Korean pine can be effectively simulated using the current LANDIS dispersal and competition algorithm. In the southern part in the region, few exotics could migrate into the area because the southern boundary of Korean pine mixed forest is too far from this region. The directive distance is about 500 km from this region to Changbai Mountain, the southern boundary of Korean pine.

Fires in the region are dominated by surface fire, especially the anthropogenic surface fire (Hu and Jin, 2002). They often occur in spring and autumn (Zhou, 1994; Jin, 2002; Jin and Hu, 2002). Fires are thought to be a disaster by the government and have been effectively excluded. The occurrence of surface fires with smaller burnt size in the region could affect younger trees and seed on the ground, and make our results for percent of the area harvested overestimated. However, only shrubs, grass and younger trees are burnt in these fires, and they do not significantly affect the forest regeneration and forest structure (Zhou, 1994).

One assumption in LANDIS is that after species establish on a site, trees die because of disturbance, longevity induced mortality, and a small chance of random mortalities (He et al., 2005; Wang et al., 2006). Other types of mortalities, like the direct effects of a warming climate on seedlings and saplings
that are more vulnerable to the climate change than mature trees, are not considered in the LANDIS model. In addition, the survival rates of planted young trees on sites unsuitable for establishment are affected by the quality of seedlings and care after planting (e.g. Tan, 1994). The lower mortality in the simulation could cause distribution overestimation for planted species and further overestimate their proportion in harvested species. Therefore, the proportion of warming-adapted-species harvested may be underestimated. Finally, the dead seedlings occupy the spaces where they were planted and delay the warming adapted species spread onto those sites. They likely decrease the overall timber in the harvest area. However, our results would be realistic under the assumption that survival is ensured by the input of manpower, as is common in this region.

5. Conclusion

Landscape models are an efficient tool when coupled with logistic regression models for evaluating the sustainability of forest harvesting and planting strategies under a warming climate. They provide insight into species distribution and composition, as well as sustainable harvesting and planting under a warming climate landscape. Under a new warming climate, in the region (1) Korean pine and ribbed birch will increase while larch, Khingan fir, spruce and Dahur birch will decreases. (2) The average percent of the area harvested without planting increases by 11.2% as compared to harvests under the current climate. (3) The harvested species primarily consist of warming-adapted deciduous species. (4) Planting does not mitigate the effects of over-harvesting effects. (5) Twenty percent of the area planted with 58% of the area harvested is the better management strategy in the region when considering the sustainable variations of average percentage of the area harvested. (6) Therefore, NFPP should be revised for this region. These results have important implications for forest managers to design sustainable forest harvesting and planting strategies for the landscape under a new warming climate.

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References

