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RESEARCH ARTICLE

Scale effects of vegetation and topography on burn severity under prevailing fire weather conditions in boreal forest landscapes of Northeastern China

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Understanding the controlling factors of burn severity requires consideration of the scale at which these factors work. This investigation explored how well topography and vegetation factors can explain variation of burn severity in a boreal forest landscape of northern China under prevailing fire weather conditions. Eight grain sizes were examined that ranged from 30 to 2500 m. A burn severity map was derived from calculating the difference between pre- and post-fire Normalized Difference Vegetation Index of two Landsat Thematic Mapper images. Results indicate that (1) burn severity in the boreal forest landscape of northern China was mainly controlled by vegetation at grain sizes smaller than 500 m. At grain sizes larger than 1000 m, topography accounted for more variation in burn severity; (2) the relative importance of topography factors was stable with increasing grain sizes and generally ranked in order of aspect, slope, and elevation; (3) stand age appeared to be more important where canopy cover and understory cover substantially fluctuated with increasing grain sizes; and (4) the linear relationships between burn severity and specific factors of topography and vegetation decreased with increasing grain sizes. Our study can help managers to design fire management plans according to vegetation characteristics that are found important in controlling burn severity and prioritize management locations based on the relative importance of vegetation and topography.

Keywords: burn severity; boreal forest landscape; grain size; NDVI; topography; vegetation

Introduction

In boreal forest landscapes, fire is a dominant disturbance that creates spatial mosaics of patches with varying burn severities (Johnstone & Chapin 2006; Duffy et al. 2007; Boelman et al. 2011; Wu et al. 2013). Burn severities can influence the post-fire species composition, structure, and recovery within the burned patches (Turner et al. 1999; Turner et al. 2003; Keeley et al. 2005; Johnstone et al. 2011). Understanding what and how environmental factors affect burn severity across a fire-prone landscape is essential as the severity of fires increases in many regions (Alexander et al. 2006; Oliveras et al. 2009; Bradstock et al. 2010). In general, climate and weather are of paramount importance in the timing, size, intensity, and severity of fire events in both the North American boreal forests (Bessie & Johnson 1995; Lesieur et al. 2002; Podur & Martell 2009; Bradstock et al. 2010) and the Chinese boreal forests (Fu et al. 2001; Yu et al. 2009; Liu et al. 2012).

Most studies concerning scale effects of environment (e.g. weather, vegetation, and topography) on burn severity were conducted in the North American boreal forests (Krawchuk et al. 2006; Cyr et al. 2007; Parks et al. 2011), and similar studies are lacking for Chinese boreal forests. As expected, the relative contributions of environments to burn severity vary with ecosystems and regions (Alexander et al. 2006). Basically, the Chinese boreal forests are dominated by Dahurian larch (*Larix gmelini*) (Xu 1998), whereas the typical North American boreal forest is dominated by black spruce (*Picea mariana*) (Hoy et al. 2008; Barrett et al. 2010). Black spruces often grow low crown base height with branches growing to the ground, so ladder fuels are abundantly developed (Steve 2003). Thus, fires in North American boreal forests often burn with high intensity (e.g. crown fires) (Bessie & Johnson 1995; Schoennagel et al. 2004). However, Dahurian larches often prune their branches, so ladder fuels in Chinese boreal forests are not well developed (Xu 1998). Thus, fires in Chinese boreal forests often burn with low and moderate intensity surface fires and the probability of crown fire occurrence is low. About 80% fires occurred in the prevailing fire weather conditions in Chinese boreal forests (Fu et al. 2001; Xu & Qu 2009; Yu et al. 2009). Yu et al. (2009) showed that the correlations between fire regimes (e.g. occurrence and size) and weather factors (e.g. temperature and relative humidity) were significant ($p < 0.05$) based on historical fire and weather data from 1970 to 2006 in Chinese boreal

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forests. Thus, our study was limited to considering relationships of vegetation and topography with burn severity under the prevailing fire weather conditions.

Relationships of vegetation and topography with burn severity have been reported in many studies (Turner et al. 1999; Lee et al. 2008; Holden et al. 2009; Oliveras et al. 2009). These studies were generally conducted at a single analyzing resolution (grain size), such as one field plot sampling size or the pixel size of a remotely sensed image (e.g. 30 m resolution of Thematic Mapper [TM] image) (Key 2006; Duffy et al. 2007). However, multi-grain size analysis of relationships between environment and ecological processes is essential in fire science (Falk et al. 2007) because fire is a complex spatial process, driven by factors operating across a range of scales (Falk et al. 2011). For example, climate and weather operate at larger spatial scales than vegetation and topography (Falk et al. 2007). Multi-scale phenomena warrant investigation of the relationships between burn severity and environments under various grain sizes. This means that an environment–fire relationship observed at one grain size may not hold at another grain size (Parks et al. 2011). Therefore, studies analyzing a single grain size might not address changes in scale-dependent environment–fire relationships.

