Dynamic simulations of mixed broadleaved–*Pinus koraiensis* forests in the Changbaishan Biosphere Reserve of China

Guofan Shao\(^a\)*, Peter Schall\(^b\), John F. Weishampel\(^c\)

\(^a\)Institute of Applied Ecology, Chinese Academy of Sciences, P.O. Box 417, Shenyang 110015, China

\(^b\)Lehrstuhl für Landschaftsökologie, Technische Universität München, 8050 Freising 12, Germany

\(^c\)Code 923, Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Accepted 25 May 1994

**Abstract**

The development of mixed broadleaved–Korean pine (*Pinus koraiensis* Sieb. et Zucc.) forests in the Changbaishan Biosphere Reserve, located on the border with North Korea, was simulated using the gap model KOPIDE. Forest succession was simulated under three initial conditions from: (1) bare ground after clearcutting; (2) secondary forest; (3) old-growth forest. The simulations from the different initial conditions converged and support earlier successional theory that Korean pine is the climax species on the highlands of northeast China even under disturbed conditions. In addition to clear-cutting, the resilience of the forest to different levels of other human impacts, pine seed harvesting and selective cutting, was examined. These results further demonstrate that these forests possess a relatively stable structure characterized by the dominance of Korean pine. However, the model showed successional processes of the forest to be susceptible to high levels of pine seed harvesting. To predict forest dynamics at landscape scales, KOPIDE was linked with a Geographical Information System containing site and stand data sets. Running this model to simulate a forested area initially comprising several successional stages suggests that, in the absence of disturbance, Korean pine is likely to become increasingly dominant on the area over the next century.

**Keywords:** Gap model; Regeneration; Succession; Timber harvest

1. Introduction

The mixed broadleaved–Korean pine (*Pinus koraiensis* Sieb. et Zucc.) forest is one of the most complex and valuable forest ecosystem types in northeastern China. At one time, this forest covered the whole eastern mountainous area within an elevation range of 500–1200 m and was one of the primary timber sources for China. The Korean pine forest is rich in biodiversity and is the habitat of numerous endangered species, such as the northeast tiger (*Panthera tigris longipilis* L.) and ginseng (*Panax ginseng* C.A. May). The major broadleaved species are *Acer mandshuricum* Maxim., *Acer mono* Maxim., *Betula platyphylla* Suk., *Betula costata* Trautv., *Fraxinus mandshurica* Rupr., *Juglans mandshurica* Rupr., *Phellodendron amurense* Rupr., *Populus davidiana* Dode, *Quercus mongolica* Fisch. ex Turcz, *Tilia amurensis* Rupr., *Tilia mandshurica* Rupr.
et Maxim., *Ulmus japonica* (Rehd.) Sarg. and *Ulmus laciniata* Mayr. Because of timber harvesting practices over the past several decades, the extent of the old-growth Korean pine forest has been greatly reduced and replaced by post-cut forests (i.e. the forest after large trees are removed), secondary forests (i.e. the forest after clearcutting), or plantations (i.e. primarily fast growing larch). At present, only some ‘islands’ of the old-growth forest stands can be found in reserves and remote areas of northeastern China. The management of the widely distributed secondary and post-cut forests and protection of the isolated old-growth forests are critical issues in terms of biodiversity conservation. As such, the fate of the Korean pine forests has recently become a topic of ecological controversy in China.

The study of Korean pine forest succession began in the early 1950s with the start of extensive logging. Ecological experiments and observations predicted that Korean pine would be the dominant species despite the method of cutting (i.e. clear or selective) that was applied (see Chen, 1982). Though there were no long-term temporal data, chronosequence studies supported these short-term experiments. However, such space-for-time substitutions are often flawed (Pickett, 1989; Fastie, 1990) as site locations...
may represent different environments, and historical events (e.g. time of colonization and disturbance) typically do not coincide in space.

Forest simulation models have been used to supplement observational data and to predict forest dynamics under altered environmental conditions. The first simulation model of forest succession for the Changbaishan region was a Markov model developed by Miles et al. (1983). In contrast to the experimental and chronosequential studies, the simulations predicted that maple (Acer mono) would be the dominant species as Korean pine became extinct after clearcutting. Though Markov models have been used to predict forest dynamics at varying scales (Horn, 1975; Hall et al., 1991), estimations of state-to-state transition probabilities are often fraught with difficulties (Runkle, 1981) as they are typically based on observed forest changes over relatively short periods of time (Shugart, 1984).

