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# Long-term forest landscape responses to fire exclusion in the Great Xing'an Mountains, China

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**Abstract.** Understanding of long-term forest landscape dynamics under fire exclusion, which have not been studied in north-eastern China, is increasingly needed for designing sound forest management and protection plans. In the present study, we examine whether long-term fire exclusion leads to catastrophic fires and whether the fire regimes altered by fire exclusion have changed the course of natural succession of dominant tree species. We designed two simulation scenarios – fire exclusion and no fire exclusion – and used LANDIS to study the long-term (300 years) fire regime dynamic and the succession of dominant tree species in terms of species abundance, age structure and spatial pattern. Our simulated results show that fire exclusion can lead to catastrophic fires with return intervals ranging from 50 to 120 years, increase the proportion of coniferous forests and decrease the proportion of deciduous forests, simplify tree species composition, and alter forest age structures and landscape patterns. Based on these simulated results, we suggest that prescribed burning or coarse woody debris reduction, uneven age management, and a comprehensive wildlife habitat suitability analysis should be incorporated in forest management plans in this region.

**Additional keywords:** disturbance, forest succession, LANDIS, landscape pattern, spatially explicit landscape simulation model.

## Introduction

Fire is one of the most important ecological factors shaping the dynamics of many terrestrial ecosystems (Turner *et al.* 1994; Whelan 1995; Goldammer and Furyaev 1996; Gardner *et al.* 1999). Forest fires directly affect species composition and structure (Noble and Gitay 1996; Gardner *et al.* 1999) and alter forest age distributions (Heinselman 1973; Van Wagner 1978). However, as part of the paradigm of forest management of the last century, fire exclusion was widely used in many forest ecosystems worldwide (Baker 1992; Barrett 1994; Finney 1999). Fire exclusion may modify the natural disturbance regime, such as by lengthening the fire cycle (Lesieur *et al.* 2002; Shang *et al.* 2004), by altering the range of naturally burned areas and leading to major changes in vegetation succession trajectories and forest landscape dynamics (Ryan 2002), and by increasing fuel loads of forest ecosystems (Clark 1988; Baker 1992; Bury 2004). All of these effects have the potential to cause negative ecological consequences.

In 1987, a catastrophic fire occurred in the Great Xing'an Mountains of north-eastern China and burned a total area of $1.3 \times 10^6$ ha. This fire is attributable to fire exclusion (Wang *et al.* 2007). In the Great Xing'an Mountains, fire exclusion has been carried out since the early 1950s, but it differs from fire exclusion methods employed in North America or elsewhere where fires need to be suppressed around wildland–urban interfaces. The Chinese government had invested substantially in both funding and manpower, including the army, forestry policemen, and local residents. These investments were aimed at the prevention and monitoring of forest fires during fire prevention seasons – from 15 March to 15 June and from 15 August to 15 November of every year. Once a fire was observed, the local government was notified immediately. The government then assigned the manpower to fight the fire. After 50 years of fire exclusion and technological advances, natural fires have been largely suppressed and fire regimes have been significantly changed in this area (Xu 1998). The fire return interval has extended from 120 to 150 years during the 1950s (Xu 1998) to ~500 years at present. Evidence of this shift is recorded in the statistics of fire records for the northern slope of the Great Xing'an Mountain region from 1990 to 2000. After the 1987 catastrophic fire, forest managers and policy makers have been debating whether to continue fire exclusion or to restore natural and historical fire regimes. The long-term effects of fire exclusion on forest landscapes and whether fire exclusion fosters catastrophic fires have become priority concerns for forest managers and planners. The answers to these questions can provide valuable information needed for determining ecologically sound forest management planning.

Most fire-related studies in this region have focused on forest succession at the plot level (e.g. Yan *et al.* 2000; Du *et al.* 2002; Luo 2002) and are therefore of limited applicability in answering

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forest landscape-level questions. At the landscape level, forest fires often result in burned patches with variable sizes due to variations of fire frequency and severity. Post-fire vegetation succession is often influenced by the spatial configuration of these patches (Wang *et al.* 2006). Low biodiversity and low vegetation cover can often be found on larger burned patches (Li *et al.* 2004). High severity forest fires may cause large burned patches that, in turn, can result in homogeneous landscapes. Low severity fires usually create small burned patches that result in heterogeneous landscapes (Deng *et al.* 2003). The dynamics of forest landscapes where stand-replacing fires are common can be revealed by examining the variations of forest patches of different age classes (Heinselman 1973).

Study of long-term impacts of disturbance on forest landscape dynamics often requires a modelling approach for two reasons. First, field experiments with large-scale disturbances are difficult or impossible to conduct in large areas. Second, repeating large-scale experiments or sampling regimes is often prohibitively expensive or impossible (Turner *et al.* 1994). In the present study, we used a spatially explicit forest landscape model, LANDIS (He and Mladenoff 1999*a*), to explore forest landscape responses to fire exclusion in the Great Xing'an Mountains. The LANDIS model possesses an established capability of simulating forest landscape dynamics across a wide range of ecosystems (He and Mladenoff 1999*b*; He *et al.* 1999; Gustafson *et al.* 2000; Shifley *et al.* 2000; Franklin *et al.* 2001; He *et al.* 2002). In the present study, we intended to examine whether long-term fire exclusion leads to catastrophic fires and whether altered fire regimes change the course of natural succession of dominant tree species in terms of the dynamics of species abundance, forest age structure, and landscape pattern.

## Materials and methods

### Study area

Our study area, located in the north-western area of Heillongjiang Province in north-eastern China (52°25′00″N 122°39′30″E to 51°14′40″N 124°21′00″E), has a total area of 937 244 ha (Fig. 1). The area falls within the cool temperate zone (Zhou *et al.* 1991) affected by the Siberian cold air mass. It possesses a terrestrial monsoon climate with a long and severe winter. Annual average precipitation is ~500 mm, more than 60% of which occurs between June and August. The annual average temperature is 4.7°C with an average of −28.9°C for February, the coldest month in the year. The average temperature for July, the hottest month in the year, is 17.1°C, with a highest recorded temperature of 35.3°C.

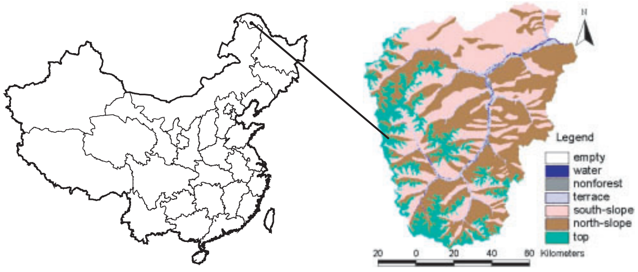

**Fig. 1.** The geographic location of the study area and different land types, among which empty, water and non-forest land types are not simulated in the model.