Strategic fire management relies on estimation of environment–fire relationships (McKenzie et al. 2000; Morgan et al. 2001; Barbour et al. 2005). A direct comparison between the impacts of different environmental factors, measured at different grain sizes, may fail to identify the most important environmental factors and consequently, limit the effects of management (Moreira et al. 2012). Moreover, understanding the grain size specific environment–fire relationships is important in spatially explicit fire prediction. Most fire simulators (computer programs that simulate fire behavior and effects) use fine scale data to derive baseline environment–fire relationships for predicting fire at coarse scales (McKenzie et al. 1996; Peterson & Schmoldt 2000; Sullivan 2009). However, McKenzie et al. (1996) found that using data derived at relatively small grain sizes to predict fire at much larger grain sizes can result in substantial errors because the simulated fires are sensitive to the spatial resolution at which the raw data are aggregated. Therefore, it is essential to combine multi-grain size data that accounts for environment–fire relationships to improve fire prediction accuracy.

The primary objective of our study was to test the hypothesis that relationships between vegetation and topography with burn severity vary across grain sizes. Specifically, we aimed to answer three questions: (1) Do correlations exist between vegetation and topography factors and burn severity at small grain sizes (fine resolutions)? (2) Whether the correlations at coarse resolutions are contradictory to those at the fine resolutions, and (3) Is there a grain size threshold that marks the transition of primary importance between vegetation and topography for controlling burn severities?

Materials and methods

Study area

The focus of this investigation is in the Huzhong Forest Bureau (hereafter referred to as HFB) located on the north side of the Great Xing'an Mountains, in northeastern China (52°25′00″ N, 122°39′30″ E to 51°14′40″ N, 124°21′00″ E). The study site covers 937,244 ha, ranging in elevation from 440 to 1500 m (Figure 1). The study area falls within the cool temperature zone affected by the Siberian cold air mass and has a typical terrestrial monsoon climate. Mean annual temperature is 4.7°C with a January mean minimum of −28.9°C and a July mean maximum of 17.1°C. Mean annual precipitation is 500 mm, where more than 60% of rainfall occurs between June and August. In the Chinese boreal forests, about 80% of fires historically occurred during the prevailing fire weather conditions in spring fire seasons from April to June (Table 1) (Wang & Zhang 1989; Fu et al. 2001; Yu et al. 2009):

Most of the HFB is forested, primarily with larch (*Larix gmelini*), pine *(Pinus sylvestris L. var. mongolica)*, spruce (*Picea koraiensis*), birch (*Betula platyphylla*), and two species of aspen (*Populus davidiana* and *Populus suaveolens*). With the exception of some portions of wetland near rivers, larch is widely distributed over 65% of the study site. Birch and pine are mixed with larch in most areas owing to fire disturbance and forest harvesting, with pine having a small area of distribution (1.8%). Aspen is confined to terraces along the rivers where water is plentiful. Spruce, being highly shade tolerant, occurs mostly in valleys and high elevation areas. Dwarf Siberian Pine (*Pinus pumila*) occurs mostly at elevations >800 m (Xu 1998). Birch is an early successional pioneer species. Spruces prefer cold and wet environment conditions. However, environmental conditions are general dry in our study area. Limited by the hydrothermal conditions, spruces are sporadically distributed in our study area (with small area). Larch outcompetes spruce to be the seral climax species since larch is drought tolerant (Zhou 1991).

Fire characteristics

We obtained a fire database from 1965 to 2005 in the study area developed by fire managers of the Great Xing'an Mountains Forest Bureau. The fire database contains fire origin location (recorded as x, y coordinates), size, cause, and date of occurrence and extinction. Three fire patches were mapped based on the fire database and post-fire Landsat TM images (Figure 1). To cover the area containing the three burned patches,
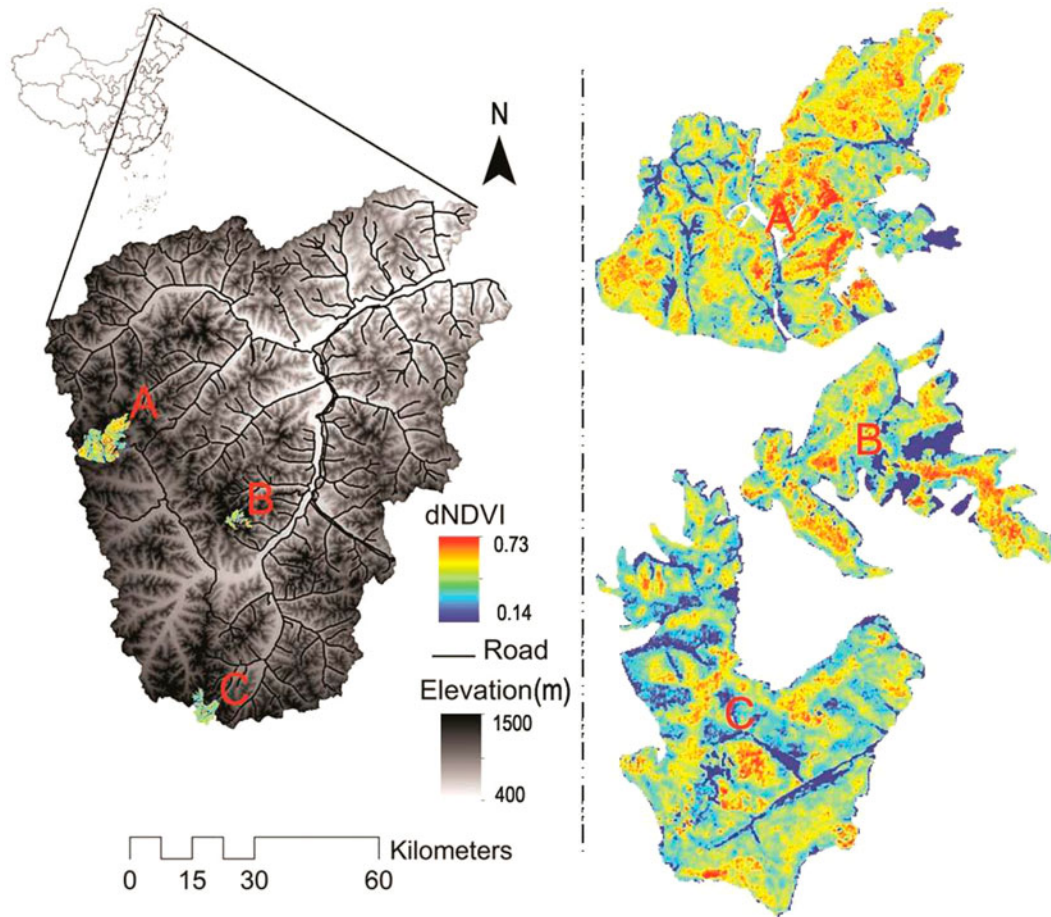
Figure 1. The geographic location of the study area and three fire patches overlaid on the digital elevation model.
Note: Letters (A, B, C) indicate the three fire patches.