For this paper, we used an individual-based model of succession (i.e. gap model; Botkin et al., 1972; Urban and Shugart, 1992), called KOPIDE, to simulate the dynamics of the Changbaishan Korean pine forest, one of three classes of Korean pine forests distributed in northeastern China (Chen, 1982; Wang, 1986). Though this method to model the long-term dynamics of uneven-aged, multi-species stands is more mechanistic than the Markov approach (Shao, 1989), gap models are readily parameterized with stand remeasurement and site data. Using such data collected from the Changbaishan Reserve on the boundary between China and North Korea (Fig. 1), we used KOPIDE to analyze the resiliency of the Korean pine forest to different management practices.

2. Methods

2.1. Description of KOPIDE

KOPIDE consists of three primary subroutines: regeneration, growth, and mortality. These are the same in principle as found with most gap models; however, some of the approaches have been adapted to the particulars of the broad-leaved-Korean pine forest and the data base available for model calibration.

Tree regeneration occurs only if two conditions are satisfied: (1) viable seeds exist and (2) they are dispersed to an area where environmental conditions are suitable for germination and seedling growth. Because there are many micro-environmental factors involved in these processes, it is almost impossible to simulate the mechanism of regeneration at a fine spatial scale. Thus, gap modeling approaches use statistical relationships between sapling availability and one or more environmental variables.

To derive such a relationship, the number of saplings (i.e. trees between 0.3 and 1.0 cm diameter at breast height (dbh)) for each species found under canopies of different leaf area indices (LAI) were recorded. Thus, each species had a characteristic distribution pattern for the maximum number of saplings for a given LAI. This relationship was defined by the following function

\[ X = A \exp\left[ B (LAI - LAI_{opt})^2 \right] \]  

where \( X \) is the maximum number of saplings for a given LAI, \( LAI \) is canopy leaf area index, \( A \) is the maximum number of saplings for the optimal LAI, \( B \) is a curve-fitting parameter that defined the range of suitable LAI, and \( LAI_{opt} \) is the optimal LAI for regeneration.

The values of parameters \( A \), \( B \), and \( LAI_{opt} \) are directly related to the biological characteristics of the species involved. The value of \( A \) is a function of seed production. Aspen and birch have relatively large values of \( A \), and Korean pine has a relatively smaller one (Table 1). The value of \( B \) is related to the light sensitivity of a species. Shade-intolerant species have a lower value than shade-tolerant species. The value of \( LAI_{opt} \) expresses the difference between the two extremes of suitable light with higher values corresponding to more shade-tolerant species. Regeneration is then calculated using the formula

\[ N = XR \]  

