Evaluations on the Consequences of Fire Suppression and the Ecological Effects of Fuel Treatment Scenarios in a Boreal Forest of the Great Xing'an Mountains, China

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Abstract: With global warming, catastrophic forest fires have frequently occurred in recent years, posing a major threat to forest resources and people. How to reduce forest fire risk is a hot topic in forest management. Concerns regarding fire suppression and forest fuel treatments are rising. Few studies have evaluated the ecological effects of fuel treatments. In this study, we used the LANDIS PRO model to simulate the consequences of fire suppression and the ecological effects of fuel treatments in a boreal forest of the Great Xing'an Mountains, China. Four simulation scenarios were designed, focusing on whether to conduct fuel treatments or not under two fire-control policies (current fire suppression policy and no fire suppression policy). Each scenario contains nine fuel treatment plans based on the combinations of different treatment methods (coarse woody debris reduction, prescribed burning, coarse woody debris reduction plus prescribed burning), treatment frequency (low, medium, and high), and treatment area (large, medium, and small). The ecological effects of the fuel treatments were evaluated according to the changes in fire regimes, species succession, and forest landscape patterns to find a forest fuel management plan that is suitable for the Great Xing'an Mountains. The results showed that long-term fire suppression increases fuel loads and the probability of high-intensity forest fires. The nine fuel management plans did not show significant differences in terms of species succession and forest landscape patterns while lowering forest fire intensity, and none of them were able to restore historical vegetation structure and composition. Our results consolidate the foundation for the practical performance of forest fuel treatments in fire-prone forest landscapes. We suggest a suitable fuel treatment plan for the Great Xing'an Mountains, with a low treatment frequency (20 years), large treatment area (10%), and coarse woody debris reduction, plus the prescribed burning measure.

Keywords: forest management; fuel treatments; LANDIS PRO; the Great Xing'an Mountains; ecological effects; fire suppression

1. Introduction

As the major component of terrestrial ecosystems, forests store 86% of the global vegetation carbon pool and play an irreplaceable role in the protection of regional ecological environments, maintaining the carbon balance of forest ecosystems and alleviating climate change [1]. However, forests are often disturbed by fires. Fire is one of the key driving agents of forest renewal and forest succession [2] and plays a critical role in maintaining biodiversity and landscape heterogeneity [3]. Despite its natural functions, fire also poses threats to people's lives, infrastructure, and valuable forest resources [4]. Hence, fire suppression policies have been implemented worldwide over the last century to reduce the negative effects caused by fires [5,6]. China adopted a strict fire suppression policy to reduce the losses caused by forest fires. Fire suppression has reduced the number of fires and changed natural fire patterns, such as extending the mean fire-return interval [7]

and affecting forest succession [8]. This has caused the wildfire problem to become more serious in some areas [9], such as the Great Xing'an Mountains, where long-term fire suppression has led to an excessive accumulation of fuels, higher forest fire intensity, and an increased probability of catastrophic forest fires [10]. Therefore, it is important to assess the consequences of implementing fire suppression policies on species succession and forest landscapes from the perspective of ecological effects.

To reduce the negative impacts of fire suppression, some regions around the world have begun to implement fuel treatment policies, but China started implementing fuel treatment policies later [11–13]. The three factors that primarily drive wildfire behavior are as follows: fuel, topography, and weather. Of these factors, only fuels can be manipulated by land managers [14]. All organic materials in the forest belong to fuels, including the surface layer, herbaceous layer, shrub layer, and tree layer [15]. The main fuel treatment methods generally include coarse woody debris reduction [16], prescribed burning [17], thinning [18], and fuel breaks [19]. Coarse woody debris reduction and prescribed burning aim to reduce the fine and coarse fuel loads [20], while fuel breaks via the removal of fuels decrease the spatial continuity of fuels [21]. Implementing forest fuel treatments can effectively reduce the frequency and intensity of forest fires [21]. For example, Salis simulated fuel treatments in the Mediterranean region and analyzed the changes in fire behavior after treatment and found that the probability of fire occurrence and burnt area significantly decreased with increases in the area of fuel treatment [22].

Forest fuel treatments have two purposes: one is to reduce the occurrence of high-intensity fires, and the other is to restore historical vegetation structure and composition [18]. Most studies only focused on reducing fire intensity and not on the ecological effects of fuel treatments. At the same time, previous evaluations of fuel treatment effects often focused on one or two aspects of fire disturbance, species composition, and forest landscape. For example, Wu evaluated fuel treatment effects in terms of fire disturbance in the Huzhong Forest [23]. Volkova evaluated fuel treatment effects in terms of fuel load and forest carbon in southeastern Australia [16]. Therefore, it is necessary to conduct a comprehensive assessment of the ecological effects of fuel treatments. Evaluating the ecological effects of fuel treatments could help in the formation of appropriate fuel treatment plans. The impacts of fuel treatments are complex, pertaining to fire regime, species succession, forest landscape [13,24–27], and the effective duration of fuel treatments [11,28,29]. Forest succession after fuel treatments may vary depending on the treatment methods, intensity, the climatic environment of the treatment area, etc. [28,30]. The effectiveness of fuel treatments can also be affected by the pre-treatment state of the fuels, the fuel treatment itself, and the productivity of the vegetation [31]. Most current fuel treatment studies have paid attention to reducing high-intensity fires, ignoring the effects of fuel treatments on the forest landscape [22,24,26]. Furthermore, these studies only focus on fuel treatments under the current fire suppression policy, without a comparative study in the context of different fire control policies. A comparison with the ecological effects of fuel treatments in a natural fire scenario can provide a more scientific basis for selecting suitable forest management plans.

Descriptive studies and field experiments are often inadequate for managers to develop and implement forest fuel treatment plans on a large landscape. In addition, forest fuel treatments are restricted in China, except for several places in Yunnan province [32]. Model simulations have become a crucial tool for evaluating fuel treatment effects. Simulation models include fire behavior models, non-spatial models, and spatially explicit models. Fire behavior models, such as BEHAVE [33], cannot simulate the relationship between vegetation and fuel decomposition and accumulation. Non-spatial models, such as FVS-FEE [34], cannot simulate fire occurrence and spread processes. The spatially explicit landscape model, LANDIS [35], can simulate the interaction between fuel treatments and other landscape processes and has been successfully applied worldwide, including in the Great Xing'an Mountains, China [23,36]. Liu et al. [25] parameterized the LANDIS model using a dataset (1990–2000) and simulated the effects of long-term fire suppression on fuel dynamic and fire risks in Huzhong of the Great Xing'an Mountains.