two radiometrically and geometrically corrected and cloud-free Landsat TM images (path 121, row 024) were downloaded from the International Scientific Data Service Platform (http://datamirror.csdb.cn/index.jsp). The first image was pre-fire that occurred on 5 September 1999 and the second image was post-fire on 13 September 2002. The three fires mainly burned between 17 and 23 June 2000 were ignited by lighting and were constrained by suppression. The three fire patches burned a total area of 12586.1 ha and ranged in size from 1409.2 to 8226.8 ha with an average size of 4195.4 ha. The primary burnt vegetation type within the three fire patches was larch (*L. gmelini*).

All three fires reported in our study were under the similar climate and weather conditions, which are within the prevailing fire weather conditions in the Chinese boreal forest region (Table 1). Specifically, the maximum daily temperatures measured at the Huzhong weather station from 17 to 23 June 2000 ranged from 18.5°C to 33.4°C, with average maximum temperature of 28.5°C. Minimum temperatures ranged from 1.8°C to 10.4°C, with an average of 7.0°C. Maximum daily wind speeds ranged from 8.3 to 36 km/h, with an average maximum wind speed of 19.5 km/h. Average daily wind speed ranged from 3.6 to 9.0 km/h during the burning days.

Table 1. The prevailing fire weather conditions for the Chinese boreal forests.

Fire weather variable	Prevailing fire weather conditions	Average fire weather conditions in our study
Temperature (°C)	5–20	17.1
Relative humidity (%)	35–75	68.0
Precipitation (mm)	0–5	4.7
Wind speed (m/s)	1.5–6	1.7
Continuous no rainfall days	>10	14

Deriving historical burn severity map

In our study, burn severity was defined as the degree of vegetation change caused by fires (Lentile et al. 2006a). The burn severity map (Figure 1) was derived from calculating the difference between pre- and post-fire Normalized Difference Vegetation Index (dNDVI) of the two Landsat TM images (Epting et al. 2005).

The NDVI was calculated using the equation:

$$\frac{ETM4 - ETM7}{ETM4 + ETM7},$$

where ETM4 is the near-infrared band and TM7 is the visible red band. The dNDVI was computed as:

$$dNDVI = NDVI_{pre\text{-}fire} - NDVI_{post\text{-}fire}.$$

A greater dNDVI value equates to a more severe fire (Oliveras et al. 2009). ERDAS Imagine 9.3 software was used to perform all image processing.

Deriving vegetation and topography factors

Nine explanatory variables were used to assess the relationships of vegetation and topography with burn severity (Table 2). The variables examined are important and widely used in assessing the relative contributions of vegetation and topography to spatial variation of burn severity (Alexander et al. 2006; Lentile et al. 2006b; Oliveras et al. 2009). These vegetation variables are proxies for species developmental conditions, niche space, and structure and consequently influence burn severity. For example, tree high and understory cover can determine the vertical-continuity of fuels that consequently affecting the probability of a surface to move up to a severe crown fire. Topographic variables (e.g. elevation and aspect) strongly affect solar radiation which then controls the amount and moisture content of fuels to burn (Falk et al. 2011).

Vegetation variables ($n = 5$) were derived from the forest management and planning inventory (FMPI) database and include canopy cover (%), tree height (m), tree diameter (cm), stand age, and understory cover (%). In the FMPI database, canopy and understory cover are estimates percentages. Tree height (m) was measured as the average height of three dominant tree species at the specific sample site. Tree diameter at breast height (cm) was computed as the average diameter of each sample tree. Stand age was also measured as the average age of dominant trees.