The vegetation of this area belongs to cool temperate coniferous forests, which are the southern extension of eastern Siberian boreal forests (Zhou *et al.* 1991). The forest area accounts for 86.98% of the study area. The canopy species composition is relatively simple, including larch (*Larix gmelini*), pine (*Pinus sylvestris* var. *mongolica*), spruce (*Picea koraiensis*), birch (*Betula platyphylla*), two species of aspen (*Populus davidiana*, *Populus suaveolens*), and willow (*Chosenia arbutifolia*). With the exception of some portions of wetland near the river, larch is widely distributed and accounts for 65% of the study area. Birch and pine are mixed with larch in most areas owing to fire disturbance and forest harvesting, with pine having a small area of distribution (1.8%). Aspen and willow are confined to terraces along the rivers where water is plentiful. Spruce, being highly shade tolerant, occurs mostly in valleys and high elevation areas (Xu 1998). Analyses of the dynamics of every species in this area are unfeasible. Therefore, in the present study, we analyzed four representative species: larch, pine, spruce, and birch. We selected these species for their characteristics: larch is a late successional, climax species; birch is an early successional, pioneer species, and pine and spruce are common species with high economic value in this region.

### LANDIS model

LANDIS is a cell-based, spatially explicit forest landscape model of disturbance, succession, and management (Mladenoff *et al.* 1996; Mladenoff and He 1999). It simulates species-level forest dynamics by tracking the presence or absence of species age cohorts at 10-year time steps under natural and anthropogenic disturbances, including fire, windthrow, insects and disease, harvesting, and fuel management. Detailed descriptions of various LANDIS components can be found in studies conducted by He and Mladenoff (1999*b*), He *et al.* (2002), and Gustafson *et al.* (2000). The version used in the present study was LANDIS 3.7.

Fire disturbance is an important spatial process in landscapes. It is a bottom-up disturbance with young age cohorts being killed first. Fire exclusion in LANDIS 3.7 is simulated by lengthening the Mean Return Interval (MRI) of various land types. The LANDIS 3.7 fire disturbance module simulates disturbance size, probability, ignition, spread, and severity using mathematically defined distributions.[1]

Fire size ($S$) is a function of mean fire size (MFS) based on the following formula (He and Mladenoff 1999*a*; He *et al.* 2003):

$$S = a(10.0)^r \times \mathrm{MFS}$$

where $S$ is the fire size, MFS is the mean fire size, $a$ is the fire disturbance size coefficient designed for model calibration, and $r$ is a normalised random number. With similar mean fire return intervals, very different fire regimes can be obtained ranging from small, frequent fires to large, infrequent fires, which are defined by $S$ distribution.

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[1] Note that LANDIS 4.0 uses new approaches to simulate fire and fire suppression.

**Table 1. Species' vital attributes derived for Huzhong Forestry Administrative Bureau**

ED, effective seeding distance (m); FT, fire tolerance class (1 to 5, with 1 for the least tolerant and 5 for the most tolerant); LONG, longevity (years); MD, maximum seeding distance (m); MTR, age of maturity (years); MVP, minimum age of vegetative reproduction (years); ST, shade tolerance class (1 to 5, with 1 for the most shade intolerant and 5 for the most shade tolerant); VP, vegetative reproduction probability

| Species name | Abbreviation | LONG | MTR | ST | FT | ED | MD | VP | MVP |
|---|---|---|---|---|---|---|---|---|---|
| *Larix gmelini* | LAGM | 300 | 20 | 3 | 4 | 100 | 300 | 0 | 0 |
| *Pinus sylvestris* var. *mongoloca* | PISY | 210 | 40 | 1 | 2 | 50 | 200 | 0 | 0 |
| *Picea koreansis* | PIKO | 300 | 30 | 4 | 2 | 50 | 150 | 0 | 0 |
| *Betula platyphylla* | BEPL | 150 | 15 | 1 | 3 | 200 | 2000 | 0.8 | 40 |
| *Populus davidiana* | PODA | 180 | 30 | 1 | 3 | −1 | −1 | 1 | 40 |
| *Populus suaveolens* | POSU | 150 | 25 | 1 | 4 | −1 | −1 | 1 | 40 |
| *Chosenia arbutifolia* | CHAR | 250 | 30 | 2 | 2 | −1 | −1 | 0.9 | 30 |
| *Pinus pumila* | PIPU | 250 | 30 | 3 | 1 | 50 | 100 | 0 | 0 |

Fire probability follows a negative exponential distribution based on the mean fire return interval (MRI), which can be formulated as follows:

$$P = b \times lf \times \mathrm{MRI}^{-(e+2)},$$

where $P$ is the fire probability of a cell, MRI is the mean fire return interval of a given ecoregion or land type on which the cell resides, $b$ is the fire probability coefficient designed for model calibration, and $lf$ is the number of years since the last fire within that cell. $P$ varies among different land types with MRI and can be further altered by the $lf$ recorded for each cell. For example, if a fire occurs in a given cell in a given time step, $lf$ of the cell is reset to 0 and $P$ for that cell is calculated as 0 during that time step. This eliminates the probability of cells being burned twice in the same time step regardless of how short the MRI for that cell is (He and Mladenoff 1999*a*; He *et al.* 2003).

Fire severity is directly related to fuel accumulation and decomposition, which is categorised within five severity classes (ranked 1 to 5, with 1 for the least severe and 5 for the most severe) according to the amount of time since the last fire. Fuel accumulation varies with site characteristics, and fuel accumulation and decomposition curves are mediated by land types in LANDIS. For example, fuel may need 20 years of accumulation to reach a level that causes severity class 1 fire, 40 years to class 3, and 80 years to class 4 fire. The combination of fire severity class and species fire tolerance determines which species age classes are killed at each cell (He and Mladenoff 1999*a*; He *et al.* 2003).

At each 10-year time interval, LANDIS yields age cohort maps and species maps for each species, as well as a fire history map showing burned areas and fire severity classes. Only the oldest cohorts are included for each cell in the age cohort map for each species.

