Historic and current fire regimes in the Great Xing’an Mountains, northeastern China: Implications for long-term forest management

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Abstract

Understanding both historic and current fire regimes is indispensable to sustainable forest landscape management. In this paper, we use a spatially explicit landscape simulation model, LANDIS, to simulate historic and current fire regimes in the Great Xing’an Mountains, in northeastern China. We analyzed fire frequency, fire size, fire intensity, and spatial pattern of burnt patches. Our simulated results show that fire frequency under the current fire scenario is lower than under the historic fire scenario; total area burnt is larger with lower fire intensity under the historic fire scenario, and smaller with higher fire intensity under the current fire scenario. We also found most areas were burned by high intensity fires under the current fire scenario, but by low to moderate fires under the historic fire scenario. Burnt patches exhibit a different pattern between the two simulation scenarios. Large patches burnt by high intensity class fires dominate the landscape under the current fire scenario, and under historic fire scenario, patches burnt by low to moderate fire intensity fires have relatively larger size than those burnt by high intensity fires. Based on these simulated results, we suggest that prescribed burning or coarse woody debris reduction should be incorporated into forest management plans in this region, especially on north-facing slopes. Tree planting may be a better management option on these severely burned areas whereas prescribed burning after small area selective cutting, retaining dispersed seed trees, may be a sound forest management alternative in areas except for the severely burned patches.

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1. Introduction

Over the last decade, scientists and forest managers have begun to explore emulating natural fire disturbance in managing forest landscape (Cissel et al., 1999; Seymour et al., 2002; Cleland et al., 2004; Nitschke, 2005) because natural fire is a key process in regulating vegetation succession, plant regeneration, and maintaining biodiversity in many forest ecosystems (Gardner et al., 1999; Rollins et al., 2004). Understanding the spatial and temporal variation of natural fire provides a long-term perspective of dynamics of ecosystem processes and vegetation patterns (González, 2005; Nonaka and Spies, 2005). However, many factors, including land use changes, population increases, climate change and fire suppression have affected natural fire regimes. For example, fire suppression lengthens the fire cycle (Shang et al., 2004; Chang et al., 2007), increases fuel load of forest ecosystems (Bury, 2004), and increases fire intensity (Chang et al., 2007). The alterations to natural fire regimes have led to major changes in vegetation succession and forest landscape structure in many forest ecosystems (Baker, 1992; Ryan, 2002; Franklin et al., 2005). Therefore, implementation of a management policy of emulating natural fire requires a good understanding of both natural and human influenced fire regimes (Morgan et al., 2001; Li et al., 2005). Natural fire regimes provide baseline information relevant to forest restoration and management, such as timber harvest prescriptions approximating the frequency, intensity, and sizes of past fires (Cissel et al., 1999; Thompson et al., 2006), and current fire regimes may be used to evaluate departures from historic fire regimes (Hardy et al., 2001).

In the Great Xing’an Mountains of northeastern China, fire suppression is an important influence on fire regime. Fire suppression in this region has been carried out for over a half century. The Chinese government has invested greatly in both funding and manpower, including the army, forestry policemen,
and local residents for fire control. These investments aimed for fire exclusion. From 15 March to 15 June and from 15 August to 15 November of each year, fire monitoring and prevention is actively conducted. When a fire is observed, the local government is notified immediately and they assign the manpower to fight the fire. After 50 years of fire suppression and technological advances, the mean fire return interval has been significantly altered (Xu, 1998) from 120–150 years in the 1950s (Xu, 1998) to about 500 years at present. Therefore, the Great Xiang'an Mountains provided a rare opportunity that addressed impact of human disturbance on natural fire regimes. Several studies have shown that the current forest management policy is inadequate for preventing catastrophic fires from occurring (Wang et al., 2006, 2007; Chang et al., 2007). On 6 May 1987, a catastrophic fire occurred in the northern slopes of Great Xiang'an Mountains, burning a total area of $1.3 \times 10^6$ ha, with disastrous effects on forest composition and structure, ecosystem processes and landscape pattern (Xiao et al., 1988; Shu et al., 1996; Wang et al., 2007). This catastrophic fire was caused by the flammable debris built-up due to fire suppression, coupled with the warmer, drier climate due to global warming (Xu, 1998), which had resulted in fires of greater intensity than those that occurred historically in the region. Vegetation recovery in such a large, severely burned area is very slow, increasing the risk of soil erosion and other environmental degradation (Wang et al., 2006). Local forest managers have realized the deficiency of previous fire exclusion policies and urgently need information on key fire occurrence characteristics both historically and currently, including fire frequency, fire size, fire intensity and fire pattern. However, until the change of fire regimes and their negative ecological consequences is fully understood, fire suppression continues to be used as the forest management policy. Few studies have examined long-term changes of the characteristics of fire regime in this region.