Topographic variables ($n = 4$) were extracted from a digital elevation model (DEM) with 30 m spatial resolution and included elevation (m), slope (degree), aspect index, and topographic position index (TPI). The degree of slope values ranged from 0 to 90. Aspect was derived from the DEM and then converted into an aspect index using the following equation:

$$\text{Aspect index} = -\cos((h \times 2 \times PI)/360),$$

where θ is the aspect derived from the Arc/Info "aspect" function, which ranged from 0 to 360. The aspect index ranges from -1 to 1, with higher values indicating higher potential solar radiation. The TPI was derived in Arc/Info according to the Jeff Jenness algorithm that expresses whether a given cell is higher or lower than its neighbors (http://www.jennessent.com/downloads/TPI_Documentation_online.pdf). TPI is an index that expresses whether a given cell is higher or lower than its neighbors. Positive values of TPI represent cells that are higher than their surroundings, whereas negative values represent cells that are lower.

Grain sizes

Eight grain sizes were selected for the analysis: 30, 90, 150, 250, 500, 1000, 1500, and 2500 m, ranging from 0.09 ha to 625 ha in size. Grain sizes were selected based on the following three considerations: size of historic fires, spatial resolution of available data (TM satellite images and DEM), and the stand maps for fire management. According to the historic fire database, 131 fires occurred in the HFB from 1969 to 2005 and the fire sizes ranged from 0.7 to 8700 ha. The mean fire size was 280.2 ha, and 92% of these fires burned areas less than 500 ha. The finest grain size used matched the spatial resolution of the Landsat TM image and DEM (30 m). The scale of the stand map (source of vegetation variables) ranged from 0.1 to 122.4 ha in size, with an average of 20.9 ha. Therefore, the selected spatial grain sizes can cover the patterns of the historic fire size, DEM, TM image, and stand map.

The original maps of burn severity, vegetation, and topography variables were upscaled into the eight grain

Table 2. Descriptive statistics for the topography and vegetation variables of the three fire patches in the study area.

Variable	Unit	Mean ± standard deviation (SD), range
Burn severity (dependent)	–	0.49 ± 0.08, 0.14–0.73
Topography		
Elevation	m	1036.2 ± 94.4, 760.0–1345.8
Aspect	–	−0.1 ± 0.8, −1.0 to 1.0
Slope	degree	10.9 ± 9.0, 0.0–74.8
TPI	–	−0.1 ± 3.3, −68.5 to 110.8
Vegetation		
Stand age	year	117.6 ± 27.9, 25.0–203.0
Canopy cover	–	0.6 ± 0.1, 0.1–0.8
Tree diameter	cm	17.9 ± 3.9, 6.0–32.0
Tree height	m	15.9 ± 3.1, 4.0–25.0
Understory cover	%	49.0 ± 17.2, 1.0–95.0

sizes with the random rule-based aggregation method. The random rule-based aggregation is a standard geographic information system (GIS) data aggregation technique. It assigns the value for the output cell by randomly picking a value from the subset cells of the input grid. The method produces unbiased representations of map classes when scaling raster data from fine to coarse resolutions (He et al. 2002). It maintains spatial information more precisely than the ordinal aggregation method (e.g. blurring the raster data values into averages) (He et al. 2002).

Statistical analysis

All of the statistical analyses were conducted using R statistical software (Team 2009). Specifically, the statistical analyses were conducted to explore (1) the potential collinearity among vegetation and topography variables; (2) the correlation coefficients between burn severity and variables of vegetation and topography; (3) the linear relationships between burn severity and variables of vegetation and topography; and (4) the relative importance of vegetation and topography in determining burn severity.

To avoid the potential collinearity among vegetation and topography variables, Pearson's correlation matrices were constructed for all variables at each grain size to identify the coefficients of greatest correlation where $|r| > 0.8$. Variables that were highly correlated with each other and similarly correlated with burn severity were subsequently dropped. A correlation analysis was performed to explore the relationships between burn severity and individual variables of vegetation and topography using Pearson correlation matrices method.

Back stepwise multiple regressions were conducted to examine how the burn severity relates to variables of topography and vegetation. The best regression model was selected by the Akaike information criterion (AIC). This analysis was used to detect whether there is a stable linear relationship between burn severity and variables of topography and vegetation at the eight grain sizes ($p < 0.05$) (Lentile et al. 2006b; Lee et al. 2009).

The generalized additive model (GAM) with the "mgcv" package in R was used to detect the differences in determining burn severity that were explained by the topography group and vegetation group. We defined the data distribution as the "binomial" family, and set gamma = 1.5 to fit the GAM model. The relative importance of topography and vegetation was expressed by the deviance explained (DE).

The "lmg" metric in the "Relaimpo" package in *R* was used to assess the relative importance of each variable within vegetation (stand age, canopy cover, and understory cover) and topography (elevation, aspect, and slope) groups. The relative importance in the "Relaimpo" package was defined as the proportionate contribution each variable makes to the R^2, which considering both its direct effect and its effect when combined with the other variables in the regression equation.