### *LANDIS parameterisation*

The required parameters for a successful simulation include the vital attributes for each species simulated in the study, land types in which each species has a uniform response in terms of establishment probability, disturbance regimes (MFS, MRI), and a forest composition map that contains information on species and their age cohorts at each cell. The available materials for parameterisation include a forest stand map and a stand attribute database compiled from the forest inventory taken in 1990 in the Huzhong area, two Landsat TM scenes taken in 1990, the fire records from 1990 to 2000, and a digital elevation model (DEM) generated from the contour lines delineated by the general staff of the Chinese army from aerial photographs taken in 1971. The forest stand map records boundaries of stands and compartments. The stand attribute database provides the relative percentage occurrence of each canopy species, the average age of dominant canopy species, timber volume, and crown density, among other factors.

In LANDIS, forest succession and dispersal are driven by species' vital attributes. In the current study, we simulated eight of the most common species and compiled the vital attributes for each of them (Table 1) based on field work and existing studies in the region (Zhou *et al.* 1991; He *et al.* 2002).

We used the 1990 stand map to generate the forest composition map. Each compartment in the stand map contains a dominant tree species with its age cohort. It also contains subdominant and accompanying tree species with no age information available. We assigned these species with the area-weighted average age of the dominant species in their corresponding stand. In addition, age information for the species *Pinus pumila* was not available in the forest inventory. In the present study, we assigned *P. pumila* an age of 100 years based on tree ring investigations conducted by us in July 2001 and July 2002. For each stand, information on canopy species and their average ages was available. By aggregating the combination of species and their age cohorts in each stand of the map, we derived a forest composition map that contained individual species and age class distributions for the study area. To reduce the LANDIS simulation time, the forest composition map was resampled at 180 × 180 m resolution, yielding 740 rows × 637 columns.

In LANDIS, the heterogeneous landscape was divided into relatively homogeneous units called land types. It is assumed that, for a given land type, similar environmental and disturbance regimes will be found (Mladenoff and He 1999). In the present study, six land types were derived based primarily on terrain attributes; these land types include South-facing Slope, North-facing Slope, Ridge Top, Terrace, Residential Land and Water Body. All land types were interpreted from the 2001 Enhanced Thematic Mapper imagery and DEM. Non-active land types (not simulated in LANDIS), including Water Body and

**Table 2. Attributes and species establishment coefficients for each land type in the Huzhong area**

The last eight columns are species establishment coefficients for each species on various land types. These coefficients were empirically derived from available literature (Li *et al.* 1987; Zhao *et al.* 1997; Xu 1998; Liu *et al.* 1999). (Refer to Table 1 for details of species name abbreviations.) The residential land and water body were not used for effective area during our simulations and the parameters were set to 0. FI, fire ignition coefficient; FP, fire probability coefficient; MAS, minimum age of cohort growth in years required before sufficient shade is created; MRI, mean fire return interval in years; TLF, time in years since last fire

| Land type | Attributes | | | | | Species establishment coefficients | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAS | MRI | FI | FP | TLF | LAGM | PISY | PIKO | PIPU | BEPL | PODA | POSU | CHAR |
| South-facing slope | 50 | 600 | 0.5 | 10 | 300 | 0.4 | 0.2 | 0.03 | 0 | 0.3 | 0.2 | 0 | 0 |
| North-facing slope | 40 | 500 | 0.4 | 10 | 250 | 0.4 | 0.1 | 0.05 | 0 | 0.2 | 0.2 | 0 | 0 |
| Ridge top | 100 | 400 | 0.6 | 10 | 200 | 0.3 | 0.08 | 0 | 0.1 | 0.05 | 0 | 0 | 0 |
| Terrace | 40 | 1500 | 0.3 | 0.4 | 750 | 0.01 | 0 | 0 | 0 | 0.05 | 0.05 | 0.07 | 0.2 |
| Residential land | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Water body | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Residential Land, account for 0.76% of the total area; Terrace, South-facing Slope, North-facing Slope and Ridge Top account for 4.78, 37.25, 42.53, and 14.68% of the total area, respectively. The land type map was also resampled at 180 × 180 m resolution, rendering it consistent with the forest composition map. The attributes for each type are listed in Table 2.

The species establishment coefficient refers to the probability for a given species to establish itself within a given land type. The most sensitive range of the coefficient is between 0.05 and 0.3 (Mladenoff and He 1999). The establishment coefficients for all species are listed in Table 2. These were determined based on the relative suitability of each species to establish itself within each land type, which was empirically derived from available literature (Li *et al.* 1987; Zhao *et al.* 1997; Xu 1998; Liu *et al.* 1999).

Windthrow occurs rarely in the study area, and forest harvesting ceased in 1999; only fire disturbance was simulated in the present study. While under natural conditions, the MRI for these land types are roughly between 120 and 150 years (Xu 1998), but owing to effective fire exclusion the MRI have been substantially altered. Consequently, we derived these at 600 years for South-facing Slope land type, 500 years for North-facing Slope land type, and 400 years for Ridge Top land type. These derivations were based on the fire locations in a fire database that included coverage from 1990 to 2000. The MRI for each land type was derived by the following procedures. First, we overlaid the fire location map from 1990 to 2000 on the land type map to determine fire locations in each land type. We then calculated burned area for each land type and finally calculated the MRI for each land type based on the burned area and the total area of that land type. We set the mean fire size to 203.7 ha, which was compiled from the 1990 to 2000 coverage within the fire database, and the maximum fire size was set to the size of our study area for two simulation scenarios.