In this study, we used the parameters (1990–2000) of Liu et al. [25] to parameterize LANDIS PRO to simulate forest landscape dynamics and changes under different fuel treatment plans and fire control policies in the Great Xing'an Mountains. These scenarios were designed by combining different fire control policies, fuel treatment methods, fuel treatment frequencies, and fuel treatment areas. The ecological effects of various fuel management scenarios were comprehensively evaluated in terms of the changes in fire regime, species succession, and forest landscape over a simulated 100-year period. Our aim is to illustrate what the ecological consequences would have been if we had adopted fuel treatments 30 years ago and to ultimately select an appropriate fuel treatment plan for the Great Xing'an Mountains, China, to reduce forest fire risks.

2. Materials and Methods

2.1. Study Area

Our study area was the Huzhong Forestry Bureau of northeastern China (51°14′40″ N–52°25′00″ N, 122°39′30″ E−124°21′ E). This area spans 125 km from north to south and 115 km from east to west, with a total area of 937,244 km^2 (Figure 1). The study area belongs to the cool temperate zone and has a continental monsoon climate, with warm, wet, short summers and cold, dry, long winters, influenced by the high-pressure Siberian–Mongolian air mass. The mean annual temperature is 4.7 °C. February is the coldest month, with an average of −28.9 °C; July is the hottest, with an average of 17.1 °C. The average annual precipitation is ~500 mm, with most occurring between June and August. Spring and autumn are the seasons of high fire incidence due to the influence of the Mongolian dry winds, alternating high and low temperatures, and significant windy weather. The vegetation type is cold–temperate coniferous forest, with larch (*Larix gmelini* Rupr. Kuzen) as the dominant species in the area, and other species include pine (*Pinus sylvestris var. mongolica* Litv.) and spruce (*Picea koraiensis* Nakai). The main broad-leaved tree species are birch (*Betula platyphylla* Sukaczev), two species of poplar (*Populus davidiana* Dode, *Populus suaveolens* Fisch. ex Poit. & A.Vilm.), and willow (*Chosenia arbutifolia* (Pall.) A. Skv).
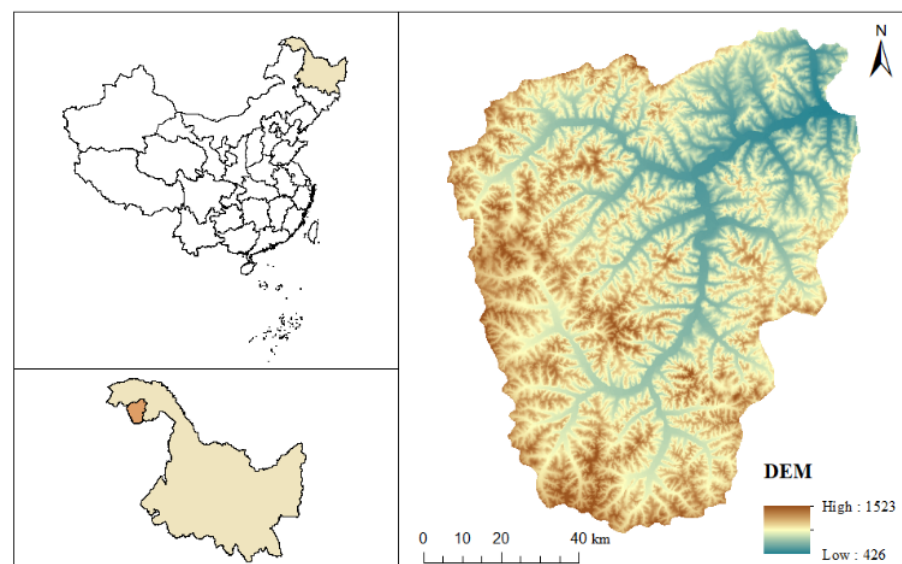
Figure 1. The geographic location of the Huzhong Forest.

Forest fire is an important disturbance factor in the Daxing'an Mountains. On May 6, 1987, a catastrophic fire occurred on the northern slopes of the Great Xing'an Mountains. As a result, the country issued the "Regulation on Forest Fires" in 1988 and started officially preventing forest fires. In recent years, Heilongjiang Province has implemented regular forest fuel load survey work and used prescribed burning to reduce fuel loads on a small scale, including the Huzhong Forestry Bureau. Firefighting agencies in the Great Xing'an

Mountains also carry out fire barrier ignitions in autumn and winter. According to statistics, from 1990 to 2019, there were 72 fires in the area. There were 42 fires with a single burned area greater than 20 ha in the Huzhong Forestry Bureau. The total burned area is 30,846.16 ha, averaging 734.43 ha per fire, and a maximum burned area of 8327.7 ha. Fires in the Huzhong Forestry Bureau are mainly caused by lightning strikes, accounting for more than 60% of all fires. Affected by forest fire disturbance, the primary forest in Daxing'an Mountains gradually degenerates into a secondary forest. White birch is the major species in the pioneer stage. Larch is the dominant species in the top stage. With the progress of succession, the abundance of white birch in each age class gradually decreases, whereas that of larch gradually increases. Forest fire, as the main disturbance factor in the area, significantly affects the relative proportions of white birch and larch.

2.2. The LANDIS PRO Model

We used LANDIS PRO 7.0, a spatially explicit forest landscape model, to simulate forest landscape succession, seed dispersal, spatial disturbance, and fuel treatments [37–39] on large spatial and temporal scales (10^3 to 10^6). This model has been widely used worldwide [36–38]. The LANDIS PRO model is based on a raster data structure, which treats the landscape as a grid of equally sized pixels, with each recording information about the trees. This information is used to simulate changes in forest succession and disturbance. This model also does not track individual trees, which is different from stand simulation models [40].

In the LANDIS PRO model, a heterogeneous landscape is stratified into land types by using GIS layers of climatic, soil, or topographic variables (slope, aspect, and landscape position). Each land type is assumed to have a relatively homogeneous range of ecological conditions corresponding to the same patterns of species establishment and fire disturbance, such as ignition frequency and mean fire return intervals (MRI) [39]. The model assumptions were validated by relevant studies [41,42]. The LANDIS PRO can simulate several spatial processes and many non-spatial processes; the following modules were utilized in this study. The data sources for performing the parameterization are shown in Table 1.

Table 1. Use of datasets in the parameterization process.