Results

Collinearity diagnosis analysis of vegetation and topography variables

The collinearity diagnosis analysis showed that three vegetation variables (stand height, tree diameter, and stand age) were highly correlated (correlation coefficients $|r| > 0.80$) with each other. The stand age generally presented higher correlation with burn severity than that of stand height and tree diameter. Therefore, the stand height and tree diameter were dropped. There were no high correlations between topography variables (correlation coefficients $|r| < 0.4$); however, the TPI showed low correlation to burn severity at most grain sizes ($|r| < 0.05$). Therefore, only three vegetation variables (understory cover, stand age, and canopy cover) and three topography variables (elevation, aspect, and slope) were employed in the subsequent analysis.

Effects of grain size on the correlation of vegetation and topography variable to burn severity

The correlation analysis showed that variables of topography and vegetation correlated with burn severity and varied with grain sizes (Table 3). From the topography variables examined, elevation was generally negatively correlated to burn severity except at grain sizes of 500 and 1500 m. Aspect index was negatively correlated to burn severity at all grain sizes, and the correlation relationship was stronger with increasing grain sizes. Slope was positively correlated to burn severity except at grain size of 1000 m. The correlation relationship between slope and burn severity was generally stronger with increasing grain sizes.

For the vegetation variables examined, stand age and understory cover were generally negatively and positively correlated to burn severity, respectively, except at the 1000 m grain size. The correlation relationship between both stand age and understory cover and burn severity generally increased with increasing grain sizes. The correlation of canopy cover with burn severity fluctuated substantially, but generally there was a trend toward a stronger correlation relationship with burn severity with increasing grain sizes (Table 3).

Effects of grain size on the linear relationship of vegetation and topography variable with burn severity

The results of regression analysis showed that there was not a stable or significant linear relationship ($p > 0.05$) between the burn severity and six explanatory variables (Table 4). Generally, linear relationships between the burn

Table 3. Results of correlation analysis between the burn severity and variables of vegetation and topography at eight grain sizes.

Grain sizes (m)	Vegetation and topography variables					
	Elevation	Aspect index	Slope	Understory cover	Stand age	Canopy cover
30	−0.015**	−0.051**	0.013**	0.005	−0.055**	0.001
90	−0.007	−0.046**	0.028**	0.014	−0.059*	−0.007
150	−0.013	−0.045**	0.033**	0.017	−0.050**	0.004
250	−0.004	−0.036	0.022	0.024	−0.053*	−0.022
500	0.031	−0.048	0.052	0.055	−0.082	−0.004
1000	−0.169	−0.011	−0.041	−0.011	0.073	0.109
1500	0.068	−0.15	0.054	0.102	−0.059	0.103
2500	−0.04	−0.626**	0.324	−0.16	−0.382	0.045

Note: Asterisks indicate significant levels of correlations between vegetation and topography and burn severity.
*Statistical significance level at the $\alpha = 0.05$.
**Statistical significance level at the $\alpha = 0.01$.

severity and explanatory variables of topography and topography had smaller R^2 values and larger p values as grain size increased. These results (the values of R^2 presented in thousandths) suggest that the linear relationships between burn severity and variables are extreme weak (Table 4). This weak relationship was also observed by many previous studies while addressing the relationship between fire regimes (e.g. occurrence, burn severity, and probability) and potential influencing variables (Lee et al. 2009; Finney et al. 2011; Parks et al. 2012; Zumbrunnen et al. 2012).

Effects of grain size on the relative importance of vegetation and topography in determining burn severity

The GAM analysis showed that spatial variation in burn severity explained by the two variable groups (topography and vegetation) is dependent on the grain sizes considered (Figure 2). As grain sizes increased from 30 to 500 m, the variable group of vegetation explained a higher percentage of variation for burn severity than that of topography. As grain sizes increased from 1000 to 2500 m, variable groups for topography were more important in determining burn severity (Figure 2). The shared contributions (interaction effect) of topography and vegetation increased from 0.32 to 56.4% with increasing grain sizes.

We ranked quantitatively (%) the relative importance values of vegetation and topography factors in determining burn severity (Figures 3 and 4). The "Relaimpo" analysis showed that the relative importance of variables within the topography group was generally ranked in order of aspect, slope, and elevation with increasing grain size (Figure 3). Of the vegetation variables, the relative importance of variables varied with grain sizes (Figure 4). Stand age explained the most variation ($R^2 = 0.69$) at grain sizes ranging from 30 to 500 m. Understory cover was more important than canopy cover at grain sizes ranging from 30 to 500 m, but less important at grain sizes between 1000 and 2500 m.

Discussion
Scale effects of vegetation and topography on burn severity

The cross-grain sizes analysis result has demonstrated that when analyzing the relationships between burn severity and environments (vegetation and topography), one should keep in mind that the observed impact of a given predictor is affected by the grain size at which it was measured. In practical, there are diverse data sources of vegetation and topography exist for predicting burn severity (Morgan et al. 2001). Each data source with its

Table 4. Results of linear stepwise regression between the vegetation and topography variables and burn severity at eight grain sizes.