### Simulation scenarios, result verification, and data analysis

We designed two simulation scenarios: No Fire Exclusion (NFE), representing the scenario of forest landscape succession under historic fire conditions, and Fire Exclusion (FE), representing the scenario of the altered fire regime under fire exclusion. We began the simulation with realistically parameterised forest composition and land types that represent the initial status of the landscape during the 1990s. From this starting point, the entire study area was simulated for 300 years. Each scenario was replicated five times, with different random seed numbers. To test whether LANDIS realistically simulated the fire regimes under both the FE and NFE scenarios, we used SPSS (version 13.0; SPSS, Chicago, IL, USA) to evaluate the simulated results, including MRI, MFS, and fire frequency per decade or times burnt per decade (TBD). Specifically, we examined whether a significant difference exists between the derived and the simulated fire parameters under the FE and NFE scenarios. For MRI, a Wilcoxon signed ranks test was used; for MFS and TBD, a one-sample *t*-test was used. To test whether fire exclusion may result in catastrophic fires, we defined catastrophic fires as individual fire events with burned areas exceeding 3500 ha and with fire severity classes of 4 or greater based on the fire statistics in this region. In order to quantify the spatial pattern of dominant tree species cover types, we measured average area per patch (AA) using the landscape statistical software APACK (Mladenoff and Dezonia 1997). Higher AA values indicate larger patch sizes and, indirectly, higher degrees of aggregation. We examined the composition, age structure, and spatial distribution of the four species selected. To improve the clarity of figures and tables and to aid interpretation of the results, age class data were summarised into the following forest age classes: sapling (0–40 years), mid-age (41–80 years), near-mature (81–100 years), mature (101–140 years), and old-growth (>140 years) for conifers, and sapling (0–30 years), mid-age (31–50 years), near-mature (51–60 years), mature (61–80 years), and old-growth (>80 years) for broadleaf trees (Xu 1998; Shifley *et al.* 2000). Forest succession was divided into three stages: early stage (sapling, mid-age), middle stage (near-mature, mature), and late stage (old-growth) (Hu *et al.* 2004). Results from the simulations were summarised as percentage cover of the study area.

## Results

### Verification of the simulated fire regimes

The results showed that there was no significant difference (95%) between the MRI derived from the fire records and the MRI simulated on various land types in both the FE ($P = 0.715$) and

**Table 3. Statistical test for mean fire return intervals (MRI) to evaluate whether there is significant difference between inferred and simulated MRI for the fire exclusion (FE) and no fire exclusion (NFE) scenarios at 95% confidence**

| Land type | MRI under the FE Scenario | | MRI under the NFE scenario | |
|---|---|---|---|---|
| | Inferred | Simulated | Inferred | Simulated |
| Terrace | 1500 | 1206 | 500 | 427 |
| South slope | 600$^{A}$ | 605 | 160$^{B}$ | 164 |
| North slope | 500$^{A}$ | 515 | 150$^{B}$ | 156 |
| Ridge top | 400$^{A}$ | 410 | 140$^{B}$ | 164 |
| Wilcoxon signed ranks test | $P = 0.715$ | | $P = 0.715$ | |

$^{A}$Values were calculated based on real fire records, with locations and burned area, from 1990 to 2000.
$^{B}$Values were derived based on published data (Xu 1998).

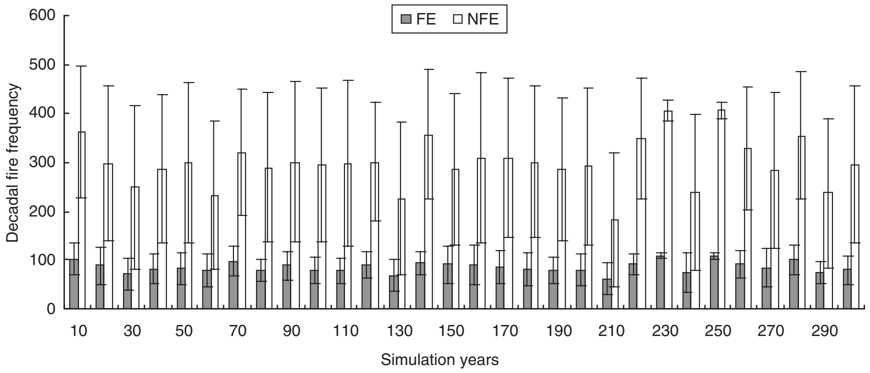

**Fig. 2.** Fire frequency over the 300 simulation years under fire exclusion (FE) and no fire exclusion (NFE) scenarios. Bars represent the mean value from five replicate simulations. Variation of fire frequency is the standard deviation from five replicate simulations.

NFE ($P = 0.715$) scenarios (Table 3). There was no significant difference (95%) between the MFS derived from fire records and the MFS simulated in both the FE ($P = 0.357$) and NFE ($P = 0.325$) scenarios. There was also no significant difference (95%) between the TBD derived from the fire records and the TBD simulated ($P = 0.570$) in the FE scenario. Therefore, the model correctly simulated key fire characteristics (e.g. MFS, fire frequency, MRI) of the two fire regimes. This ensured the validity of subsequent analysis involving fire and the interaction between fire and vegetation.

### *Fire disturbance dynamics*

We summarised fire frequency, burned area, and MFS for each decade over the 300-year simulation. Fires were less frequent under the FE scenario than under the NFE scenario. TBD was less than 100 under the FE scenario, but it was more than 200 under the NFE scenario (Fig. 2). The area burned per decade under the NFE scenario (Fig. 3*b*) was larger than that under the FE scenario (Fig. 3*a*). Under the FE scenario, the burned area per decade accounted for 2% of the landscape (Fig. 3*a*); under the NFE scenario, it accounted for 5–9% of the landscape (Fig. 3*b*). The MFS was higher under the FE scenario (Fig. 3*a*) than that under the NFE scenario (Fig. 3*b*). The MFS was between 4 and 5 under the FE scenario (Fig. 3*a*) and between 2 and 3 under the NFE scenario (Fig. 3*b*).

Fire exclusion does indeed result in catastrophic fires in this region. We identified the largest fire size simulated for every decade from each of the five replicate simulations. The results showed that four catastrophic fires on average occured in the FE scenario during the 300-year simulation (Fig. 4*a*). The sizes ranged from 3500 to 5000 ha. In addition, these catastrophic fires had a return interval of 50–120 years (Fig. 4*a*).

### *Species distribution and abundance*

The simulated age mosaic of larch was different for the two scenarios; the NFE scenario had the largest burned patches and consequently had more young age cohorts than the FE scenario (Fig. 5). More young age cohorts of birch were scattered in the landscape under the NFE scenario than under the FE scenario owing to fire disturbance (Fig. 5), and more old age cohorts of pine and spruce existed under the FE scenario than under the NFE scenario (Fig. 5) owing to fire exclusion.