Datasets	Obtain Parameters
Two scenes of the 2000 TM remote sensing imagery (WRS: P/R: 120/24 and 121/24)	For determining the land-cover types
The 1990 forest stand maps	For determining the forest composition map, land-cover types of water and non-forested areas.
Topographic maps (1: 50,000)	For determining the land-cover types.
Fire records in the Huzhong Forest from 1990–2000	For determining the fire return interval, burned area, and ignition density.
Relevant literature and field surveys	For determining the species' life history attributes, fire return interval, burned area, and ignition density during the no fire suppression period

2.2.1. Succession Module

Succession is a non-spatial, site-level process. Succession at each site is a competitive process driven by the species' life history attributes [39], including longevity, age of sexual maturity, shade tolerance class, fire tolerance class, effective seeding distance, maximum seeding distance, probability of vegetative propagation, and minimum age of vegetative reproduction. Since the model tracks the presence or absence of species age cohorts, the succession dynamics were simplified and simulated, such as birth, growth, and death processes acting on species age cohorts. Firstly, LANDIS PRO simulates seed dispersal based on species' effective and maximum seeding distance [39]. Secondly, due to competition among or within species, when seeds reach a location, only seedlings of shade-tolerant species can grow if the growing space is already occupied. Once the canopy of the area is completely closed, intra-stand competition, meaning self-thinning, starts. Less

shade-tolerant trees, as well as old, vulnerable trees that are close to longevity, might be outcompeted and die as a result of the self-thinning process. Later, the resulting canopy gaps are filled by the cross-growth of adjacent trees or by new seedlings. In this iterative process, the succession also interacts with other modules. The main input files of this module are the species attribute file, land type attribute map file, species composition map file, and map attribute file [43]. The species attribute file contains all the life history attributes as mentioned above for each species, along with the reclassification coefficient, species group, biomass group, maximum diameter, maximum stand density, number of seeds, and carbon coefficient. The main parameters are listed in Table 2. The LANDIS model requires land type data reflecting differential species establishment coefficients among land types. To achieve this, a synthetic land type or ecoregion was created from abiotic data layers such as climate, soil, geology, and topography. The species composition map or map attribute file consists of species and their age classes.

Table 2. Species' vital attributes for the study area.

Species Name	LONG	MATUR	SHADE	FIRE	EFFD	MAXD	VP	MVP
Larix gmelini	300	20	3	4	100	200	0	0
Pinus sylvestris var. mongoloca	250	40	1	1	50	200	0	0
Picea koreansis	300	30	4	2	50	150	0	0
Betula platyphylla	150	15	1	3	200	2000	1	40
Populus davidiana	180	30	1	3	−1	−1	1	40
Populus suaveolens	150	25	1	4	−1	−1	1	40
Chosenia arbutifolia	250	30	2	2	−1	−1	0.9	30
Pinus pumila	250	30	3	1	90	100	0	0

LONG: longevity of the species (year); MATUR: maturity age of the species (year); SHADE: shade tolerance class (1–5). 1 = least tolerant; 5 = most tolerant; FIRE: fire tolerance class (1–5). 1 = least tolerant; 5 = most tolerant; EFFD: species' effective seeding distance (m); MAXD: maximum seeding distance (m); VP: probability of vegetative propagation; MVP: minimum age of vegetative reproduction (year); the negative numbers in Table 2 means unlimited maximum seeding range.

2.2.2. Fire Module

Fire disturbance is a spatial landscape process based on the probability distributions of the fire cycle and mean fire size for various land types [39]. Fires occur at random at individual locations. However, at the landscape scale, there are repeating patterns in ignition, location, size, and shape. To show the influence of vegetation and topography on the occurrence of forest fires, we classified different land types and determined the input parameters for different land types by reviewing literature and fire record data. This is reflected in the different input parameters, such as mean fire return interval, mean fire size, standard deviation of fire size, and ignition density. The fire disturbance module has three main processes: when and where the fire occurs, how the fire propagates, and the impacts this has on the forest landscape [35,39].

First, for a given time step, LANDIS PRO generates the number of ignitions (X) in a given fire unit based on the Poisson distribution and the parameter λ (i.e., the average number of ignitions per decade). At the time of ignition, LANDIS is subjected to a Bernoulli trial. The result is denoted by Yi, and the parameter is the probability of fire (Pi), whose value is defined by the time since the last fire in the ignited unit. The probability of fire (P) for each unit is calculated by the following equation:

$$P(t) = 1 - e^{-t/\text{FC}}$$

where *FC* is fire cycle, *t* is the time since last fire, and *P* is fire initiation probability. After ignition is completed, LANDIS will randomly select a fire size, denoted by Z, from a log-normal distribution with parameters μ (mean fire size (MFS)) and σ^2 (standard deviation of fire size (STD)) to simulate fire spread. The specific structure is described in reference [43].

Secondly, LANDIS PRO 7.0 has two algorithms to simulate fire spread. The first one is a percolation algorithm. The fire can only spread in four directions: up, down, left, and right. The second algorithm is a modified penetration algorithm that takes fuel accumulation, topography, and prevailing winds into account. The fire can spread from the fire line to adjacent locations in eight directions (N, NE, E, SE, S, SW, W, NW).

Third, fire intensity is determined by the quantity and quality of fuels. Fires of specific intensities interact with individual species and age groups based on two attributes, species' fire resistance and age susceptibility. Differences in species' fire resistance are reflected by the different species' fire resistance classes in the species' property input table. Once the fire intensity is determined, the model will calculate the mortality rate for each age group within each species using a series of functions, which are not listed.

2.2.3. Fuel Module

The LANDIS PRO tracks fine fuels, coarse fuels, and live fuels and simulates various types of fuel management [43]. In this module, fine fuels (FF), mainly the leaf litter and small dead branches of less than $\frac{1}{4}$ inch in diameter, is the main prerequisite for ignition. Coarse fuels (CF) include any dead tree materials greater than or equal to three inches in diameter. They affect the intensity class of the fire. Live fuels, also known as canopy fuels, are live trees that may be ignited during high-intensity fires, such as canopy fires. Fine fuel quantities were derived from the age of the tree species and corrected by the fuel quality factor (FQC). In contrast, coarse fuels were determined using stand age (oldest age group) in combination with disturbance history (time since last disturbance) [44,45]. Accordingly, both coarse and fine fuel loads were classified into five grades. The actual fuel load cases corresponding to the five grades of coarse fuels are Grade 1 ($<$0.5 kg·m^{-2}), Grade 2 (0.5–1.0 kg·m^{-2}), Grade 3 (1.0–1.5 kg·m^{-2}), Grade 4 (1.5–2.0 kg·m^{-2}), and Grade 5 ($>$2.0 kg·m^{-2}).

Fuel management is divided into two categories: prescribed burning and physical fuel load reduction (removal and mechanical thinning). The intensity of treatment is reflected by the degree of changes in rank before and after fuel treatment in the input file. At the same time, parameters such as the area and frequency of treatment can also be set by the input file [35,46]. The model will first treat areas with the highest potential fire risk based on potential risk ranking.

