大兴安岭北坡火烧迹地森林郁闭度恢复及其影响因子

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摘要: 1987 年发生在大兴安岭北坡的特大森林火灾, 总过火面积达 1.33 × 10^6 hm^2, 形成了各种火烧强度区与未火烧区构成的异质镶嵌体。火烧强度、地形以及火后人类的恢复干预都不同程度地对火后森林恢复产生了影响。研究目的有二: 一是为了揭示火后森林恢复状况; 二是探寻火烧强度、地形以及火后更新措施等因素对火后森林恢复的影响程度。选取了位于火烧区的图强林业局中部的育英和图强两林场为研究区, 选取反映森林景观质量的郁闭度指标作为研究对象, 利用地理信息系统软件, 将 1987 年火前与 2000 年的郁闭度等级分布图叠加, 分析火后森林质量的恢复状况; 利用多元线性回归法对火烧强度、海拔、坡度、坡向、坡位等地形因子以及各种更新方式对郁闭度恢复的影响程度进行了定量研究。结果显示, 2000 年郁闭度等级与火前相比发生了明显变化, 2000 年各林型郁闭度优势等级均由较高的等级 4, 5 降为等级 3; 而等级 1 的比重也有所降低。表明, 火后森林总体生长状况良好, 无林地比重降低, 但由于恢复时间较短, 具有较高郁闭度的森林所占比重仍较低。多元线性回归显示, 各因子均对火后郁闭度恢复产生了显著性影响。其中, 海拔影响最大, 与郁闭度等级呈正相关; 其次是火烧强度, 呈负相关; 其它地形因子以及更新方式影响较小。

关键词: 火烧强度; 更新措施; 地形因子; 多元线性回归
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Forest crown density restoration and influencing factors in the burned area of northern Great Xing′an Mountains

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Abstract: The Great Xing′an Mountains' fire in 1987 affected more than 1.33 × 10^6 hm^2, creating a mosaic of burn severities across the landscape, which strongly affected the post-fire vegetation succession. In addition, undulate landform and anthropogenic disturbance inevitably influenced post-fire vegetation succession. In this paper, a typical area was selected for a case study, including two forest farms, covering more than 1.2 × 10^5 hm^2. In order to reveal how the forest changed in 2000 (3 years after fire), compared to 1987 (pre-fire), and to find out the relationship between the forest succession and affecting factors, forest crown density was selected as the criterion, and forest type, fire severity, silviculture practice, elevation and topography gradients were designed as affecting variables. With the support of GIS software, each variable was classified and entered the multivariate regression model. The result showed that the forest crown

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density changed notably in 2000 compared with that of pre-fire, and all the variables significantly affected the forest crown density. The most important affecting variable was elevation, which was positively correlated with forest crown density. The next was fire severity which was negatively related with forest succession. The effects of topographic factors and silviculture practices on forest crown density were relatively small.

Key Words: Fire severity; silviculture practices; topographic factors; Multiple regression analysis

Introduction Natural disturbance regimes (including frequency, size, severity etc.), environmental variability (including topographic relief, soil characteristics, and available resources), life-history characteristics (such as dispersal, growth rates, and longevity) and anthropogenic activities (such as human ways) can affect forest succession and create vegetation patterns at the landscape scale [1-11]. The unprecedented forest fire occurred in the Great Hing′an Mountains on May 6, 1987, which affected more than $1.33 \times 10^6 hm^2$ natural forest, and provided an opportunity to study the effects of large disturbance event on forest ecosystem. The destructive fire resulted in lots of mosaics of fire severity and unburned area due to variations in wind, topography, vegetation type, moisture, natural fuel breaks, and the burned days of forest fire [2-16], which further influenced the post-fire vegetation succession [6,17,18]. Studies after the fire mainly concentrated on the effect of fire severity on vegetation succession [9-23]. A few study considered the effects of topographic gradients [24], though topographic relief can exert important influences on forest vegetation in mountainous regions [25-28]. Similarly, study on the effects of human silviculture ways on forest restoration was also ignored, though human silviculture ways were broad ly applied following fire, in order to restore the forest landscape as soon as possible [29,30]. Few study considered the forest succession following such large disturbance event under multiple ecological factors at large scale, especially with the reduction of the studies on post-fire vegetation restoration from 1995.