The abundance of larch remained relatively stable, covering 70–80% in each of the two scenarios, with a slight increase in the FE scenario (Fig. 6*a*). Pine occurred on ~1.8% of the landscape at the beginning of the simulation. The abundance of pine increased steadily in the two scenarios. However, the largest increase occurred in the FE scenario (up to 7%) (Fig. 6*b*). Spruce accounted for 0.4% of the landscape at the starting year of the simulation. The abundance of spruce over the 300-year simulation showed a linear increase in each of the two scenarios. However, the largest increase occurred in the FE scenario (up to 11.5%) (Fig. 6*c*). The continuous increase of pine and spruce forest was due to the cessation of harvesting of these

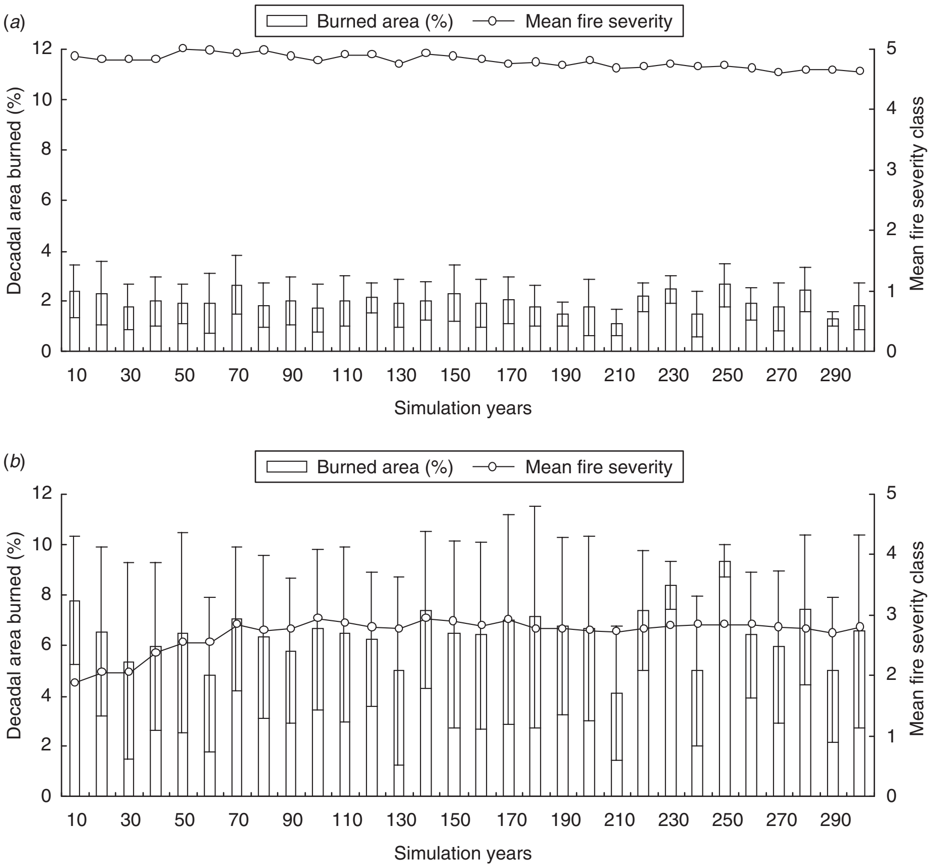

**Fig. 3.** Percentage of burned area and mean fire severity class under (*a*) fire exclusion, and (*b*) no fire exclusion scenarios. Bars represent percentage of burned area that is the mean value from five replicate simulations. Variation of the burned area is the standard deviation from five replicate simulations. Lines represent the mean fire severity class, which is also the mean value from five replicate simulations.

trees since 1999 and their natural regeneration. The abundance of birch across the 300-year simulation increased periodically owing to the effects of fire disturbance, with a higher proportion occurring in the NFE scenario (Fig. 6*d*).

### Species age structure

Our simulated results showed that a larger proportion of old-growth forests and a smaller proportion of sapling and mid-aged forests were observed under the FE scenario than under the NFE scenario (Fig. 7). In addition, the age structures of pine forests at year 300 under the NFE scenario (Fig. 7*d*) were similar to those at year 200 under the FE scenario (Fig. 7*c*), indicating that FE advanced the succession of pine forests for ∼100 years. The age structures of spruce forests at year 300 under the NFE scenario (Fig. 7*f*) were similar to those at year 190 under the FE scenario (Fig. 7*e*), indicating that FE advanced the succession of spruce forests for ∼110 years. The age structures of birch forests at year 300 under the NFE scenario (Fig. 7*h*) were similar to those at year 220 under the FE scenario (Fig. 7*g*), indicating that FE advanced the succession of birch forests for ∼80 years. The rapid change in age class distributions in the first 50 years of simulation was likely caused by the initialisation of the forest composition map and the species age cohorts information.

### Spatial pattern of the dominant tree species

The AA values were different among simulation scenarios (Fig. 8). The trajectory for larch suggested that larch had larger patch sizes under the FE scenario than under the NFE scenario, except during six decades at the beginning of the simulation (Fig. 8*a*). The patch size of pine forests remained stable – less than 10 ha in both scenarios – with a slight increase in the FE scenario (Fig. 8*b*). The spruce forests tended to aggregate in both scenarios. The patches of spruce forests increased in both scenarios, with a great increase (up to 65 ha) in the FE scenario (Fig. 8*c*). Birch had larger patch sizes under the NFE scenario than under the FE scenario (Fig. 8*d*). These trends were similar to their successional trajectories (Fig. 6*d*).

## Discussion

Our results show that over a short time period (a few decades), fire exclusion may be effective in controlling catastrophic fires; however, over a long time span, fires of greater severities are more likely to occur under fire exclusion. This finding is comparable with those reported for other ecosystems (Knight and Wallace 1989; Bury 2004; Shang *et al.* 2004). In the Great Xing'an Mountain area, current forest management uses fire