2.3. LANDIS Parameterization

The data imported for the LANDIS model's initialization were split into two categories: non-spatial parameters (DAT files) and spatial parameters (GIS layers). Non-spatial parameters included the biological attributes of tree species, species establishment probability, fire disturbance parameters, etc. Spatial parameters included tree species composition maps, stand type maps, management area maps, etc. The available data for parameterization of LANDIS PRO included two scenes of the 2000 TM remote sensing imagery (WRS: P/R: 120/24 and 121/24), topographic maps (1: 50,000), 1990 forest stand maps and fire records in the Huzhong Forest from 1990 to 2000. The utilization of these datasets is shown in Table 1.

2.3.1. Species' Vital Attributes and Forest Composition Map

Eight tree species and their vital attributes were incorporated into LANDIS PRO. The major life history characteristics of tree species included: longevity, maturity age, shade tolerance value, fire tolerance value, species type, carbon coefficient, etc. [47]. The life history attributes of the eight species were obtained from the literature and field survey studies [41,48,49]. The main parameters are shown in Table 2. The forest composition map was generated from the 1990 forest stand map, which contains species and age information for the species in each image element. The forest stand map records the boundaries of stands and compartments. A forest inventory unit usually contains 10–100 forest stands. In order to reduce the computational load during the model simulation, the forest composition map was processed at a resolution of 90 m $\times$ 90 m, with 1480 rows $\times$ 1274 columns generated.

This study only discusses two major tree species (larch and white birch), as the other six species represent a small proportion of the study area.

2.3.2. Land Type Map

The LANDIS model divides the heterogeneous landscape into relatively homogeneous land-cover type units. The same land type is assumed to have the same environmental conditions. We classified the study area into six land types: non-forest, water, terrace, southern slope, northern slope, and ridge top (>1000 m). Non-forested land type and water areas were obtained from the 1990 forest stand map of the Huzhong Forestry Bureau. The southern and northern slopes were divided according to the slope direction from the DEM. The ridge top and terrace were further determined by calculating the elevation from the DEM. Non-forest and water accounted for 0.82% of the total area. Terrace, southern slope, northern slope, and ridge top areas accounted for 4.95%, 38.41%, 45.19%, and 10.61%, respectively. The land type map was also sampled to a 90 m × 90 m resolution (Figure 2).
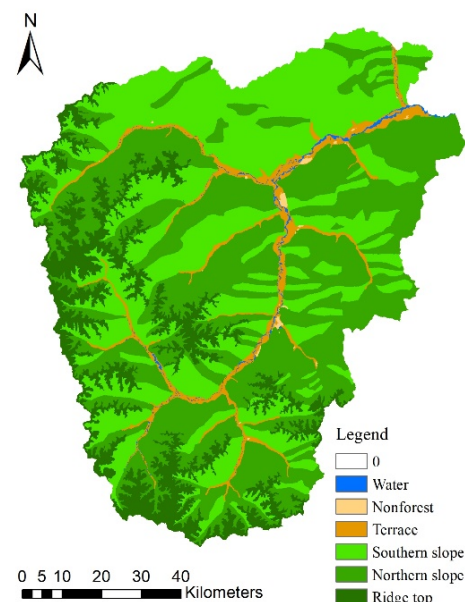
Figure 2. Land type map of the Huzhong Forestry Bureau.

2.3.3. Forest Fire Data

The study only simulates the fire disturbance, as windfall and insect pests are not common in the Huzhong Forest. It assumes that each land type has the same fire disturbance pattern (mean fire return intervals, mean burned area, etc.). By calculating the fire records from 1990 to 2000, we obtained the mean fire return intervals for different land types in the current fire suppression scenario. The mean fire return intervals under the no fire suppression scenario were obtained by consulting the other literature [7,50].

2.4. Simulation Scenarios

2.4.1. Scenarios Design

We considered two fire-control policies: the no fire suppression (NFS) policy, representing historical fire regimes before 1950, and the current fire suppression (CFS) policy representing the current fire regimes after 1950. Four simulation scenarios were formed based on whether or not fuel treatment was performed under the two policies: A) no fuel treatment (NFT) under CFS, B) fuel treatment (FT) under CFS, C) FT under NFS, and D) NFT under NFS. Scenarios A and D were for contrast and did not include fuel treatments. Scenarios B and D showed the implementation of fuel management policies under the CFS scenario and NFS scenario, respectively, and each of them included nine fuel treatment plans (Table 3).

Table 3. Fuel treatment plans and parameters.

Plans	Treatment Methods	Treatment Area	Treatment Frequency	Type	Grade
	No treatment			Fine fuels	0 1 2 3 4 5
				Coarse fuels	0 1 2 3 4 5
11	Coarse woody debris reduction	Small (2%)	High (5 years)	Fine fuels	1 2 3 4 5 5
12		Medium (6%)	Medium (10 years)	Coarse fuels	0 0 0 0 1 2
13		Large (10%)	Low (20 years)		
21	Prescribed burning	Small (2%)	High (5 years)	Fine fuels	0 0 0 0 0 0
22		Medium (6%)	Medium (10 years)	Coarse fuels	0 1 2 3 4 5
23		Large (10%)	Low (20 years)		
31	Coarse woody debris reduction plus prescribed burning	Small (2%)	High (5 years)	Fine fuels	0 0 0 0 0 0
32		Medium (6%)	Medium (10 years)	Coarse fuels	0 0 1 1 1 1
33		Large (10%)	Low (20 years)		

We simulated three fuel treatment methods, including reductions in coarse woody debris, prescribed burning, and coarse woody debris reduction plus prescribed burning. Coarse woody debris reduction was designed to remove all the coarse fuels less than or equal to grade three on a pixel, while the coarse fuels of grades four and five were reduced to levels one and two, respectively. Coarse fuel treatment results in a one-level increase in each of the fine fuel classes. Prescribed burning did not change the grade of coarse fuels but consumed all the fine fuels. Coarse woody debris reductions plus prescribed burning only reduced the coarse fuels of less than grade three by one level, while the coarse fuels greater than or equal to grade three were changed to level one. At the same time, the fine fuels were all burned. The details are described in Table 3.

To find a suitable treatment size and frequency, we designed three combinations of treatment size and frequency by considering the treatment costs for each treatment method, small size (2%) with high frequency (5 years), medium size (6%) with medium frequency (10 years), and large size (10%) with low frequency (20 years). A total of nine simulation plans were determined (Table 3).

2.4.2. Model Run Setting

To reduce the simulation uncertainty, we chose different random seed numbers and replicated ten simulations for each simulation plan, and then used the average value.