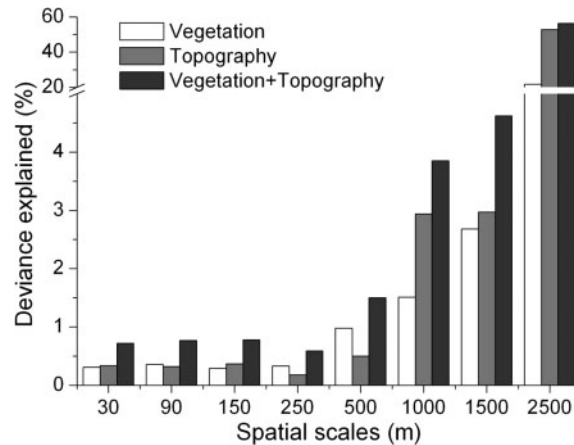| Grain size (m)	30		90		150		250		500		1000		1500		2500	
Variable	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p
Elevation	0.007	<0.01	0.007	<0.01	0.007	<0.05	–	–	–	–	–	–	–	–	–	–
Slope	0.006	<0.01	0.007	<0.01	0.006	<0.05	–	–	–	–	–	–	–	–	–	–
Aspect	0.006	<0.01	0.006	<0.01	0.005	<0.05	–	–	–	–	–	–	–	–	0.392	<0.01
Stand age	0.003	<0.01	0.003	<0.01	0.002	<0.01	0.03	<0.05	–	–	–	–	–	–	–	–
Canopy cover	0.007	<0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Understory cover	0.007	<0.01	0.008	<0.05	–	–	–	–	–	–	–	–	–	–	–	–

Figure 2. The unique and shared contributions (expressed as DE) of topography and vegetation at the eight spatial scales (grain sizes).

specific grain size that inputs to a fire simulation model has strengths and weaknesses for predicting burn severity (McKenzie et al. 1996, 2000). Generally, the grain size of environments inputs to a fire model should vary at stand (typically grain size of 5–30 m), landscape (typically grain size of 30–500 m), and regional (typically grain size of 500 m–5 km) levels (Keane et al. 2001, 2010). Our study showed that vegetation presented a stronger correlation to burn severity at grain sizes smaller than 500 m. This indicated that vegetation is more important than topography in predicting burn severity at the stand and landscape levels; topography is more important than vegetation at the regional level. Therefore, careful analysis of the environment–fire regime relationship from one grain size to another can be very important to improve the reliability of a burn severity prediction.

Our study illustrated that the selection of grain size can considerably influence the ability to explain variation of burn severity. The differences of the effects of vegetation and topography on burn severity may be due

to the differences in heterogeneity between these variables' spatial pattern as grain size changes (Figure 5). The heterogeneity in variables' spatial pattern across grain sizes in affecting fire regime was also observed in forest landscapes of Canada and the USA (Cyr et al. 2007; Parks et al. 2011). For example, Cyr et al. (2007) found that southwest and northeast aspects were correlated to fire frequency in a boreal forest of eastern Canada only when characterized within a neighborhood delimited by 4000 to 10,000 m radii (grain sizes). Our results can further support the findings in North American forest landscapes that relationships of environments (e.g. vegetation and topography) and fire regimes (e.g. burn severity) are grain size-dependent (Cyr et al. 2007; Falk et al. 2007; Parisien et al. 2011; Parks et al. 2011).

The results of regression analysis indicated that the relationships between burn severity and vegetation and topography were complex and nonlinear as grain size increases (especially when grain size >500 m) (Table 4). This finding in Chinese boreal forest is in agreement to results reported elsewhere (Lee et al. 2009; Finney et al.
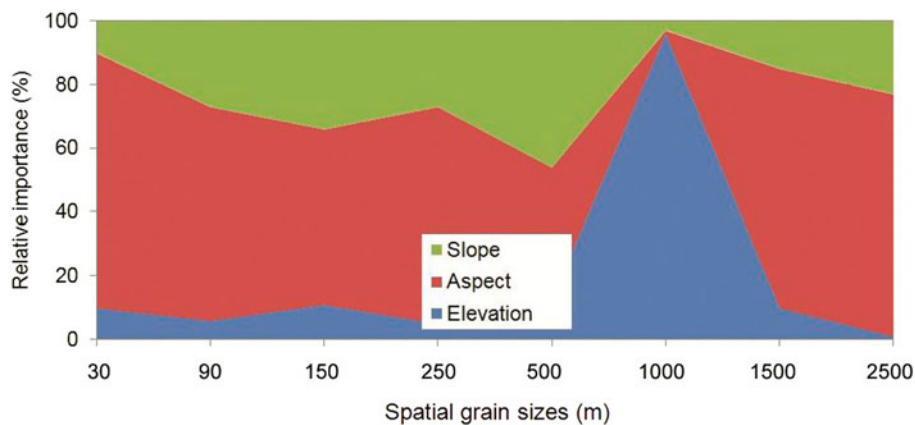