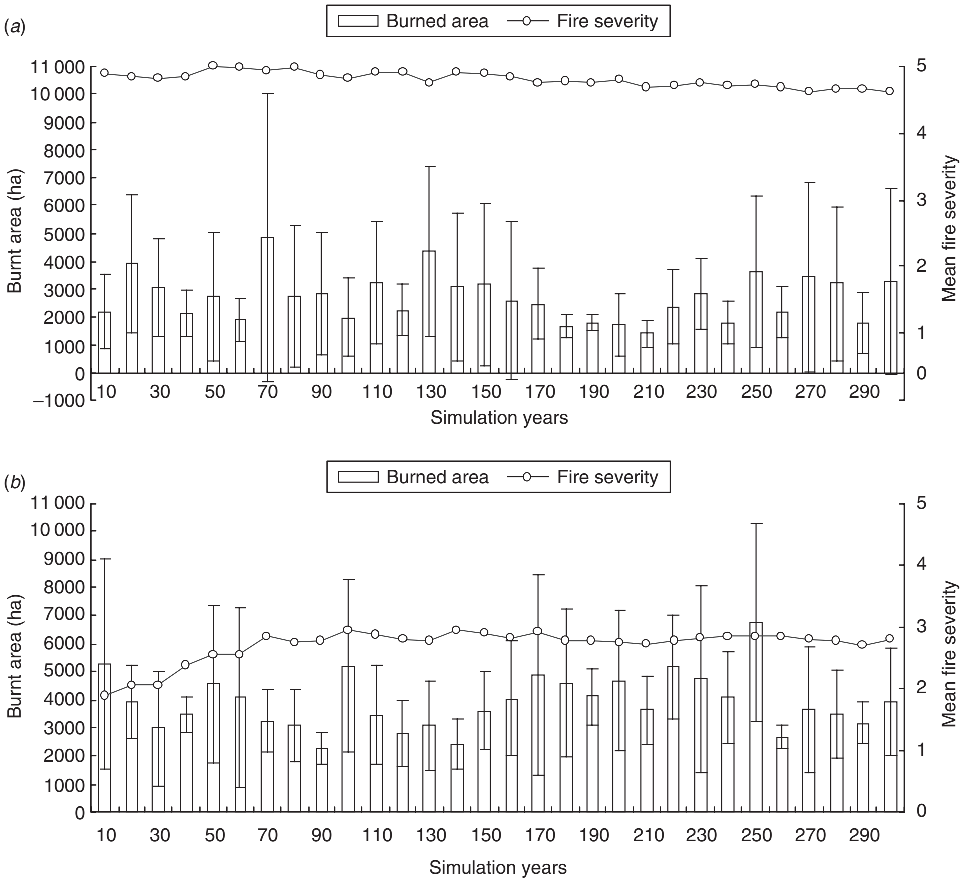

**Fig. 4.** Largest fire size and mean fire severity for every decade under (*a*) fire exclusion, and (*b*) no fire exclusion scenarios. Bars represent the mean value from five replicate simulations. Variation of burnt area is the standard deviation from five replicate simulations. Lines represent the mean fire severity class from five replicate simulations.

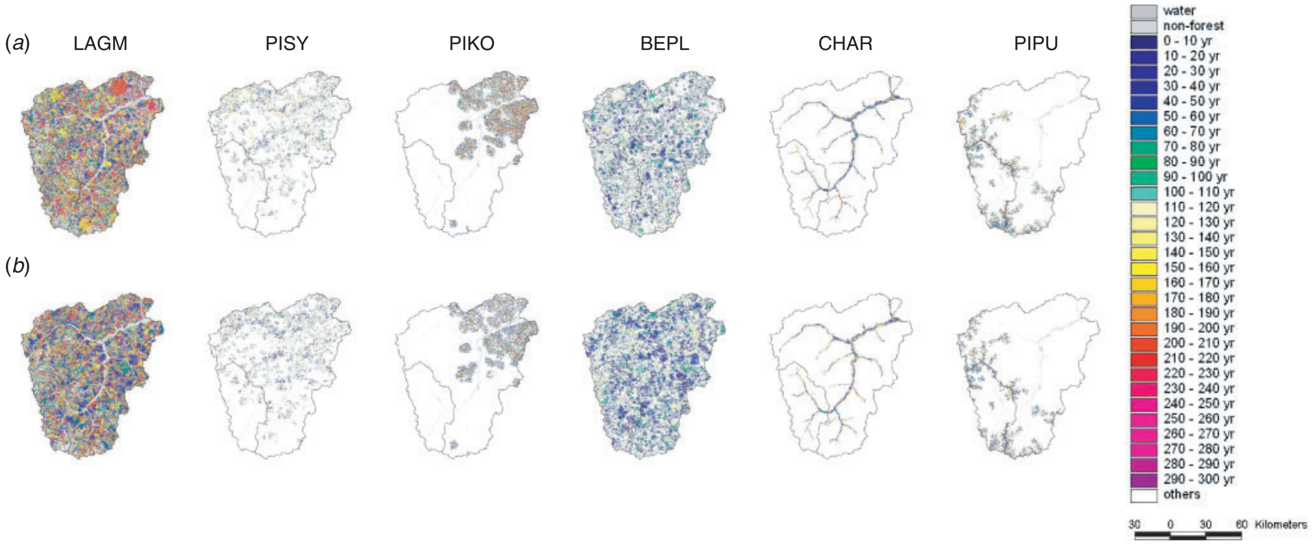

**Fig. 5.** Snapshots of simulated distributions and age classes of six major tree species at year 300 for the two simulation scenarios: (*a*) fire exclusion, and (*b*) no fire exclusion. LAGM stands for *Larix gmelini*, PISY for *Pinus sylvestris* var. *mongoloca*, PIKO for *Picea koreansis*, BEPL for *Betula platyphylla*, CHAR for *Chosenia arbutifolia* and PIPU for *Pinus pumila.*