2.4.3. Parameter Test and Data Analysis

The Wilcoxon signed ranks test was used to test inferred and simulated MRI at 90% confidence intervals, and no significant difference was found (CFS, $p = 0.875$; NFS, $p = 0.7715$) (Table 4). In this study, one-way ANOVA analysis was used for significance tests among various simulation plans using SPSS 22.0. The test model output variables included average burn intensity, total burned area, burned area with different intensities, aggregation index, etc. (Table 5). The tested values were the average value from the ten replicate simulations.

Table 4. Statistical test for mean fire return intervals (MRI) between the inferred and the simulated for the current fire suppression (CFS) and no fire suppression (NFS) scenarios.

Land Type	MRI under the CFS Scenario		MRI under the NFS Scenario	
	Inferred	Simulated	Inferred	Simulated
Terrace	1500	2031	500	465
South slope	600	596	160	164
North slope	500	513	150	152
Ridge top	400	382	140	150
Wilcoxon signed ranks test	$p = 0.875$		$p = 0.7715$	

Table 5. Evaluation indicators used in this study.

Property	Indicator	Calculation Method
Fire disturbance	Burnt area Fire intensity Fuel load	The model directly outputs relevant data such as burnt area. The model outputs burnt area maps of different fire intensities. The model outputs fuel load maps.
Species distribution and age structure	Percentage of landscape (PLAND) Percentage of mature age species (MAS)	Total patch area for a given species/total area of the study area. (Total number of broadleaf trees older than 60 years + total number of conifers older than 100 years)/total number of tree species.
Forest landscape pattern	Largest patch index (LPI) Aggregation index (AI)	Area of the largest patch/total area of the study area. Common boundary of identical patch of the tree species/all boundaries of the tree species.

3. Results

3.1. Effects of Fire Suppression and Fuel Treatments on Fire Regimes and Forest Fuel Loads

By comparing the simulation results of scenario A and scenario D, the ecological effects of the current fire suppression could be inferred. We found that fire suppression significantly reduced the total burned area ($p < 0.001$) (Figure 3a) and obviously increased the mean fire intensity ($p = 0.004$) (Figure 4a). Furthermore, fuels accumulate significantly faster in scenario A compared to scenario D (Figure 4b). Both the mean coarse fuel loads class ($p = 0.001$) and the mean fine fuel loads class ($p = 0.007$) of scenario A were significantly higher than those in scenario D (Figure 4b).
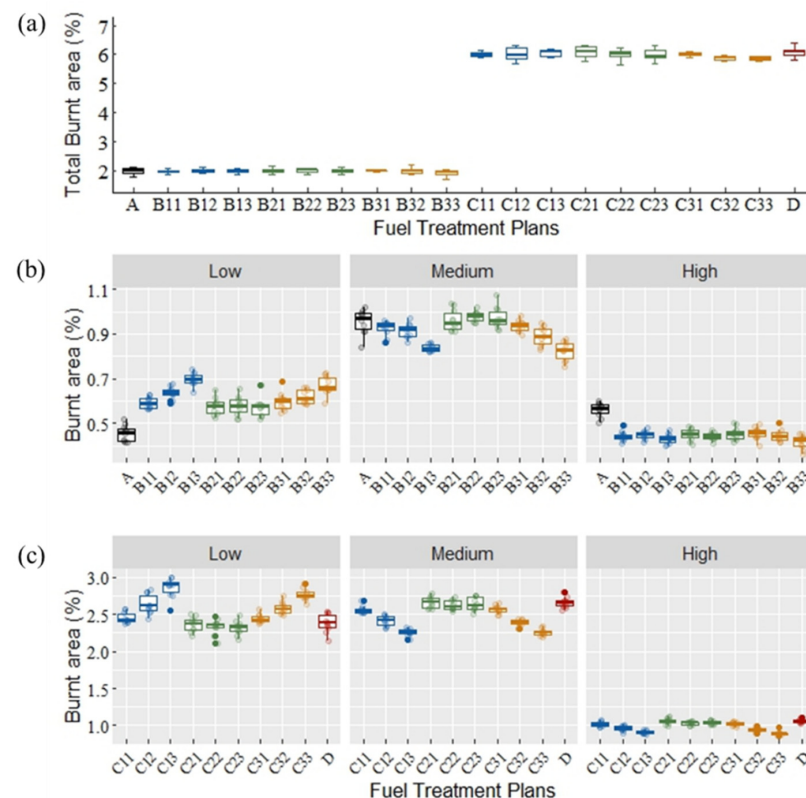
Figure 3. Total burnt area and area burned by different fire intensities for all scenarios. (**a**) Mean decadal total burnt area for all scenarios. This includes scenario A for the fire suppression scenario, scenario D for the no fire suppression scenario, and scenarios B and C for the implementation of fuel treatments corresponding to scenarios A and D. (**b**) Area of different-intensity fires under the nine fuel treatment plans included in scenario B. (**c**) Area of different-intensity fires under the nine fuel treatment plans included in scenario C. Low-intensity: class 1 and class 2; medium-intensity: class 3; high-intensity: class 4 and class 5.
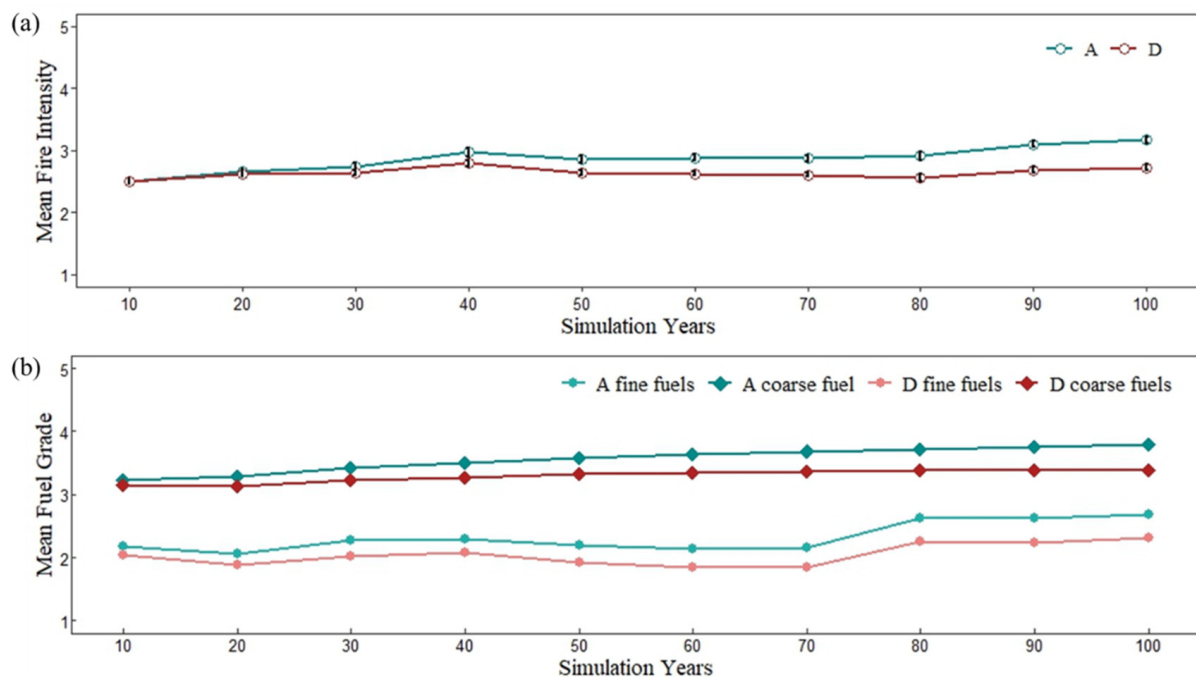
Figure 4. Mean fire intensity (**a**) and mean fuel loads grade (**b**) under scenario A and scenario D.