Figure 3. Relative importance of topography variables (elevation, aspect, and slope) in determining burn severity with increasing grain sizes.
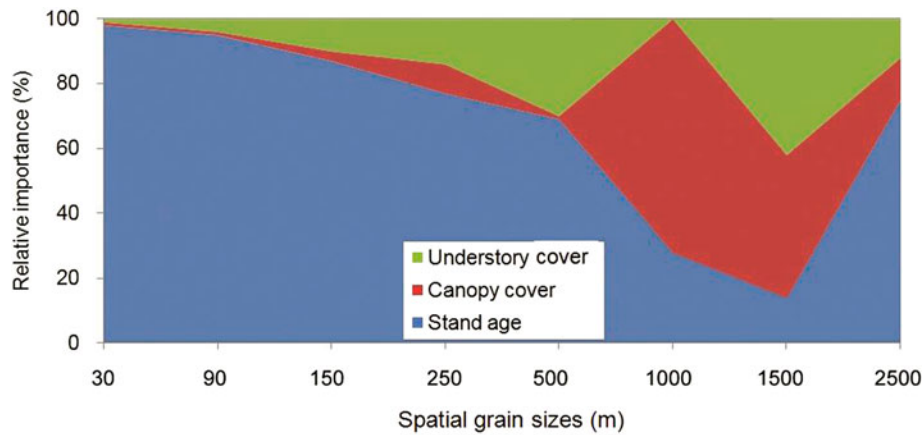
Figure 4. Relative importance of vegetation variables (stand age, canopy cover, and understory cover) in determining burn severity with increasing grain sizes.

2011; Parks et al. 2012; Zumbrunnen et al. 2012). Parks et al. (2012) found that the relationships between the spatial configurations of ignitions, fuels, and topography and burn probability were nonlinear in four fire-prone landscapes of western North America. The nonlinear relationships between burn severity and variables of vegetation and topography (Table 4) at grain sizes greater than 1000 m may be due to the dominate effects of other variables, such as weather conditions.

In our study, the variables of elevation, aspect, and stand age presented negative correlations to burn severity, which contradicted to the relationships reported in some previous studies. These negative relationships are localized to our study area, but do provide the causal effects to the burn severity to which other systems can reference. For the three fires examined in our study, forests change from relatively dense to open as elevation increases. Commonly, fires burn less severe as stand density decreases, resulting in the negative correlation between elevation and burn severity in our study.

Aspect was negatively correlated to burn severity at all grain sizes in our study. These results continue the debate from previous findings (Weatherspoon & Skinner 1995; Alexander et al. 2006; Oliveras et al. 2009). Oliveras et al. (2009) found that more severe fires occurred on south aspects in a Mediterranean basin landscape, whereas Rollins et al. (2002), Holden et al. (2009), and Thompson and Spies (2009) reported the opposite in some North American forest landscapes. In general in the northern hemisphere, south aspects receive more solar radiation than north aspects. Therefore, south aspects are hotter, drier, and have greater burn severity. Such conditions favor fire ignition and spread. However, in our study area, fire weather is general dry. The understory shrub layers of the *Ledum palustre* and *Vaccinium uliginosum* (up to 0.4 m) are better developed in north aspects than in south aspects because of the better water conditions in north aspects. Therefore,

surface fuel continuity is higher in north aspects than that in south aspects. Consequently, the north aspects have more severe fires, resulting in the negative correlation between aspect and burn severity.

Our study also found that young-aged stands presented high burn severities, which contradicted to the pattern observed in many other ecosystems (Lentile et al. 2006b; Keeley et al. 2008; Lee et al. 2008). Studies from other ecosystems suggested that stands with older ages had higher biomass accumulation and relatively lower decomposition of dead organic matters (Keeley et al. 2008), and consequently burned with greater severity fires. Generally, the young regeneration is less apt to burn because there is a lack of woody debris and other flammable materials in the understory. In our study, the three fires covered stands of larch (*L. gmelini*) and birch (*Betula platyphylla*). The birch dominated forests are younger (average age is 85) than larch dominated forests (average age is 120). In general, the larches are more fire resistant than birches. Consequently, the fires burned less severe in the larch dominated forests than that in the birch dominated forests. This led to the negative correlation between stand age and burn severity.