where \( N \) is the actual number of surviving sa-
Table 1
Species-specific parameters used in implementing KOPIDE. The numbers in parentheses after the parameter signify the related equation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Species</th>
<th>A. mo</th>
<th>B. pl</th>
<th>F. ma</th>
<th>P. da</th>
<th>P. ko</th>
<th>Q. mo</th>
<th>T. am</th>
<th>U. ja</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age max (years)</td>
<td></td>
<td>200</td>
<td>100</td>
<td>300</td>
<td>60</td>
<td>400</td>
<td>350</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>DBH max (cm)</td>
<td></td>
<td>70</td>
<td>80</td>
<td>110</td>
<td>60</td>
<td>160</td>
<td>140</td>
<td>120</td>
<td>90</td>
</tr>
<tr>
<td>Height max (cm)</td>
<td></td>
<td>2200</td>
<td>2700</td>
<td>3300</td>
<td>2400</td>
<td>3500</td>
<td>2800</td>
<td>3100</td>
<td>2600</td>
</tr>
<tr>
<td>$a$ (4 and 5)</td>
<td></td>
<td>0.926</td>
<td>0.875</td>
<td>0.940</td>
<td>0.713</td>
<td>0.967</td>
<td>0.915</td>
<td>0.790</td>
<td>0.832</td>
</tr>
<tr>
<td>$b$ (4 and 5)</td>
<td></td>
<td>-0.058</td>
<td>-0.071</td>
<td>-0.042</td>
<td>-0.096</td>
<td>-0.025</td>
<td>-0.040</td>
<td>-0.052</td>
<td>-0.057</td>
</tr>
<tr>
<td>$w$ (4 and 5)</td>
<td></td>
<td>1.08</td>
<td>1.45</td>
<td>1.14</td>
<td>1.83</td>
<td>0.95</td>
<td>1.24</td>
<td>2.03</td>
<td>1.67</td>
</tr>
<tr>
<td>$c$ (5)</td>
<td></td>
<td>8.13</td>
<td>19.5</td>
<td>43.6</td>
<td>29.7</td>
<td>29.3</td>
<td>17.9</td>
<td>13.4</td>
<td>20.0</td>
</tr>
<tr>
<td>$d$ (5)</td>
<td></td>
<td>2.01</td>
<td>1.69</td>
<td>1.61</td>
<td>1.70</td>
<td>1.75</td>
<td>1.72</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>$G$ (5)</td>
<td></td>
<td>16</td>
<td>36</td>
<td>13</td>
<td>29</td>
<td>11</td>
<td>18</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>$D_{l_{max}}$ (8)</td>
<td></td>
<td>1.39</td>
<td>1.70</td>
<td>1.25</td>
<td>1.75</td>
<td>1.05</td>
<td>1.64</td>
<td>1.40</td>
<td>1.55</td>
</tr>
<tr>
<td>DEGD $\text{max}$ (7) (°C days)</td>
<td></td>
<td>3800</td>
<td>4000</td>
<td>3400</td>
<td>4000</td>
<td>3250</td>
<td>3800</td>
<td>3400</td>
<td>3800</td>
</tr>
<tr>
<td>DEGD $\text{min}$ (7) (°C days)</td>
<td></td>
<td>1450</td>
<td>1350</td>
<td>1600</td>
<td>1400</td>
<td>1350</td>
<td>1450</td>
<td>1500</td>
<td>1450</td>
</tr>
<tr>
<td>$G_{L_1}$ (9)</td>
<td></td>
<td>1.00</td>
<td>1.73</td>
<td>1.06</td>
<td>1.73</td>
<td>1.00</td>
<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$G_{L_2}$ (9)</td>
<td></td>
<td>6.66</td>
<td>1.15</td>
<td>3.14</td>
<td>1.15</td>
<td>4.66</td>
<td>3.14</td>
<td>3.14</td>
<td>3.14</td>
</tr>
<tr>
<td>$G_{L_3}$ (9)</td>
<td></td>
<td>0.05</td>
<td>0.25</td>
<td>0.10</td>
<td>0.25</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>$A$ (1)</td>
<td></td>
<td>5</td>
<td>60</td>
<td>5</td>
<td>50</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$B$ (1)</td>
<td></td>
<td>-0.100</td>
<td>-3.91</td>
<td>-0.178</td>
<td>-3.91</td>
<td>-0.038</td>
<td>-0.402</td>
<td>-0.178</td>
<td>-0.100</td>
</tr>
<tr>
<td>LAI $\text{opt}$ (1)</td>
<td></td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$d_{L_{max}}$ (mm)</td>
<td></td>
<td>0.01</td>
<td>0.05</td>
<td>0.03</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$t$ (years) (10)</td>
<td></td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>LAI/biomass (m$^2$ kg$^{-1}$)</td>
<td>12.6</td>
<td>16.5</td>
<td>15.0</td>
<td>15.0</td>
<td>17.5</td>
<td>15.0</td>
<td>14.8</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Sapling a (years)</td>
<td></td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>16</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Volume parameter $\text{a}$ (m$^2$ kg$^{-1}$)</td>
<td>0.564</td>
<td>0.693</td>
<td>0.884</td>
<td>0.693</td>
<td>0.829</td>
<td>0.863</td>
<td>0.722</td>
<td>0.777</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ A. mo, Acer mono; B. pl, Betula platyphylla; F. ma, Fraxinus mandshurica; P. da, Populus davidiana; P. ko, Pinus koraiensis; Q. mo, Quercus mongolica; T. am, Tilia amurensis; U. ja, Ulmus japonica.

KOPIDE simulates the maximum growth rate ($dB_{max}$) of an individual tree in terms of tree biomass ($B$) and tree leaf area ($LA$)

$$dB_{max} = Gf(B, LA)$$  

where leaf area itself is also a function of tree biomass. The determination of parameter $G$ is based on the hypothesis of Botkin et al. (1972) that two-thirds of maximum diameter is reached at one-half of maximum age. This hypothesis was validated against site index curves for the Changbaishan species (Shao, 1991).