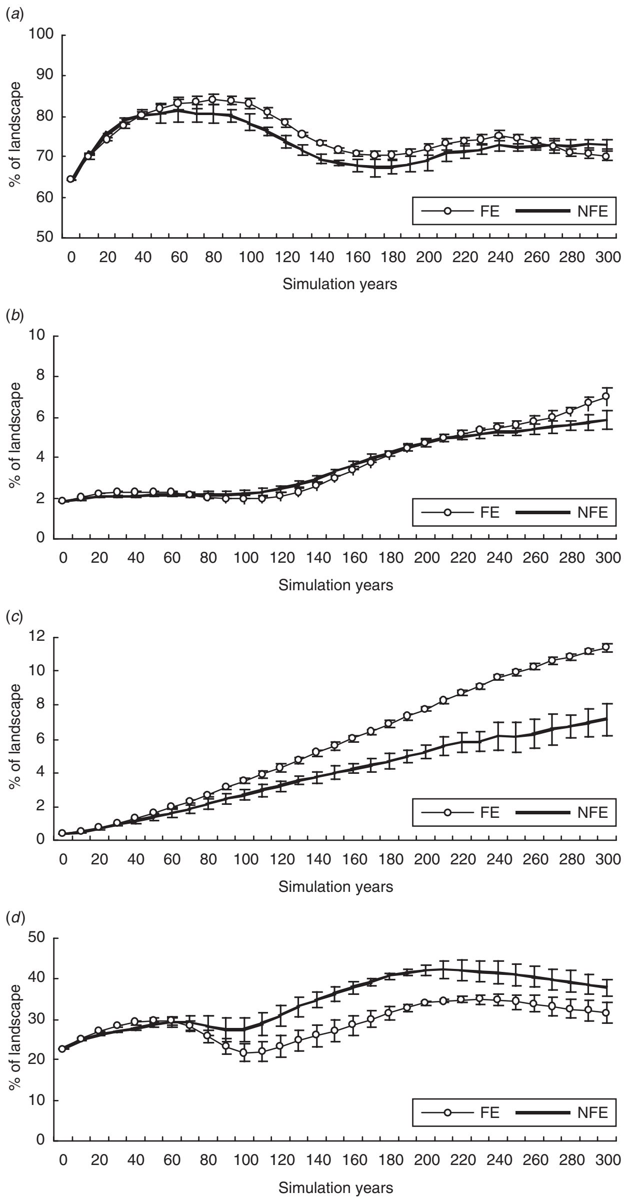

**Fig. 6.** Simulated major tree species abundance in percentage cover of the study area over 300 years under fire exclusion (FE) and no fire exclusion (NFE) scenarios. Lines represent the mean value from five replicate simulations. Variation of tree species abundance is the standard deviation from five replicate simulations. (*a*) Larch, (*b*) pine, (*c*) spruce and (*d*) birch.

exclusion as a means to reduce or even eliminate catastrophic fires. Our results present challenges to the current fire management paradigm in this region. Scientists and forest managers in other regions have increasingly begun to embrace the idea of emulating natural disturbance processes (Lesieur *et al*. 2002; Seymour *et al*. 2002; Nitschke 2005) and reintroducing fires to ecosystem management (Scheller *et al*. 2005). The local forest managers for the Great Xing'an Mountain area have not fully realised the negative consequences of fire exclusion. Key fire management issues should involve how to prevent catastrophic fires through reducing the level of fuels accumulated owing to decades of fire exclusion. Prescribed burning or coarse woody debris reduction should be incorporated into forest management plans in this region. Based on the return intervals of catastrophic fires found in the present study, the fuel treatment interval should be 50 to 120 years in this region.

Our study likely underestimates the occurrence of catastrophic fires under fire exclusion. This is because we did not include extreme weather conditions and climatic change in the simulations. Studies have shown that catastrophic fires correlate strongly to extreme weather conditions (Ryan 2002; Pinol *et al.* 2005). With climate warming predicted for northern China over the next 100 years (Yan *et al*. 2000), warmer and dryer climate may create more extreme weather conditions that can increase the probability of catastrophic fire occurrence (Gao *et al.* 2003; Shu *et al*. 2003).

Our results show that fire exclusion increases the proportion of coniferous forests and decreases the proportion of deciduous forests compared with the natural fire scenario (Fig. 6). The direct effect of such a change is the increase of canopy fuels, which are common fuel sources of forest wildfire in this region. Increases in canopy fuels can lead to greater frequencies of high severity fires, as reported in other forest ecosystems (Hessburg *et al*. 1999; Fleming *et al*. 2002; Sturtevant *et al*. 2004). Our results also show the simplification of tree species composition and the increasing homogeneity of age structure under fire exclusion. This may suggest that the potential outbreaks of forest insects and diseases (Huang 1999; Sturtevant *et al*. 2004) are more likely to occur under fire exclusion than under the natural fire regimes. Changes of species composition and homogeneity of age structure require additional management activities, such as uneven age management (cutting) to reduce the proportion of coniferous species and increase the proportion of deciduous species. These management activities can help to reduce canopy fuels as well as mediate forest age structures to levels that are resistant to insects and disease and comparable with their historical ranges.

Fire exclusion significantly alters forest age structures, increasing proportions of old-growth forests and decreasing proportions of sapling forests (Fig. 7). In addition, fire exclusion increases the patch sizes of coniferous forest (including larch, pine, and spruce) and decreases the patch size of birch (Fig. 8). These changes have multiple implications for wildlife species. High proportions of old-growth forests in large patches may reduce habitat fragmentation and edge effects (Woodroffe and Ginsberg 1998; Desrochers *et al*. 2003) and increase the core area of suitable habitats. This is beneficial to some wildlife species, such as sables (*Martes zibellina*), one of the first-class protected animals in China (Zhang and Ma 2000*a*; Xie *et al.* 2006), because old-growth forests may better protect sables from being attacked by predators (Zhang and Ma 2000*b*). However, diminishing sapling forests occurring in small patches may have negative effects on other wildlife species in this region, such as moose (*Alces alces*), red deer (*Cervus elaphus*), and roe deer (*Capreolus capreolus*), which prefer early successional forest ecosystems (Zhang 2001). Therefore, a more comprehensive wildlife habitat suitability analysis is needed (Larson *et al.* 2004). The simulation results derived in the present study provide the basis for such an analysis.