By comparing scenario A with scenario B, we could determine the fuel treatment effects under the current fire suppression policy. Although the total burnt area for the nine fuel treatment plans showed no obvious difference compared to scenario A ($p = 0.429$) (Figure 3a), it was worth noting that all the nine fuel treatment plans significantly reduced the area burnt by medium-intensity fires ($p < 0.001$) and high-severity fires ($p < 0.001$), while the area burnt by low-severity fires was significantly increased ($p < 0.001$) (Figure 3b). The greatest reduction in the area burnt by high-intensity fires occurred under fuel treatment plan B33, with a low treatment frequency (20 years), large treatment area (10%), and coarse woody debris reduction in addition to the prescribed burning measure.

By comparing scenario C with scenario D, the fuel treatment effects under the no fire suppression policy could be explored. The results showed that the total burnt area for the nine fuel treatment plans showed no obvious difference from scenario D ($p = 0.213$) (Figure 3a). Unlike the results of the fuel treatments under the CFS scenario, the coarse woody debris reduction (C11, C12, C13) and coarse woody debris reduction plus prescribed burning (C31, C32, C33) under the NFS scenario could obviously reduce the area burnt by medium- and high-intensity fires, while prescribed burning (C21, C22, C23) did not have a significant effect (Figure 3c).

3.2. Effects of Fire Suppression and Fuel Treatments on Species Abundance and Age Structure

As larch is the dominant coniferous species, and white birch is the major broadleaved species in our study area, we chose these two species to analyze species abundance and age structure affected by fire suppression and fuel treatments. In general, with a simulation time ranging to 50 years, fire suppression significantly reduced the abundance of white birch ($p = 0.036$) (Figure 5a), while that of larch was overall increased ($p = 0.022$) (Figure 5b), as indicated by the PLAND. Fuel treatments had no significant influence on the abundance of white birch and larch under the CFS policy (Figure 5a,b) and NFS policy (Figure 5d,e).
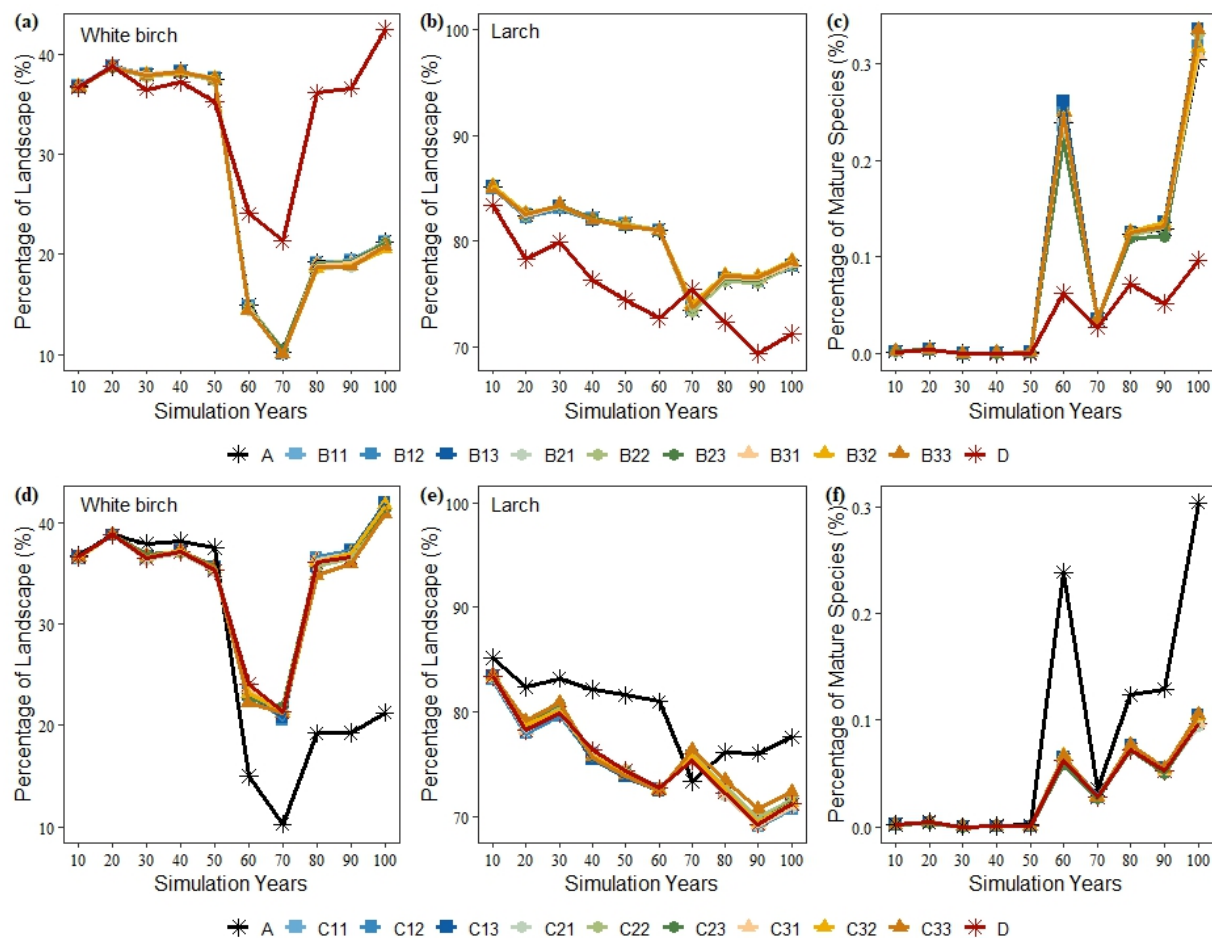
Figure 5. Percentage of landscape and percentage of mature age species for all scenarios. Scenario A and scenario D are the baseline scenarios for comparison, and they do not treat for fuels. (**a**–**c**) are the PLAND for white birch, the PLAND for larch, and MAS under the nine fuel treatment plans included in scenario B, respectively. (**d**–**f**) are the PLAND for white birch, the PLAND for larch, and MAS under the nine fuel treatment plans included in scenario C.