Tree growth results in changes of leaf, branch, root, and stem biomasses. Although diameter at breast height (DBH) growth is not strictly correlated to the growth of these components, it does represent the most easily measurable indicator (Shao, 1991). Thus, tree biomass and tree height ($H$) are usually represented as a function of DBH ($D$). The height of a tree is an indicator of its competitive status in a stand. In contrast to other gap models that typically use the parabolic function of Ker and Smith (1955), we used a Richard's function for describing the relation of DBH to height

$$H = H_{max} [1 - aexp(bD)]^w$$

where $a$, $b$, and $w$ are species-specific constants. This function was found to better fit the remeasurement data than other standard growth equa-
tions for all the species studied. When DBH = 0, height was set to 1.3 m.

Following techniques analogous to those of Botkin et al. (1972) that assume leaf area can be approximated as a function of diameter, the following differential equation was derived for the maximum annual DBH growth increment

\[
\frac{dD_{\text{max}}}{dt} = G_c D^d \frac{1 - DH/D_{\text{max}} H_{\text{max}}}{2DH + D^2 H_{\text{max}} abw(1 - ak)^{(w-1)}k}
\]

(5)

where \( c \) and \( d \) are the two parameters of the power function that estimate leaf area from DBH, and \( k = \exp(bD) \).

KOPIDE assumes that the actual DBH growth \( (dD) \) results from restrictive environmental effects \( F(0) \) representing the reaction of species to the water, temperature, and light regimes on the inherent growth properties \( (dD_{\text{max}}) \) of the tree species

\[
dD = dD_{\text{max}} F(0)
\]

(6)

where \( dD \) is actual growth of DBH, \( dD_{\text{max}} \) is potential maximum growth of DBH, \( F(0) \) consists of three sub-multipliers

\[
f(01) = \frac{4(DEGD - DEGD_{\text{min}})(DEGD_{\text{max}} - DEGD)}{(DEGD_{\text{max}} - DEGD_{\text{min}})^2}
\]

(7)

\[
f(02) = 4DI(DI_{\text{max}} - DI)/DI_{\text{max}}
\]

(8)

\[
f(03) = GL_1 [1 - \exp\{-GL_2(AL - GL_3)\}]
\]

(9)

where \( f(01) \) is the growth multiplier for air temperature, DEGD is growing degree-days with base of 10°C, \( f(02) \) is the growth multiplier for moisture, \( DI \) is a drought index defined as the ratio of potential evapotranspiration, following Thornthwaite and Mather (1957), to precipitation, \( f(03) \) is the growth multiplier for light, \( AL \) is available light (determined by the cumulative leaf area index (LAI) of all the trees in the plot taller than the tree being considered), the studied species are classified into three shade-tolerance groups with different parameters \( GL_1, GL_2 \) and \( GL_3 \).

Tree mortality is considered in two situations: (1) owing to senescence (assumes that 1% of trees will live to maximum age); (2) owing to critically reduced carbon gain, i.e. respiration nearly equals assimilation. Stress-related mortality is modeled as dependent upon a species-specific critical growth rate of DBH and the maximum possible number of years for survival if growth rate is below the critical growth rate.

\[
MP = 1 - 0.01^{1/(1/q)}
\]

(10)

where \( MP \) is mortality probability for a given year, \( q \) is maximum age (\( Age_{\text{max}} \)) in years or the probable number of years a tree can survive \((t)\) if the growth rate is below the critical growth rate.

Thus, mortality, like regeneration, is modeled as a stochastic event. A tree dies when a uniform random number is less than the \( MP \) for that tree.

For simulations of the Changbaishan forests, the species pool included: maple (\( Acer mono \) Maxim.), birch (\( Betula platyphylla \) Suk.), ash (\( Fraxinus mandshurica \) Rupr.), pine (\( Pinus koraiensis \) Sieb. et Zucc.), aspen (\( Populus davidiana \) Dode), oak (\( Quercus mongolica \) Fisch. ex Turcz.), basswood (\( Tilia amurensis \) Rupr.), and elm (\( Ulmus japonica \) (Rehd.) Sarg.). Parameter estimations (Table 1) were made at two scales. The more physiological parameters, such as \( DEGD \), \( DEGD_{\text{min}} \), \( DI_{\text{max}} \), etc. were estimated from the geographic distribution of the species. The more demographic parameters, such as \( D_{\text{max}} \), \( DEGD_{\text{min}} \), \( DI_{\text{max}} \), etc. were estimated from field investigations and other research (Yang and Lin, 1981) from the Changbaishan Forest Ecosystem Research Station of the Chinese Academy of Sciences.