Many techniques and approaches have been used to study fire regimes (Morgan et al., 2001; Keane et al., 2003). Historic fire regimes are often studied using dendrochronological techniques to date fire scars (Batek et al., 1999; Heyerdahl et al., 2001; González, 2005; Guyette et al., 2006) and infer fire return interval, fire size and frequency. Current fire regime is often studied by using remote sensing techniques (Mollicone et al., 2002) based on vegetation succession stages and spatial patterns of burnt areas to infer fire return intervals and to map fire intensity (White et al., 1996; Melder and Yool, 1997; Rollins et al., 2004). However, these research approaches were limited in spatial extents and time scale. They are not appropriate for exploring dynamics of fire regimes through long time spans and large spatial domains. Simulation modeling methods are often used to examine long-term changes of fire regimes because it has obvious advantages. By using simulation modeling approaches, large-scale fire disturbance experiments in large areas can be repeatedly conducted with relatively low costs (Turner et al., 1994). In addition, various simulation scenarios can be compared in the same modeling environment (Keane et al., 2003). Moreover, future trends of fire regime change can be projected, which are useful for making fire management decisions (Chang et al., 2007). Modeling simulations generally use stand or landscape models and vegetation succession over time to simulate fire events and are considered cost effective and efficient approaches for deriving fire regimes (Keane et al., 2003).

In this paper, we intend to identify the differences between current and historic fire regimes by examining the long-term changes of fire frequency, fire intensity, fire size, and fire patterns of the two fire regimes in the Great Xiang'an Mountains region. Specifically, we intend to investigate whether the current fire exclusion policy can achieve its objectives: fewer catastrophic fires with low fire intensity over long temporal scales (300 years). We will make management recommendations in terms of forest harvesting and fuel treatment based on the differences between the historic and current fire regimes in the region. We will do this by using a spatially explicit forest landscape model (LANDIS) that simulates species-level succession and various fire regimes.

2. Methods

2.1. Study area

Our study area is in northeastern China (52°25′00″N 122°39′30″E to 51°14′40″N 124°21′00″E) with a total area of 937,244 ha (Fig. 1). It has a terrestrial monsoon climate with a long, severe winter. Annual average precipitation is about 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, and with an average of 17.1 °C for July, the hottest month in the year. The vegetation of this area is classified as cool temperate coniferous forests, which are the southern extension of eastern Siberian boreal forests (Zhou, 1991). The forest area accounts for 86.98% of the study area and the canopy species composition is relatively simple. The most dominant tree species is larch (Larix gmelinii), covering 65% of the study area. The second dominant tree species is birch (Betula platyphylla), covering 20–30% of the study area. Other species, including pine (Pinus sylvestris var. mongolica), spruce (Picea Koraiensis), two species of aspen (Populus davidiana, Populus suaveolens), and willow (Chosenia arbutifolia) cover less than 5% of the study area.

2.2. The LANDIS model

LANDIS is a spatially explicit forest landscape disturbance and succession model that facilitates the study of the effects of natural and anthropogenic disturbances, vegetation succession, and management strategies on forest landscapes (Mladenoff et al., 1996; He and Mladenoff, 1999a). Various LANDIS components have been described elsewhere (He and Mladenoff, 1999b; He et al., 2002; Gustafson et al., 2000). It simulates species-level forest dynamics by tracking the presence/absence of species age cohorts at 10-year time steps under natural and anthropogenic disturbances (e.g. fire, windthrow, insects and disease, harvesting, planting, and fuel management) as well as...
the long-term changes of disturbance regime, such as burning characteristics of fire regimes.

Fire disturbance is an important spatial process in landscapes. Fire suppression 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 intensity using mathematically defined distributions.1

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

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

where $S$ is the fire size, MFS the mean fire size, $a$ the fire disturbance size coefficient designed for model calibration, and $r$ is a normalized 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.