In terms of age structure, the percentage of mature age species (MAS) can reflect the tree species' ability to resist disturbance. Although there was no significant difference in MAS between scenario A and scenario D for the first 50 years of the simulation, fire suppression could increase the MAS of forests after 50 years of simulation (Figure 5c). All the fuel treatment plans did not significantly affect MAS in the study area under both the CFS policy (Figure 5c) and the NFS policy (Figure 5f).

3.3. Effects of Fire Suppression and Fuel Treatments on Forest Landscape Pattern

We used the largest patch index (LPI) and aggregation index (AI) to quantify forest landscape patterns. The change in LPI can reflect the intensity and frequency of disturbances and, in AI, the connectivity of the landscape. The LPI and AI of white birch under scenario D were generally larger than those under scenario A (Figure 6a,c), indicating that fire suppression could limit the spread of white birch. However, the LPI and AI of larch under scenario D were smaller than those under scenario A (Figure 6b,d), demonstrating that fire suppression favors the expansion of larch. Although there were fluctuations in the LPI of larch under scenario C after 70 years of simulation, they were not significant compared to scenario D ($p = 0.992$). The various fuel treatment plans implemented under both CFS and NFS policies had no significant influence on the forest landscape pattern.
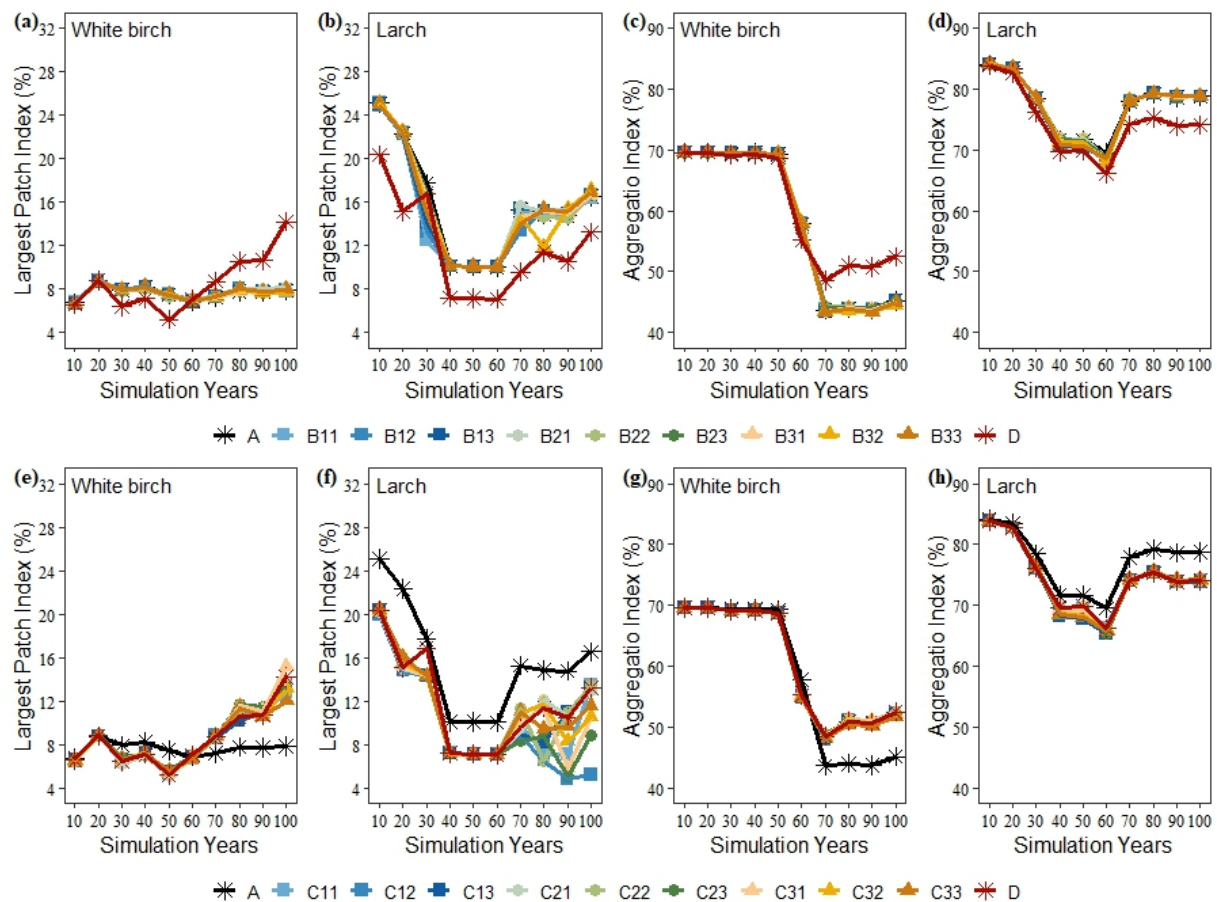
Figure 6. Largest patch index (LPI) and aggregation index (AI) for all scenarios. Scenario A and scenario D are the baseline scenarios for comparison, and they do not treat for fuels. (**a**,**b**) are the LPIs for white birch and larch, respectively, under the nine fuel treatment plans in scenario B. (**c**,**d**) are the AI of white birch and larch, respectively, under the nine fuel treatment plans in scenario B. and (**e**,**f**) are LPI for white birch and larch, respectively, under the nine fuel treatment plans in scenario C. (**g**,**h**) are the AI of white birch and larch, respectively, under the nine fuel treatment plans in scenario C.