2.2. Model experiments

To test the effects of clearcutting, KOPIDE was used to simulate the successional dynamics associated with three initial forest conditions of the Korean pine forests found at the Changbaishan Biosphere Reserve. These initial states represented: (1) a stand after clearcutting; (2) a sec-
ondary-growth, 30-year-old stand; (3) an old-growth, over 200-year-old stand. For the first scenario, the simulations started with bare ground. For the second and third scenarios, the simulations were initiated with a previously established forest structure. The size-class distributions of the trees for these two scenarios were each derived from ten arbitrarily chosen 225 m² inventory plots from areas thought to be representative of the secondary and old-growth forest types within the Changbaishan Biosphere Reserve. The size of these plots corresponds to the size of a KOPIDE plot.

Besides clearcutting, the possible consequences of two additional human impacts were also investigated. Though timber harvesting from the Korean pine forest is restricted in the Changbaishan Biosphere Reserve, the local people harvest pine seeds, which are used for planting pine trees or for food. Korean pine tree regeneration is aided by small mammals (e.g. the gray squirrel) that store pine seeds under soil (Chen, 1982). It is thought that extensive harvesting of pine seeds will reduce the mammal populations as well as the number of viable seeds and subsequently, the natural regeneration of Korean pine. To mimic the effects of pine seed harvesting, the sensitivity of the model to different levels of Korean pine regeneration were analyzed. The effects of selective cutting, an alternative to clearcutting used in Korean pine forest management (Wang et al., 1980), were also explored. During World War II, a large number of big trees were cut throughout most of the Korean pine forest distribution. These post-cut stands generally have a lower density and biomass than less disturbed stands. KOPIDE was used to predict the dynamics of the post-cut forests by simulating the effects of different cutting intensities.

The model output includes annual summations at the forest stand and at the individual tree scale over a 400 year period. At the stand level, tree density, LAI, volume, stem productivity, and leaf productivity are calculated. At the tree level, the size-class distributions of trees are tallied by species. To minimize variation due to stochasticity in the model, each simulation experiment was repeated 50 times; thus, the total stand size exceeded 1 ha.

The spatial nature of gap models have recently been extended to cover landscape scales (Urban et al., 1991). To predict coarser-scale dynamics using KOPIDE, a forested area of about 400 ha at 750–850 m elevation on the north slope of Changbaishan Mountain was selected based on the regional suitability of the model. The ground cover was inventoried using infrared aerial photographs and field measurements. The landscape consisted of patches of the succession series of the mixed broadleaved–Korean pine forest: bare ground, secondary forest, mixed forest dominated by broadleaved species, and mixed forest dominated by Korean pine. Maps of water availability and temperature conditions were derived from macro- and mesoclimatic relationships with elevation, slope, and aspect, giving drought index (DI) and growing degree-days (DEGD) for the forested area. Simulations consisted of patches that differed only in existing ground cover as differences in environmental parameters among the patches were minimal. The patch simulations were run for 150 years and periodically mapped back onto the landscape using a Geographic Information System (GIS). If a simulated patch was dominated by birch or aspen, it was designated a secondary forest; if the dominant species were ash, bathwood, oak, or elm, and pine accounted for less than 15% of the stand volume, it was designated a hardwood forest; if the stand was dominated by the hardwood species and pine accounted for over 15%, it was designated a hardwood-dominated mixed forest; if dominated by pine, it was designated a pine forest.