The objectives in this study were to reveal how the forest restored 13 years after fire, and to find out the relationship between forest succession and affecting factors at coarse scale. We focused on the forest crown densities, which is one of the important indices reflecting forest growth, as well as a key statistic data in forest inventory in China. Considering different growth rhythm of various forest types, mainly coniferous, mixed and broad-leaved forest in this region, forest succession research was conducted based on these three forest types respectively. Affecting variables included fire severity (classified as unburned, lightly, moderately and severely burned), human silviculture ways (sorted as natural regeneration, assisted regeneration, direct seeding and planting regeneration), and topographic variables including elevation, slope, aspect and slope position. The relationships between crown density and affecting factors were based on the following hypotheses: due to 87.5% of study area was burned, the forest crown density post-fire was considered to develop from null. Based on the hypotheses, forest crown density distribution in 2000 was used as forest succession variability to identify how factors mentioned above affected forest succession.

1 Methods

1.1 Study area

Yuying and Fendou forest farms in the middle of Tuqiang Forestry Bureau on the northern slope of Great Xing′an Mountains were chosen as study area, which occupies $1.2 \times 10^4 km^2$ land area in total, and belongs to Mohe County, Heilongjiang Province. Geographic coordinates are between longitude 122°18′05″— 123°29′00″ E and latitude 52°15′55″— 53°33′40″ N. The average altitude is 599 m with gentle undulating hills and open river valleys. This area has long and cold winter and short and hot summer. Mean annual temperature is −4.94 ℃, with lowest temperature recorded at −53 ℃. Mean annual precipitation is 432 mm, with relatively dry spring and winter, and moist summer and autumn. The main forest species are Xingan larch (*Larix gmelimii*), birch (*Betula platyphylla*), pine (*Pinus sylvestris* var. *mongolica*) and aspen (*Populus davidiana*). Brown coniferous forest soil is the dominate soil genus with thickness of 10 30 cm. Several reasons were taken into account for choosing the two forest farms as study area. First, 87.5% of the area was burned, which is convenient for the study of forest restoration at large scale. Second, topographical relief in this area is steeper than the others in the burned area, which is advantageous for the study of effects of terrain factors on forest restoration. Third, the natural regeneration assisted by human silviculture ways was taken following fire, which provides a good chance to study the effect of human interference on post-fire forest succession.

1.2 Data sources

Forest crown density, silviculture ways and slope position all came from forest inventory data (forest stand maps) of Tuqiang Forestry Bureau in 1987 (pre-fire) and 2000 (3 years after fire). Firstly, sample plots, offering information of vegetation, site condition and forest management, were established. Secondly, mathematic model was built based on the correlation between remotely sensed data and sample plot data, by which data all over the forest bureau attained. At last, according to the information similarity, forest compartments were divided, and data-base with the attributes of every compartment was set up [1-33]. In forest stand map, the forest crown density value is ranged from 0 to1. Non-stocked land has the value of 0, and entirely closed represented forest crown has the value of 1. Since silviculture was only applied in coniferous forest, this variable in mixed and broadleaved forest was excluded. It was noticed that the information of forest stand map in 1987 actually came from investigation pre-fire, and the map was generated in 1987.

Fire disturbance data came from the map of fire severity in 1987, which was mapped based on percentage of the dead trees from field survey post-fire (Table 1).

Forest stand maps in 2000 and fire severity maps in 1987 were scanned and digitized using GIS software, and data-base was linked. Forest crown density of each forest type, silviculture ways, position and fire severity were extracted respectively from the digital map (Table 1).

Elevation, slope and aspect were obtained directly from DEM, which was generated from topographic map (:10000) using GIS software (Table 1).

1.3 Data analysis

In order to quantify the relationship between forest crown density and explained variables, variables were sorted into grades (or types) (Table 1). Forest crown density was reclassified into 6 grades, from 1 for non-stocked area to 6 for the value of crown density as 1 (Figure 1). Elevation grades were ranged from 1 for elevation lower than 500 m to 5 for elevation higher than 800 m with the increase of the elevation. Fire severity classes were ordered to increase with burn severity, from 1 for unburned area to 4 for severe burned area. Slope position types were ranked from 1 for valley to 5 for hilltop. Slope was scaled from 1 (flats) to 5 (sharp slope). Aspect was categorized from 1 for shaded aspect to 4 for sunny aspect, according to the radiation and heat load. Considering no comparability of no aspect with other aspects, this area was excluded. Silviculture ways was weighed with the aggravation of silviculture intensity, from 1 for no silviculture practice to 4 for planting regeneration. Then, in order to eliminate the errors regenerated from the area differences among variable grades, these digital maps were transformed into grid format with a resolution of 30 m × 30 m.