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

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

where $P$ is the fire probability of a cell, MRI the mean fire return interval of a given ecoregion, or land type, on which the cell resides, $b$ 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 MRIs 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, 1999a; He et al., 2003).

Fire intensity is directly related to fuel accumulation and decomposition, which is categorized into five intensity classes (ranked 1–5, 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 reaching a level that causes intensity class 1 fire, 40 years to reach class 3, and 80 years to reach class 4. The combination of fire intensity class and species fire tolerance determines which species age classes are killed at each cell (He and Mladenoff, 1999a; He et al., 2003).

LANDIS outputs age cohort maps and species maps for each species, as well as a fire history map showing burned areas and fire intensity classes at each 10-year time interval. It also writes disturbance log files, such as a fire log file, for the whole simulation span.

2.3. LANDIS parameterization

LANDIS (ver. 3.7) involves spatial and non-spatial parameters. The main spatial parameters include a forest composition map that contains information on species and their age cohorts at each cell, a land type map in which each species has a uniform response in terms of establishment probability, disturbance regime (e.g. mean fire size, mean return intervals) for each land type. Non-spatial parameters include the vital attributes for each species simulated and disturbance regimes. The available data for parameterization of LANDIS 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

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

2.3.1. Species’ vital attributes and forest composition map

A total of eight tree species were incorporated into LANDIS. The species’ vital attributes (Table 1) were estimated based on field work and existing studies in the region (Zhou, 1991; He et al., 2002). A forest composition map was generated from the 1990 stand map that delineated boundaries of compartments and stands (a compartment is a unit of forest inventory, generally containing 10–100 stands). Each stand contained a dominant tree species with its age cohort. It also contained sub-dominant 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 compartment. Additionally, age information for the species Pinus pumila was not available in the forest inventory. In this 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 contains individual species/age class distributions for the study area. To reduce the LANDIS simulation time, the forest composition map with 30 m × 30 m resolution was resampled at 180 m × 180 m resolution, yielding 740 rows × 637 columns.

2.3.2. Landtype map

LANDIS stratifies the heterogeneous landscape into relatively homogeneous units called land types. For a given land type, similar environments for species establishment, and disturbance regimes are assumed (Mladenoff and He, 1999). In this study, we derived six land types based primarily on terrain attributes. These land types include south-facing slope, north-facing slope, ridge top, terrace, residential land and water body. They were interpreted from the 1990 TM imagery and DEM. Non-active land types (not simulated in LANDIS), including water body and 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 m × 180 m resolution to be consistent with the forest composition map. The attributes for each land type are listed in Table 2.

The species establishment coefficient is the probability that a species will establish successfully on 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 (Table 2) were derived empirically from available literature as needed.
well as existing LANDIS parameterizations on northeastern China (Li et al., 1987; Zhao et al., 1997; Xu, 1998; Liu et al., 1999; Wang et al., 2006).

2.3.3. Fire regimes

Fire is a crucial disturbance to the forest after ceasing harvesting in 1999 in this region. Windthrow occurs rarely in the study area. Therefore, only fire disturbance was simulated in this study. While under natural conditions, the mean fire return intervals for these land types are estimated between 120 and 150 years (Xu, 1998), but due to effective fire suppression the mean fire return intervals have been substantially altered. They were estimated 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 based on the fire locations in a fire database that included coverage from 1990 to 2000. The mean fire return interval for each land type was derived by the following procedures. First, the fire location map from 1990 to 2000 was overlaid with the land type map to determine fire locations in each land type. Then, the burned area for each land type was calculated, and finally the MRI for each land type was derived on the basis of 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.

2.3.4. Simulation scenarios and data analysis

Two simulation scenarios were designed: (1) historic fire, representing the historic fire regime (frequency, size, and intensity), and (2) current fire, representing the current fire regime. We began the simulation with realistically parameterized forest composition and land types that represent the initial status of the landscape of the 1990s. From this starting point, the entire study area was simulated for 300 years for each scenario. Each scenario was replicated five times, with different random number seeds. To test whether catastrophic fires occur under both scenarios, we defined catastrophic fires as individual fire events with burned areas exceeding 3500 ha and with fire intensity classes of 4 or greater based upon the fire statistics in this region. This definition was based on the Chinese Forest Fire Control Division. To quantify the spatial pattern of burnt patches, we measured average area per patch (AA) using the landscape statistical software APACK (Mladenoff and Dezonia, 1997).