3. Results

The simulation of succession from bare ground (Fig. 2) shows dominance over the first 50–60 years, in number as well as in volume, by the fast-growing shade-intolerant broadleaf species (i.e. birch and aspen). The other species all invaded during the early stages of second-growth forest after clearcutting. Throughout the first 20–30
years, these were present as saplings. After leaf productivity reached a maximum (4000 kg ha$^{-1}$ year$^{-1}$), i.e. after canopy closure, the number of individuals of all species and the stem volume of the birch and aspen decreased, while the stem volume of ash, oak, basswood, and pine steadily increased. Over the next 200 years, the forest was dominated by relatively shade-tolerant broad-leaved species (e.g., ash) as shade-intolerant species died out. During this stage of mixed forest dominated by broadleaved species, both leaf productivity and stem productivity decreased continuously to about 3000 kg ha$^{-1}$ year$^{-1}$ owing to a higher percentage of the slow growing pine trees. After about 250 years, the slow growing Korean pine overtopped the broadleaved
Fig. 3. Simulated 300-year trend of: (a) stand volume and stand density, (b) stem volume by species, (c) stand density by species, and (d) productivity of leaves and stems using the initial condition of 30-year-old secondary growth forest.

canopy and the quasi-equilibrium climax stage (i.e. mixed forest dominated by Korean pine) was established. Leaf and stem productivity were about 2700 kg ha$^{-1}$ year$^{-1}$. The understory tree, maple, was present in all stages, but as it is limited by its maximum height, it never attained a large percentage of the total volume. This is contrary to the Markov simulations of Miles et al. (1983), which assumed the maple understory would eventually yield a maple-dominant forest.

The same tendency of succession appeared when the initial condition was a second-growth forest (Fig. 3). Because we used data to initialize the model from 30-year-old birch/aspen stands, these established species persisted in the upper canopy about 30 years longer than with succes-
Fig. 4. Simulated 300-year trend of: (a) stand volume and stand density, (b) stem volume by species, (c) stand density by species, and (d) productivity of leaves and stems using the initial condition of an old-growth mixed broadleaved–Pinus koraiensis forest.

...sion from bare ground. Although stand density was initially much greater than found with the bare-ground simulation, after 50 years the trend became similar.

The simulation using an old-growth mixed broadleaved–Pinus koraiensis forest as the initial condition shows the stability of the climax stage (Fig. 4). There are internal fluctuations, however, in the percentage of Korean pine to broadleaved species. Thus, even at a resolution of 1 ha, dynamic properties are evident (Smith and Urban, 1988) supporting the shifting mosaic steady-state theory. Both leaf and stem productivity are mainly in the range 2200–3200 kg
Fig. 5. Comparison of simulated percentage (a) stem volume and (b) stem number of Korean pine from different pine regeneration scenarios.

Fig. 6. Comparison of simulated (a) stand volume and (b) stand density from different cutting intensities: control represents no cutting; cut 1 represents an approximate 25% harvest of the largest trees; and cut 2 represents an approximate 50% harvest of the largest trees.

ha⁻¹ year⁻¹, which coincides with the values reported by Cheng et al. (1986) for a stand of similar elevation (2620 kg ha⁻¹ year⁻¹ for leaves and 2730 kg ha⁻¹ year⁻¹ for above-ground woody biomass). In general, the simulations with the different initial conditions exhibited minor differences in species composition, stand volume, stand density, stem productivity, and leaf productivity once Korean pine gained dominance between 250 and 300 years.

With the conditions of reduced regeneration for Korean pine (Fig. 5), the percentage of Korean pine stems decreased gradually after a 50 year period, but the percentage of Korean pine volume remained relatively stable over a 200 year period at 30–40%.

The lower cutting intensity (25% of the largest trees by volume) was found not to alter the forest structure as the forest returned to its precut volume and density status after 25 years (Fig. 6). For the higher cutting intensity (50% of the largest trees by volume), the post-cut forest required about 50 and 100 years to rebound to its uncut volume and density status, respectively.

The simulation results for the landscape changes over 150 years at 50 year intervals are shown in Fig. 7. Corresponding to the simulations with the different initial stand compositions (i.e. Figs. 2–4), the simulated landscape shows the different patch types to be or eventu-
ally becoming Korean pine-dominated forest. Thus, the original landscape of mixed broad-leaved–*Pinus koraiensis* forest, was reproduced by passing through the successional stages despite different land-use practices that had occurred. Though less than 30% of the landscape is presently Korean pine forest, the model predicts that more than 70% of this area will become Korean pine forest during the next century.