No aspect type was taken out to insure the order of aspect type which ranked from shaded aspect to sunny aspect. Due to the objective forest was the conifer, silviculture practice was taken away from the combined data subset of mixed forest and broad-leaved forest. Then, the attribute tables of crown density grade of each forest type were joined with those of fire severity, silviculture practice, elevation grade, slope grade, aspect type and slope position type, and new attribute tables of every cell were exported as DBF formats, which can be processed by SPSS software. The data process above was achieved by the GIS software.

Table 1 Criterion of various factors

Factors	Grade (ype)	Attribute describe
Crown density	1	Non-stocked land
	2	Crown density 0 — 0.2 (ncluding 0.2)
	3	Crown density 0.2 — 0.4 (ncluding 0.4)
	4	Crown density 0.4 — 0.6 (ncluding 0.6)
	5	Crown density 0.6 — 0.8 (ncluding 0.8)
	6	Crown density 0.8
Fire severity	1 Unburned	Without fire
	2 Lightly burned	Percentage of trees consumed by fire 30%
	3 Moderately burned	Percentage of trees consumed by fire 30% –70%
	4 Severely burned	Percentage of trees consumed by fire 70%
Silviculture ways	1 Natural regeneration	The generation completely depends on seed trees without any human measures
	2 Assisted regeneration	Seeds come from seed trees, but rooting is assisted by wiping the litter away
	3 Direct seeding regeneration	Artificially or aerially seeding
	4 Planting regeneration	Directly plant young coniferous seedlings (*arix gmelimii* or *Pinus* sylvestris var. *mongolica*)
Elevation (m)	1	Elevation < 500
	2	500 m < elevation < 600
	3	600 m < elevation < 700
	4	700 m < elevation < 800
	5	Elevation > 800
Aspect	No aspect	Dale or flat
	1 Shaded aspect	North and northeast slope
	2 Semi-shaded aspect	Northwest and east slope
	3 Semi-sunny aspect	West and southeast slope
	4 Sunny aspect	Southwest and south slope
Position	1 Valley	Area with gradients less than 5 and at the bottom of the catena
	2 Low slope position	Various aspects from piedmont to 1/3 height of mountains
	3 Middle slope position	Various aspects from 1/3 to 2/3 height of mountains
	4 Upper slope position	Various aspects from 2/3 height to peak of mountains
	5 Hilltop	Area on top of mountains
Slope (°)	1 Flats	5
	2 Gentle slope	5 — 15
	3 Moderate slope	15 — 25
	4 Steep slope	25 — 35
	5 Sharp slope	35

In order to assess the restoration of forest crown density, area percentage of each grade in 2000 and pre-fire was calculated respectively and compared. Multivariate regression analysis was used to test the relationship between forest crown density and affecting variables. First, we tested significance of correlation between the crown density and independent variables with Pearson correlation. Then independent variables with significant correlation with the crown density were used in the regression model.