3. Results

3.1. Fire frequency

We iteratively adjusted the fire size coefficient, and fire ignition probability on each land type, and calculated mean fire return interval from the LANDIS output, until the fire return interval approximates 500 years for the current fire scenario and 150 years for the historic fire scenario. This process ensures that mean fire return interval and mean fire size, the two fire input parameters that reflect our working hypothesis of historic and current fire regimes, are correctly simulated by the stochastic LANDIS fire module. After this calibration process, we were able to examine characteristics of simulated fire regimes including fire frequency, intensity, and extreme fire events (large fires).

For the simulated fire frequency, as expected, fires are less frequent under the current fire scenario than under the historic fire scenario. The fire frequency under the historic fire scenario is 300 fires per decade on average and less than 100 fires per decade under the current fire scenario. Fire frequency under the historic fire scenario is more than three times higher than that under the current fire scenario (Fig. 2).

3.2. Total area burned and average fire intensity

Under the current fire scenario, the total burned area per decade accounts for 2% of the landscape (Fig. 3a); under the historic fire scenario, it accounts for 5–9% of the landscape (Fig. 3b). The average fire intensity class is between 4 and 5 under the current fire scenario (Fig. 3a) and between 2 and 3 under the historic fire scenario (Fig. 3b). Thus, the total area burned per decade under the historic fire scenario is larger but average fire intensity is lower than those under the current fire scenario (Fig. 3).
3.3. Burned area on various land types

Under both the current fire and the historic fire scenario, north-facing slopes had larger burned areas than other land types. This is due to greater fuel accumulation in this land type (Fig. 4). For each land type except for terrace land type (Fig. 4) larger burned areas were observed under the historic fire scenario (Fig. 4b) than that under the current fire scenario (Fig. 4a). The area burned in the terrace type was similar under both simulation scenarios because of the large fire return interval on the terrace land type. The area burned on north-facing slope ranged from 1000 to 5000 cells under the current fire scenario (Fig. 4a), and 3000–15,000 cells under the historic fire scenario (Fig. 4b).

3.4. Burned area by fire intensity class

Under the historic fire scenario, over 50% of all fires simulated are low to moderate intensity fires (classes 1 and 2), which burned 2–8% of the study area (Fig. 5b). Under the current fire scenario, more than 90% of all fires simulated are high intensity fires (classes 4 and 5), which burned 1–4% of the study area (Fig. 5a). Generally, historic fire regimes have more low intensity fires and burn larger areas than those under the current fire regime.

3.5. Catastrophic fires

Statistics of the largest area burned by a single fire event for each decade across the 300-year showed that four catastrophic fires on average occur in the current fire scenario during the 300-year simulation. The catastrophic fire sizes range from
3500 to 5000 ha (Fig. 6a). Under the historic fire scenario, although the largest size burned ranges from 2000 to 7000 ha, no catastrophic fires occur due to low fire intensity from 2 to 3 (Fig. 6b).

3.6. Fire patterns

The average burnt patch is larger than 200 ha under the current fire scenario (Fig. 7a), whereas under the historic fire scenario most are smaller than 200 ha (Fig. 7b). Furthermore, under the current fire scenario (Fig. 7a) most patches burned by fire intensity class 5 have an average size of ~200 ha under the current fire scenario (Fig. 7a), whereas average patch size is less than 50 ha under the historic fire scenario (Fig. 7b). Generally, patches burned by fire intensity class 5 have larger average size under the current fire scenario (Fig. 7a). Whereas under the historic fire scenario, patches burned by fire intensity class 1 or 2 are of larger size (Fig. 7b).

4. Discussion

Our results showed that effective fire suppression over the past 50 years likely resulted in differences between the current fire regime and the historic fire regime. The current fire regime has lower fire frequency, higher fire intensity especially in the later simulation years, and greater probability of catastrophic fires than the historic fire regime. These differences are due to the anthropogenic disturbance on natural fire regimes by lengthening fire cycle (Shang et al., 2004; Chang et al., 2007), increasing fuel load of forest ecosystems (Bury, 2004; Chang et al., 2007). These findings show that the long-term results of fire suppression are contradictory to its very objectives and that the current fire suppression policy needs to be adjusted to better address these objectives.