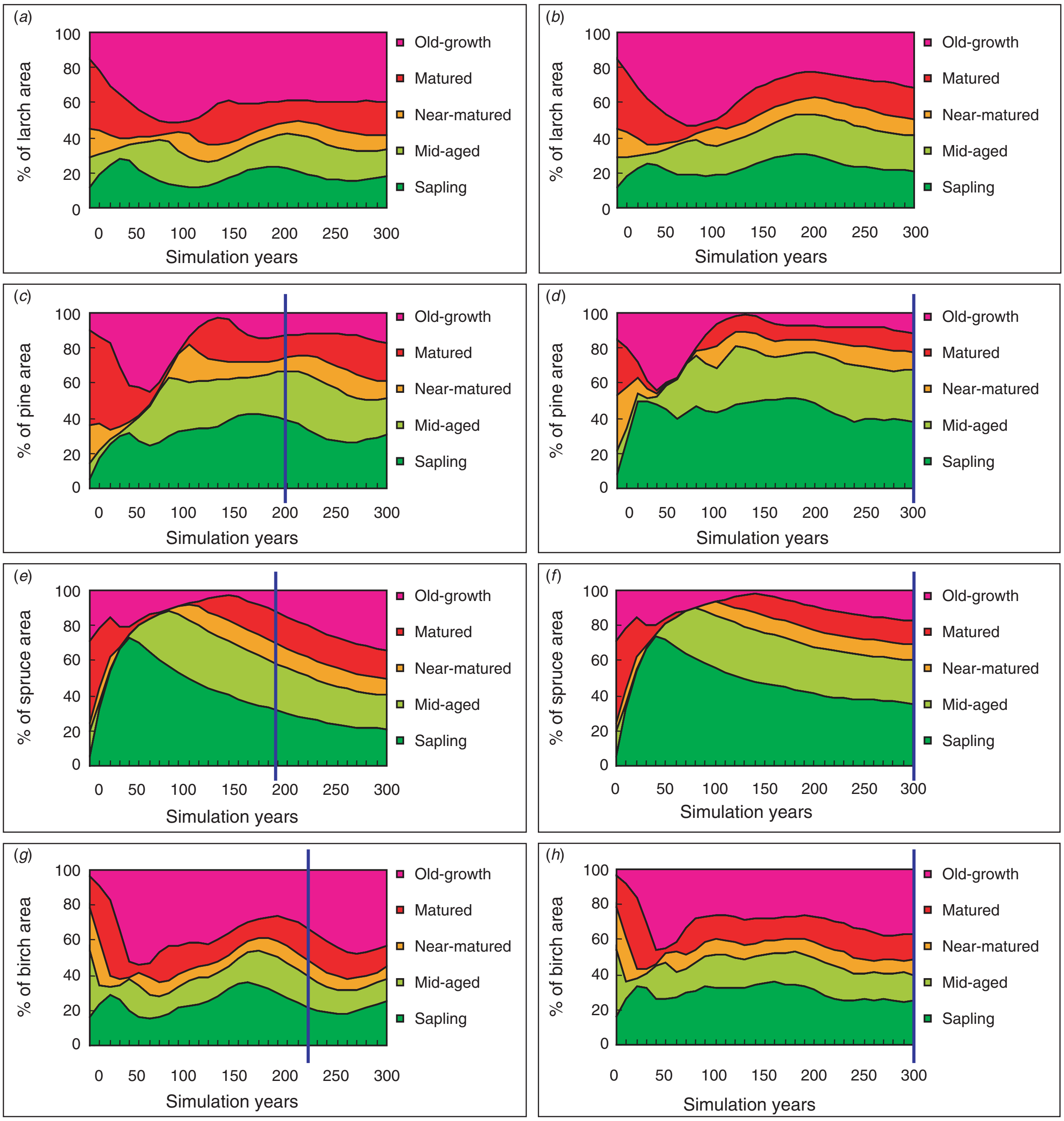

**Fig. 7.** Changes in proportion of the age classes of the major tree species over 300 simulation years under the two simulation scenarios: fire exclusion and no fire exclusion. The division of age classes is as follows: sapling (0–40 years), mid-aged (41–80 years), near-matured (81–100 years), matured (101–140 years), and old-growth (>140 years) for conifers, and sapling (0–30 years), mid-aged (31–50 years), near-matured (51–60 years), matured (61–80 years), and old-growth (>80 years) for broadleaf trees.

## Conclusion

Landscape models are efficient tools for exploring the long-term effects of fire exclusion on fire regimes and forest landscapes. Fire exclusion has significant influences on both fire regimes and forest landscapes in the study area. First, fire exclusion could alter the historical fire regimes with decreased fire frequency and increased fire severity, leading to catastrophic fires with return intervals ranging from 50 to 120 years. Prescribed burning or coarse woody debris reduction should be incorporated into forest management plans in this region. Second, fire exclusion increases the proportion of coniferous forests and decreases the proportion of deciduous forests, which may increase the risk of high severity fires and simplify tree species composition, potentially leading to outbreaks of forest insects and diseases. Additional management activities, such as uneven age management, can help to reduce canopy fuels as well as mediate forest age structures to levels that are resistant to insects and disease and comparable with their historical ranges. Third, fire exclusion

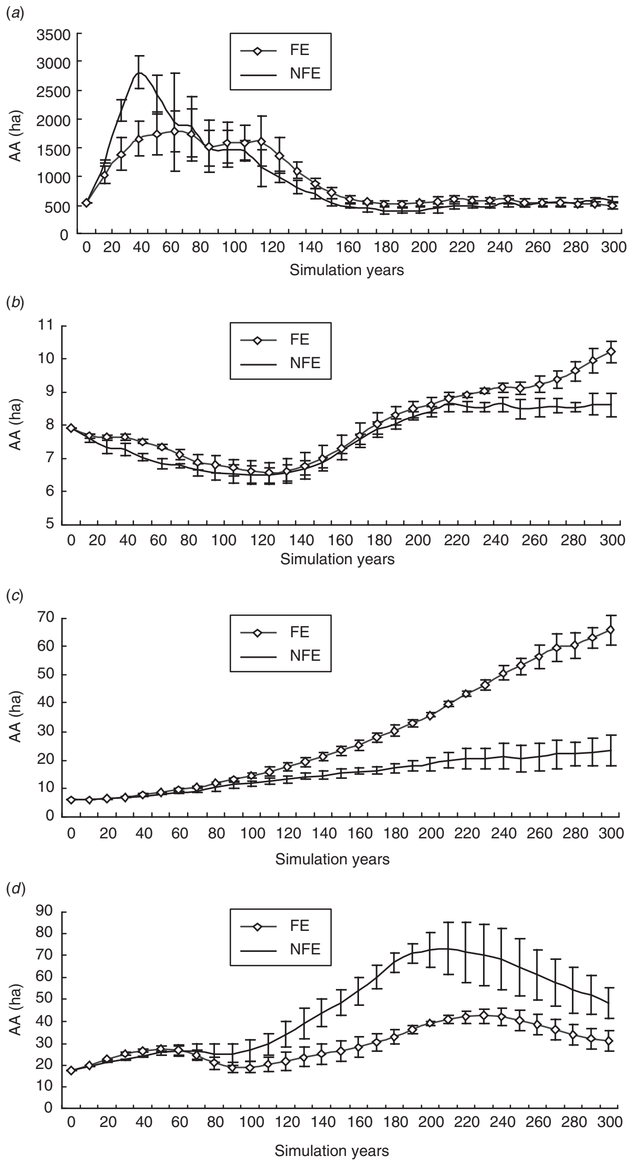

**Fig. 8.** Average area per patch (AA) for dominant tree species under the fire exclusion (FE) and no fire exclusion (NFE) scenarios. Lines represent the mean value from five replicate simulations. Variation of patch size is the standard deviation from five replicate simulations. (*a*) Larch, (*b*) pine, (*c*) spruce and (*d*) birch.

significantly alters forest age structures, increases the proportion of old-growth forests, decreases the proportion of sapling forests, increases the patch sizes of coniferous forest (including larch, pine and spruce), and decreases the patch size of birch. These changes have multiple implications for wildlife species, and a more comprehensive wildlife habitat suitability analysis is needed when designing forest management plans.

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