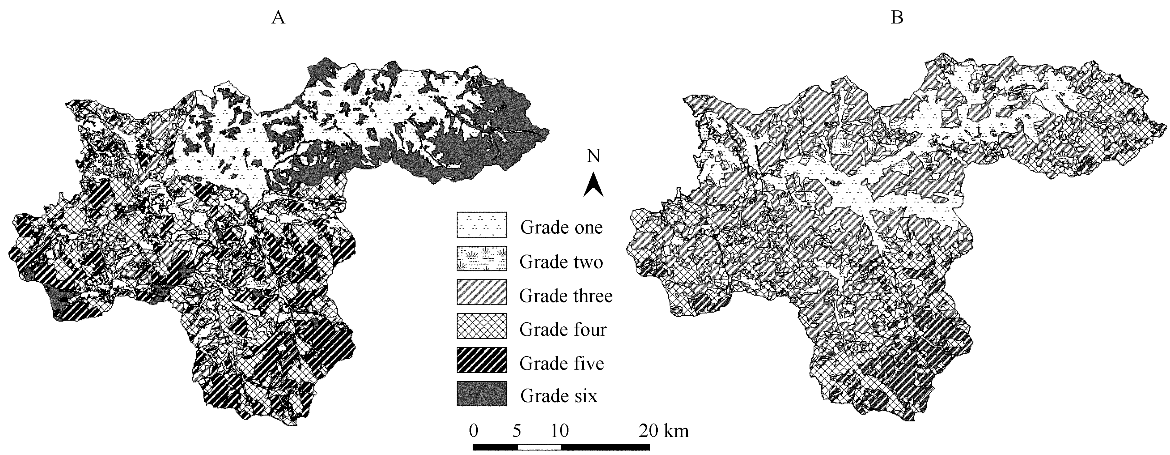

Fig. 1　Distribution map of forest crown density grades pre fire and 2000

A　pre-fire ; B　in 2000

2　Results

2.1　Change of forest crown density in 2000 compared with pre-fire

Figure 2 showed that compositions of crown density grades under all the three forest types changed a lot in 2000 compared with pre-fire. The area of crown density grade 3 under all the three forest types increased greatly, of which that of broadleaved forest even increased by more than 56%. Conversely, the area of forest crown density grade 4 and 5 decreased a lot. The area of non-stocked forest decreased slightly.

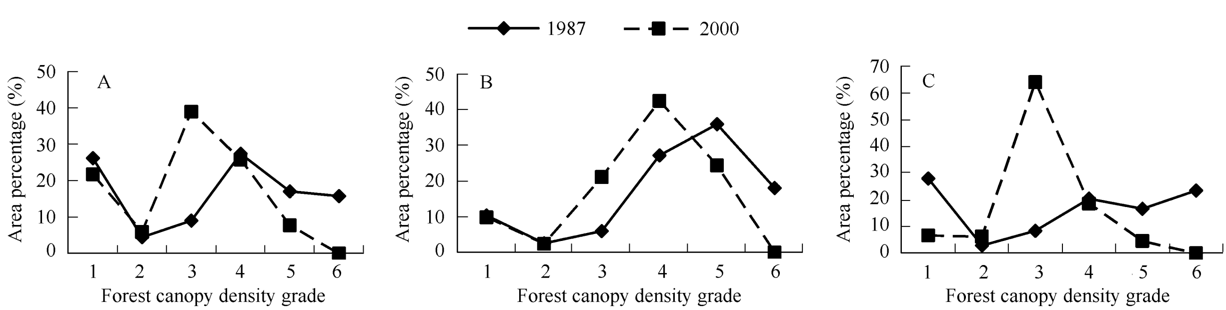

Fig. 2　Area distribution of crown density of different forest types in 1987 and in 2000

A　Coniferous forest ; B　Mixed forest ; C　Broad-leaved forest

2.2　Correlation of forest crown density and affecting factors

Pearson correlation analysis showed that each selected variable (fire severity, silviculture way, elevation, slope, position and aspect) was significantly related to the post-fire forest crown density under three forest types, though some of the correlation coefficients were low (p = 0.000) (Table 2). Whereas the study area is large, low correlation coefficients is accessible. Then all the selected variables were used in the regression model.

Table 2　Correlation of crown density and explained variables

	Fire severity	Silviculture ways	Elevation	Slope	Slope position	Aspect
Coniferous forest	− 0.471	− 0.377	0.510	0.309	0.148	− 0.139
Crown density	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001
Mixed forest Crown density	− 0.637	No	0.641	0.399	0.054	−0.082
	p < 0.001		p < 0.001	p < 0.001	p < 0.001	p < 0.001
Broad-leaved forest	− 0.408		0.485	0.192	0.096	− 0.141
Crown density	p < 0.001		p < 0.001	p < 0.001	p < 0.001	p < 0.001

Multivariate regression analysis suggested that forest crown density of each forest type can be jointly explained by the fire severity, silviculture ways, elevation, slope, slope position and aspect ($F = 61582.289$, $p < 0.001$; $F = 28620.915$, $p < 0.001$ and $F = 24187.860$, $p < 0.001$) (Table 3). The Adjusted R^2 in the models of the three forest types was 37%, 52% and 31% respectively (Table 4). The goodness of fit in mixed forest model was the best, and that in broad-leaved forest was the worst.