4. Discussion

4.1. Effects of Fire Suppression and Fuel Treatments on Fire Regimes and Forest Fuel Loads

To alleviate catastrophic forest fire occurrences, fire suppressions and fuel treatments were implemented worldwide, which significantly altered fire disturbance regimes [2]. Our simulation results indicated that fire suppression reduces the total burnt area (Figure 3a) while increasing the mean fire intensity (Figure 4a) and fuel loads (Figure 4b). Our results were in line with previous studies [10,50]. Our results also demonstrated that fuel treatment plans under the CFS policy could significantly reduce the areas burnt by medium-intensity and high-intensity fires. Some of the medium-intensity and high-intensity fires were dropped to low-intensity fires, and therefore, the area burned by low-intensity fires increased. Our results confirm the effectiveness and goal of forest fuel treatments [31]. At the same time, the effectiveness of forest fuel treatments is simultaneously influenced by the combination of fuel treatment methods, area, and frequency [28,30]. We found that, among the nine fuel treatment plans, the fuel treatment plan B33, with ten percent of the area treated, frequency of application every 20 years, and coarse woody debris reduction plus the prescribed burning measures, could greatly reduce the area burnt by high-intensity fires. Due to the limited growth rate of vegetation and slow accumulation of fuels, a high frequency of fuel treatment does not necessarily consume large amounts of fuel. Instead, it may be more effective to increase the area of fuel treatment. Coarse woody debris reductions produce large amounts of fine fuels during implementations,

which increases the probability of forest fires [51]. While prescribed burnings remove fine fuels, they do not affect coarse fuels, resulting in the accumulation of coarse fuels and high-intensity fires [52]. This observation is consistent with a previous study [26] and has crucial and practical implications for guiding forest fuel management in our study area and other related regions. However, the effects of fuel treatments under the NFS policy were less effective than those under the CFS policy. This may be due to the large burnt area under the NFS policy (Figure 3a) reducing the accumulation of fuel loads (Figure 4b), which results in fuel treatments having weaker effects [9,53,54].

4.2. Effects of Fire Suppression and Fuel Treatments on Species Abundance and Age Structure

Fire suppression has been found to alter forest composition, species abundance, and age structures [9,10]. Our results showed that fire suppression increased the abundance of larch while decreasing the abundance of white birch. This is in line with previous studies [25,50]. Larch is a shade-tolerant and non-pioneer species. White birch is a shade-intolerant and pioneer species. According to the succession process of vegetation in our study area [55,56], white birch is the major species in the pioneer stage, and larch is the dominant species in the top stage. When fires occur, canopy openings are formed. White birch, relying on its strong seed dispersal and colonization ability, is easier to establish and dominate the landscape. As the canopy cover gradually increases, the forest gap becomes smaller, resulting in less exposure to light, and larch relies on its higher shade tolerance to gradually dominate this environment. Therefore, larch is the dominant species in this area in the late successional stage. To determine the forest age structure, we only analyzed fire suppression's impact on mature-age species. The results indicated that, over the last 50 simulation years, the percentage of mature trees significantly increased under the CFS scenario compared to the NFS scenario. This is because, after decades of forest harvest in our study area, the stand age is mainly within 40 years; therefore, the percentage of mature trees showed no change during the first 50 simulation years.

There has been no documentation regarding the effects of fuel treatment on forest age structures. Our simulation results demonstrated that fuel treatments did not significantly affect the percentage of mature trees. This is somewhat expected and provides a scientific basis for the implementation of forest fuel treatments without changing forest age structures and the forest succession process while lowering forest fire severity. Our results consolidate the foundation for forest fuel treatments in fire-prone forest landscapes.

4.3. Effects of Fire Suppression and Fuel Treatments on Forest Landscape Pattern

Landscape pattern is the core concept of landscape ecology regarding many ecological processes, such as seed dispersal, animal movements, landscape fragmentation, etc. [57–59]. Many indices have been designed to quantify landscape patterns [60,61]. We chose LPI and AI to describe landscape patterns, as LPI can reflect the intensity and frequency of disturbances [62–64], and AI can reflect the connectivity of the landscape [63]. Our results indicated that fire suppression reduces the patch size and aggregation of white birch, which might impact the habitats of animals favoring white birch forests, such as red deer (*Cervus elaphus*), and roe deer (*Capreolus capreolus*), which prefer birch forest ecosystems [65,66]. However, fire suppression leads to large and aggregated patches of larch, which may reduce habitat fragmentation and edge effects [67,68] and increase the core area of suitable habitats. This is beneficial to other wildlife species, such as sables (*Martes zibellina*) [69]. Therefore, a more comprehensive wildlife habitat suitability analysis is needed [70]. Our simulation results provide the basis for such an analysis. As for the fuel treatment effects, we found that various fuel treatments had no significant influences on the forest landscape patterns. However, they affected the fire pattern, with an increase in lower-severity fires (Figure 3b). The large burnt area caused by lower-severity fires may favor the growth of grass [71,72], which could provide more forage for herbivory animals [73,74], and more food for carnivory animals [75]. Thus, the food chain of the forest

ecosystem is better maintained. Our results highlight the roles that forest fuel treatments play in maintaining the ecological balance of forest ecosystems.

4.4. The Practical Application and Promotion of Fuel Treatments

Plan B33, derived from this study, is useful for maintaining forest fire safety in the Great Xing'an Mountains and can be considered to start implementation. From the simulation results, if we had started to implement Plan B33 in 1990, the high-intensity fire in the Great Xing'an Mountains would have been significantly reduced, and it would not have affected the forest age structure and forest succession process. The study considered the difficulty and cost of implementation, so only nine representative fuel treatment plans were simulated. However, there are many fuel treatment methods, sizes, and frequency combination schemes, which should be adjusted to the specific fire situation in practice. Furthermore, the LANDIS PRO model does not simulate the dynamics of herbs and shrubs. Herbs and shrubs are also important sources of fuel [50], and they have high flammability and large biomass. Therefore, this study may have underestimated the fuel load and fire intensity.

The ideas provided in the study on assessing the ecological effects of fuel treatment scenarios can be extended and learned from, but the results obtained in this paper may not be directly applicable to other regions of China. The reason for this is the variability of vegetation cover, climatic conditions, and other factors in different regions. Currently, the LANDIS PRO model is also being used successfully in other regions [76–78]; thus, it is possible to simulate relevant fuel treatment and to provide a scientific basis for forest fire prevention work in China.

5. Conclusions

Fire is a major natural disturbance and will be exaggerated in the future with climate warming. To alleviate the damage that forest fires cause to society and forest resources, concerns regarding fire suppression and forest fuel treatments are increasing. We used the LANDIS PRO model to simulate the consequences of fire suppression and the ecological effects of fuel treatments in a boreal forest of the Great Xing'an Mountains, China. The ecological effects were comprehensively evaluated in terms of fire disturbance, species succession, and forest landscape. We observed that fire suppression led to fuel accumulation and a higher fire intensity while reducing the total burned area. Forest fuel treatments could lower forest fire severity without changing the forest age structure and forest succession process. If we had started to treat 10% of the area with coarse woody debris reduction plus prescribed burning every 20 years in 1990, there would be far fewer high-intensity fires now, and the forest age structure and forest succession process would develop as they naturally do without being affected. Our results form a foundation for practical forest fuel treatments in fire-prone forest landscapes. We suggest a suitable fuel treatment plan for the Great Xing'an Mountains, with a low treatment frequency (20 years), large treatment area (10%), and coarse woody debris reduction, in addition to the prescribed burning measure.

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