Implications for fire management

In general, our study can help managers to design fire management plans according to vegetation characteristics that are found important in affecting burn severity and prioritize management locations based on the relative importance of vegetation and topography factors (Alexander et al. 2006; Holden et al. 2009; Lee et al. 2009). For example, aspects present negative correlations to burn severity, suggesting that fuel treatments should focus on north aspects, particularly to reduce fuel continuity of the understory shrub layers of the *L. palustre* and *V. uliginosum*.
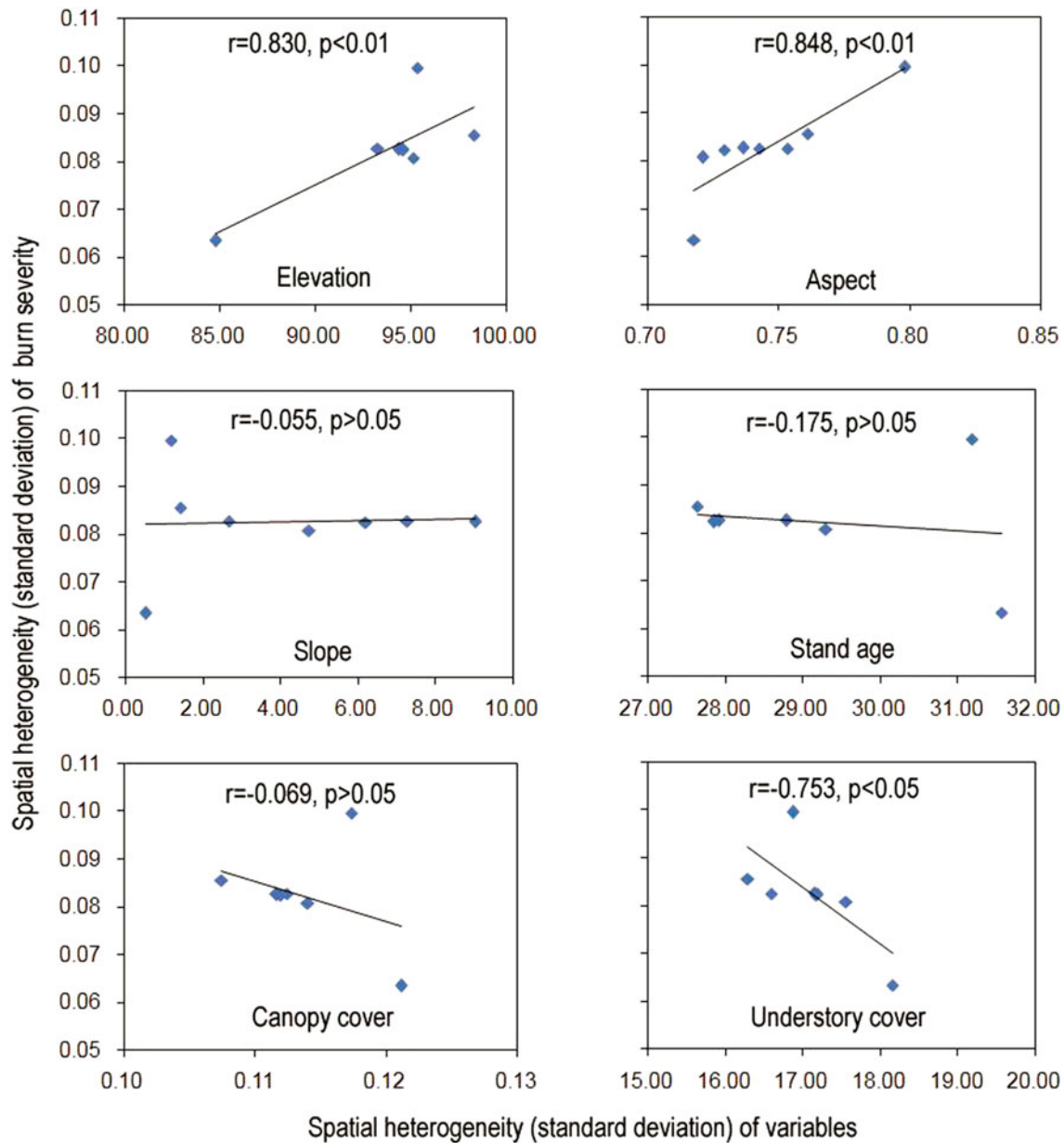
Figure 5. Correlation relationships of spatial heterogeneity between burn severity and explanatory variables of topography and vegetation.
Note: Standard deviation (SD) was used to evaluate the spatial heterogeneity of burn severity, topography, and vegetation variables.

Some limitations and future directions

Climate and weather operate at larger spatial scales than topography and vegetation. However, separating these effects requires spatially and temporally explicit real-time fire weather data. Unfortunately, such data were unavailable for our study, as they are for most other studies (Alexander et al. 2006; Lentile et al. 2006b; Lee et al. 2008). Because of this limitation, results from our study reflect currently prevailing fire weather conditions. Although the findings of our study may not reflect those occurring under extreme fire weather conditions (Wang et al. 1990), they do reflect the effects of vegetation and

topography on burn severity for the majority of fires (80%) in our region (Wang & Zhang 1989; Fu et al. 2001; Yu et al. 2009).

Surface fuel characteristics (e.g. fuel loadings and fuel moisture) not accounted for in our study may influence our ability to explain burn severity. Some studies showed that surface fuel characteristics are important in determining fire regimes (e.g. burn severity) in many forests (Cumming 2001; Sah et al. 2006; Safford et al. 2009). For example, Safford et al. (2009) found that the Angora fire in California burned at high severity (over 50% of the fire area burned at intensities

high enough to kill all or most canopy trees) was due to heavy fuel loadings.

In conclusion, this investigation emphasizes that vegetation has a stronger correlation to burn severity at grain sizes smaller than 500 m. Topography was more important at grain sizes larger than 1000 m. These results provide a necessary step toward a more clearly understanding effects of vegetation and topography on burn severity across a fire-prone forest landscape. It is important to note that the findings of our study should be carefully used when addressing potential relationships between burn severity and vegetation and topography in others forest landscapes or regions due to extreme variability. The value of our study, which was conducted in a boreal forest landscape of northern China, lies in the further provision of evidence that the relative importance of vegetation and topography in determining fire regimes (burn severity in our study) are grain size-dependent (Falk et al. 2007, 2011).

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