### 4. Discussion

The assumptions and formulae used in implementing KOPIDE have been verified from studies and observed data on the mixed broad-leaved–Korean pine forest (Shao, 1991). However, by using the stand structure of different successional stages as the initial conditions of the simulation, a self-test of KOPIDE was performed. The consistency among model results (i.e. the clearcut eventually resembled the secondary forest and both these stages eventually resembled the old-growth forest) suggests that the dynamics of this system are somewhat resilient to perturbations which change species demographic distributions such as those resulting from timber harvest. These results support data from experimental and empirical studies (Chen, 1982) that forest succession in northeastern China culminates with a forest where Korean pine is the dominant species. In all the simulations, maple (*Acer mono*) persisted as an understory species, but it never achieved a dominant role as found in the Markov model (Miles et al., 1983). Though maple has been observed to play an important role in terms of density in early secondary succession, it does not in terms of volume.

Because gap models generate more detailed information about forest structure and productivity than Markov models, this type of model can be used for more detailed analyses such as habitat changes associated with succession (Urban and Smith, 1989). The coniferous forests of northeastern China, known for their biodiversity, are dominated by Korean pine. If the role Korean pine is reduced from these forests, the forest structure will dramatically change and habitats will be lost. At present, the effects of pine seed harvesting have not been observed; but the potential danger of altering the future forest structure exists, if pine seed harvesting continues to go unmanaged.

The method of timber harvest from the Korean pine forests has been a source of controversy (Wang et al., 1980; Chen, 1982; Xu et al., 1986). Though the practice of large-scale clearcutting is the most cost-effective short-term method, ecosystem damage is severe. The compromise approach has been to use small-scale clearcutting (less than 10 ha). However, the KOPIDE simulations of the post-cut forest suggest that lower intensity selective cutting (around 25% by volume) would protect the forest structure and also would yield more and better-quality timber with a cutting cycle of 30 years. Four cycles of selective cutting (i.e. 120 years) yield the same amount of timber as a single clearcut which takes over 200 years to regenerate. Furthermore, because the majority of the post-cut forests were formed after high intensity cutting 50 years ago, the structure of these post-cut forests should parallel the old-growth forests in another 50 years. This means that ecosystem-level protection of post-cut forests should be included in the biodiversity conservation activities of northeastern China.

This paper also serves as a case study on the integration of a dynamic forest model with a GIS and shows a potential application of GIS technology in forest ecosystem research. The visual simulation results show forest dynamics with a series of GIS maps. However, this approach was somewhat simplistic as it does not involve spatial interaction among patches such as seed dispersal and species migration and needs to be tested with a more complex forested landscape that includes a variety of environmental regimes. The input data for the environmental variables and initial state variables for each plot of the landscape could come from overlaying relevant maps. If the landscape is relatively uniform, such a vector-based approach would increase the speed of the simulation making it substantially faster than raster-based ap-
approaches that have previously been used to simulate landscape scale dynamics (e.g. Smith and Urban, 1988; Weishampel et al., 1992).

5. Conclusions

The mixed broadleaved–Korean pine forest is an important ecological and economic resource. The natural successional patterns of the forest are being threatened by increasing pressure from growing local populations. Without human interference, the forest structure is relatively stable. However, excessive pine seed harvesting could lead to a decrease of Korean pine regeneration and redirect the normal successional pathway towards a hardwood forest. Artificial regeneration of Korean pine under the forest could act as a remedial measure. But the best approach is probably to prohibit or restrict pine seed harvesting in the reserve. Similarly, some of the postcut forests from the 1950s lack Korean pine saplings because of a reduced number of source trees. Again, the planting of pine seedlings could reverse the changes caused by this selective cutting. Although the secondary forests generally have a sufficient number of pine saplings to ensure regeneration, the growth rates of pine seedlings or saplings are reduced because of a dense canopy. Thus, the selective cutting of some canopy trees could enhance the growth of pine saplings. This management technique has been proved effective in areas of northeastern China.

With the addition of new subroutines or the incorporation of other data, KOPIDE lends itself to numerous applications beyond the scope of this study, e.g. studying nutrient cycling or impacts of climatic change (Pastor and Post, 1986, 1988). It is hoped that KOPIDE can serve as a framework for future modeling investigations of these forests.

Acknowledgments

The development and parameterization of KOPIDE were assisted by the Changbaishan Forest Ecosystem Research Station of the Chinese Academy of Sciences. The model implementation, preparation of the GIS database, and linkage of the GIS with the model were supported by the Changbaishan Project associated with an International Co-operative Ecological Research Program (CERP-N2) coordinated by UNESCO.

References


Shao, G., 1989. Review on computer models of forest growth