First, a key fire management issue should address catastrophic fire prevention through reduction of fuels that have accumulated through decades of fire exclusion. Fuel load reduction has not yet been adopted in forest management in China, while it is commonly used in many forest ecosystems in North America, Europe, and Australia (Stephenson, 1999; Allen et al., 2002; Knapp et al., 2005). Studies from forest ecosystems of other areas have shown that prescribed burning and coarse woody debris reduction can effectively reduce fuel and fire risk (He et al., 2004; Stephens and Moghaddas, 2005; Knapp et al., 2005). Although fuel treatment intensity (size) and frequency, as well as treatment effects remain a subject of study for many forest ecosystems (Shang et al., 2004; Knapp et al., 2005), fuel load reduction treatments are used worldwide. Because high population density as well as high fuel load accumulation induce high fire risk in this region the transition from the current fire exclusion policy to a fuel load reduction policy is not a simple issue of abandoning fire suppression. Abrupt cessation of fire suppression could have disastrous effects on both forest ecosystems and humans. Reduction of fire suppression should be implemented gradually. Special expertise is usually required for conducting fuel treatment such as prescribed fire. Training and preparing local experts and field crews for fuel treatment is an urgent but challenging issue that forest management is facing in northeastern China.

Second, high priority areas for fuel treatment must be identified. Our results show that most areas on north-facing slopes are burned by high intensity fires under the current fire scenario (Figs. 4 and 5). These north-facing slopes receive less direct solar radiation and have lower temperatures and higher relative humidity than south-facing slopes (Heyerdahl et al., 2001) and thus have a lower decomposition rate of surface fuels. The results suggest that fuel load reduction should strategically be focused on those north-facing slopes.

Third, forest recovery on burned sites should be considered when designing forest management policies. Our results indicated large and severely damaged patches under the current fire scenario. This is partly because high intensity fires are hard to be suppressed even with advanced fire suppression techniques. Other factors, such as weather conditions (Ferguson et al., 2002) and topography (Broncano and Retana, 2004; Lentile et al., 2006), pre-burning vegetation conditions (Turner et al., 1999) may also influence the size of burned patches. Early studies have demonstrated that few residual trees remained in these severely burned patches, which may hinder post-fire forest restoration (e.g. Xiao et al., 1988; Keenton and Franklin, 2005). Less than 20% of the stand basal area and less than 10% of the canopy cover of overstory vegetation remain after stand-replacement fire (Rollins et al., 2004). In addition, shrubs and herbs would soon invade these open spaces and become dense within a few years. The light levels beneath shrubs and grasses may be insufficient for the survivorship of tree seedlings (e.g. Zhou et al., 1989; Yang et al., 1998; Wang et al., 2003). Therefore, it is difficult to restore forests on these patches through natural regeneration. The long recovery processes present a risk of soil erosion and environmental degradation (Wang et al., 2006). Wang et al. (2006) showed that dispersed tree planting with medium planting intensity (e.g. 30%) would achieve better restoration results with acceptable labor input and economic costs. Thus, tree planting, which is a labor intensive and economic-costly activity, may be in greater demand under the current fire suppression scenario to prevent soil erosion and environmental degradation in the burned areas.

Our results also showed smaller (<100 ha) burned patches by non-lethal fires (class 1 or 2) under natural fire conditions. Previous studies have shown that greater than 70% of stand basal area and greater than 90% of the overstory canopy cover remain after non-lethal fires (Rollins et al., 2004). Forest restoration on these patches is not a problem because many seed trees remain, and the combustion of surface fuels is beneficial to seed germination. Large area clear-cutting does not mimic the natural fire pattern nor does it produce the results desirable for forest recovery. Thus, it should be limited as a forest management option in this region (Wang et al., 2006). Prescribed burning and uneven-aged small area selective cutting may be a suitable forest management option. However, harvest rotation and intensity in combination with fuel treatment should be the subject of future studies.
5. Conclusions

The comparison of current and historic fire regimes showed that current fire regimes result in quite different characteristics than historic fires in the Great Xing'an Mountains region. First, current fire regimes can be characterized as having lower fire frequency, higher fire intensity and higher risks of catastrophic fires compared to historic fire regimes with higher fire frequency, and lower fire intensity. Prescribed burning or coarse woody debris reduction should be incorporated into forest management plans in this region, especially on north-facing slopes. Secondly, current fire patterns in this region are dominated by large, severely damaged areas. Tree planting may be a good management option on these severely burned areas. Prescribed burning after small area selective cutting, retaining dispersed seed trees, may be a sound forest management alternative in areas that have not been severely burned.

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