Table 3 Summary of the one-way ANOVA for the multiple regression models

Forest type	Model	Sum of squares	df	Mean square	F	Sig
Coniferous forest	Regression	318762.945	6	53127.158	61582.289	< 0.001
	Residual	542618.787	628976	0.863		
Mixed forest	Regression	71153.802	5	14230.760	28620.915	< 0.001
	Residual	65886.512	132511	0.497		
Broad-leaved forest	Regression	48830.794	5	9766.159	24187.860	< 0.001
	Residual	112290.479	278110	0.404		

Comparing the Standardized Coefficients of the six (coniferous forest) or five (mixed and broadleaved forest) explained variables in the three models, elevation and fire severity were the two most important factors in succession under all the three forest types. Elevation was positively related to forest crown density, while fire severity was the other way around (Table 5). The effects of slope position, aspect and silviculture ways on crown density were relatively low (Table 5).

Table 4 Summary of the models

Model	R	R^2	Adjusted R^2	Std. Error of the estimation
Coniferous forest	0.608	0.370	0.370	0.93
Mixed forest	0.721	0.519	0.519	0.71
Broad-leaved forest	0.551	0.303	0.303	0.64

Table 5 Coefficients between forest crown density and explained variables

Forest type	Item	Unstandardized coefficients	Standardized coefficients	t	Sig
Coniferous forest	Constant	2.632		345.575	0.000
	Fire severity	- 0.307	- 0.289	-178.294	0.000
	Silviculture practice	$-3.036 \times 10 - 2$	- 0.033	-21.390	0.000
	Elevation	0.397	0.324	260.067	0.000
	Slope	0.239	0.141	121.922	0.000
	Slope position	-1.888×10^{-2}	- 0.013	-11.602	0.000
	Aspect	- 0.104	- 0.101	-100.689	0.000
Mixed forest	Constant	3.151		198.347	0.000
	Fire severity	- 0.361	- 0.372	-152.873	0.000
	Elevation	0.393	0.396	156.952	0.000
	Slope	0.115	0.071	32.523	0.000
	Slope position	-6.271×10^{-2}	- 0.044	-22.416	0.000
	Aspect	-2.575×10^{-2}	- 0.029	-14.834	0.000
Broad-leaved forest	Constant	2.723		311.729	0.000
	Fire severity	- 0.183	- 0.249	-143.877	0.000
	Elevation	0.330	0.377	205.666	0.000
	Slope	6.129×10^{-2}	0.049	28.618	0.000
	Slope position	-2.426×10^{-2}	- 0.026	-15.599	0.000
	Aspect	-5.627×10^{-2}	- 0.083	-52.058	0.000

3 Discussion

3.1 Change of forest crown density composition in 2000 compared with pre-fire

The area of forest crown density grade 4 and 5 decreased greatly compared that of pre-fire suggested that forest growth had not attained the pre-fire level. This might be due to the short period of restoration (only 13years). The great increase of grade 3 suggested that forest was at the elementary succession stage, but forest as landscape matrix has already formed. Decrease of grade 1 may be caused by the silviculture practices post-fire instead of harvesting pre-fire.

3.2 Correlation between forest crown density and affecting factors

The multivariate regression analysis suggested that the effects of explained variables on the post-fire growth of coniferous, mixed and broadleaved forest were greatly similar, which was different from the restoration of the post-fire forest composition and pattern [4,34]. Their results showed that recruitment of the various forest types post-fire were different with the variability of affecting factors. This may be because early post-fire recruitment of the different forest types was prone to be controlled by disturbance, environmental gradients and human activities, due to the different life-history characteristics of component species. Once forest composition and pattern formed, the influences of the controlled variables on different forest types were greatly weakened. For example, human silviculture ways can obviously change the vegetation composition and pattern, but with less help to forest growth.

Temperature and precipitation decreases with the elevation ascending [6,27,35], which should retard the growth of forest. But the result showed that elevation were all significantly positively related to the forest crown density under all the three forest types (Table 5), which was out of expected. This might be caused by fire severity variation with elevation gradients. Figure 3 revealed that percentage of severely burned area decreased markedly with the increase of elevation grade, while that of unburned area increased significantly. In addition, variation of elevation is relatively small, ranging from 420 m to 930 m in the study area, which restricted the variation of heat and moisture [6]. Therefore, the effect of elevation grades on forest crown density was over-ruled by its effect on fire severities.

Fire severity showed negatively significant correlation with the succession of three forest types. This may be because the more severe the fire was, the fewer trees survived from the fire. Survived trees following fire restored to grow rapidly, and that abundant seed also contributed to regeneration, while the succession of severely burned area started almost from null.

Silviculture ways showed a negatively slight relation with forest crown density under coniferous forest. It seemed that human silviculture ways post-fire had negative effect on forest restoration, though a great deal of work had been done. After referring to the management planning of Tuqing Forest Bureau, we found this result can be explained by the criterion of silviculture ways. Regeneration ways were prescribed according to fire severity and site condition. The area of natural regeneration mainly involved lightly burned area and broadleaved area, where a great deal of trees survived, and broadleaved species have better germination ability. On the contrary, silviculture ways were mostly used in severely burned area. Further more, the planted forest species was coniferous with slow growth. So the restoration of forest crown density in natural regeneration area was better than that in artificially restored area in the short term. Although no distinctive effects have been found now, silviculture ways had changed the forest composition. Figure 4 showed that the area proportion of coniferous adopting artificial treatments (direct seeding and planting) was higher than that of natural regeneration (natural and human promoted regeneration) in 2000, which greatly shortened the cycle of succession from broad-leaved to coniferous especially in severely burned area.

In addition, only silviculture ways following fire was selected as variable, without considering other artificial treatments such as post-fire clear-cutting [7], and thinning [1], which is a deficiency of our research.

Topographic factors showed slight influences on forest restoration, due to lack of extremely steep slope in the study area, which was different from steep mountainous area [5]. Aspect showed negative correlation with forest crown density, probably because it controls the soil fertility, but not the solar radiation in this study area. Highly fertilized soil is often distributed in shaded slope [8].

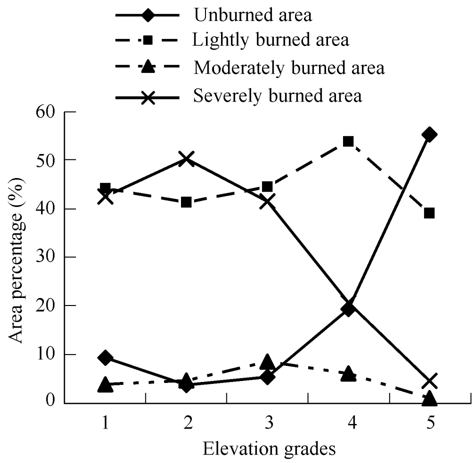

Fig. 3 Area distribution of fire severity on the elevation grades in 1987

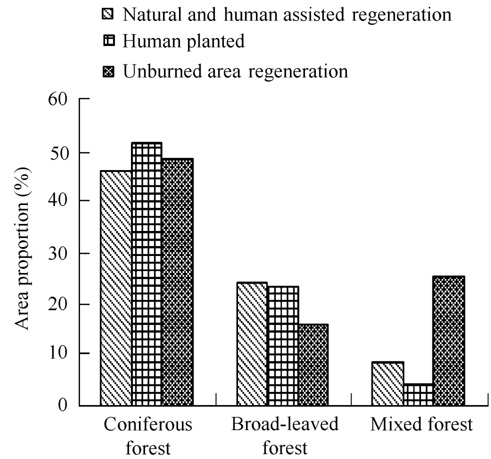

Fig. 4 Area distribution of forest types under various regeneration ways

The results of multiple regression analysis showed the main parameters that determine forest crown density variability in this study area. However, a certain part of the variability is still unexplained by the regression model. This unexplained variability may be partly due to the large study scale, at which a lot of ecological processes at fine scale were concealed, such as the effects of patch size [4], distance to the nearest neighbor of unburned patch [9], pre-fire basal area [8], and soil productivity [10]. Therefore, further research is needed in order to consider more effective controlling factors simultaneously at different scales and evaluate the relative importance of each factor.

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