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Determining Relative Contributions of Vegetation and Topography to Burn Severity from LANDSAT Imagery

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Abstract Fire is a dominant process in boreal forest landscapes and creates a spatial patch mosaic with different burn severities and age classes. Quantifying effects of vegetation and topography on burn severity provides a scientific basis on which forest fire management plans are developed to reduce catastrophic fires. However, the relative contribution of vegetation and topography to burn severity is highly debated especially under extreme weather conditions. In this study, we hypothesized that relationships of vegetation and topography to burn severity vary with fire size. We examined this hypothesis in a boreal forest landscape of northeastern China by computing the burn severity of 24 fire patches as the difference between the pre- and post-fire Normalized Difference Vegetation Index obtained from two Landsat TM images. The vegetation and topography to burn severity relationships were evaluated at three fire-size levels of small (<100 ha, $n = 12$), moderate (100–1,000 ha, $n = 9$), and large (>1,000 ha, $n = 3$). Our results showed that vegetation and topography to burn severity relationships were fire-size-dependent. The burn severity of small fires was primary controlled by vegetation conditions (e.g., understory cover), and the burn severity of large fires was strongly influenced by topographic conditions (e.g., elevation). For moderate fires, the relationships were complex and indistinguishable. Our results also indicated that the pattern trends of relative importance for both vegetation and topography factors were not dependent on fire size. 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 · Vegetation · Topography · Fire size · NDVI · Fire management

Introduction

Fire is a dominant process in boreal forest landscapes and creates a spatial patch mosaic with different burn severities and age classes (Johnstone and Chapin 2006; Duffy and others 2007; Boelman and others 2011). There are various definitions of burn severity (Keeley 2009). In this study, burn severity was defined as the degree of forest canopy changes caused by a fire and was indicated through quantifying changes in post-fire forest canopy relative to pre-fire conditions (Hammill and Bradstock 2006; Lentile and others 2006a; Lee and others 2008; Oliveras and others 2009). Burn severity was measured by computing the difference between pre-and post-fire Normalized Difference Vegetation Index obtained from two Landsat TM images. Studies have shown that variations in patterns of burn

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severity across a forest landscape are generally attributed to variations in environmental factors of weather (e.g., moisture and wind speed), vegetation (e.g., fuel type, stand structure, and succession stage), and topography (e.g., elevation, aspect, and slope) (Alexander and others 2006; Lentile and others 2006b; Oliveras and others 2009; Podur and Martell 2009; Thompson and Spies 2009).

Effects of environmental factors on burn severity have been widely described as the first-order of climate or weather factors and the second-order of vegetation (fuel) and topography factors (Bessie and Johnson 1995; McKenzie and others 2004; Thompson and Spies 2009; Bradstock and others 2010). Climate or weather is difficult to manipulate and to reconstruct. Vegetation is the only factor that can be effectively managed. Topography, however, directly influences vegetation composition and fuel structure (Keane and others 2001), often accounting for where and why fires burn severely (Dillon and others 2011). Therefore, most studies have focused on quantifying influences of vegetation and topography on burn severity (Alexander and others 2006; Lentile and others 2006a; Lee and others 2008; Holden and others 2009).

However, the relative importance of vegetation and topography in determining burn severity is highly debated (Turner and Romme 1994; Keeley and Fotheringham 2001; Oliveras and others 2009). Some studies found that burn severity was dominantly affected by vegetation factors (Odion and others 2004; Schoennagel and others 2004). For example, burn severity of the 1988 Yellowstone fires was influenced by succession stage (especially old-growth forests with ages >300) and tree diameter, not by slope and aspect (Turner and others 1999). Vegetation characteristics such as tree size can affect the susceptibility of forest to fire damage. In contrast, other studies found that topography factors were primary determinants of burn severity (Dillon and others 2011). For example, aspect was significant in explaining burn severity in the Klamath-Siskiyou region of Oregon and California in USA (Alexander and others 2006), where south aspects receive higher solar radiation (resulting in drier conditions), which can lead to burn with more severe fires than those on north aspects (Taylor and Skinner 2003; Alexander and others 2006).

Studies have shown that relationships between fire regimes (e.g., burn severity, frequency, and area burned) and factors of vegetation and topography observed at a small fire scale may not hold at a large fire scale (Ricotta and others 2001; Boer and others 2008; Oliveras and others 2009; Parisien and others 2011). For relatively small fires, fuel load, tree size, succession stage, and horizontal–vertical fuel continuity determine when and where fires occur and spread, and subsequently burn severity (Odion and others 2004). For relatively large fires, topography factors (e.g., aspect) and spatial arrangement of forest lands exert strong influences (Cumming 2001). However, most of these conclusions are derived from studies with a fire event or at a single spatial scale (e.g., fire size) and thus may fail to quantify the continuous transition of vegetation and topography factors in determining burn severities across fire sizes.

Moreover, the relative contribution of vegetation and topography to burn severity varies with ecosystems (Alexander and others 2006; Cyr and others 2007). At present, most of studies concerning this relationship are conducted in North American boreal forests (Krawchuk and others 2006; Cyr and others 2007), and similar studies are lacking for Chinese boreal forests. Basically, the Chinese boreal forests are dominated by Dahurian larches (*Larix gmelini*) (Xu 1998), whereas the typical North American boreal forest are dominated by spruce forests such as black spruce (*Picea mariana*) (Hoy and others 2008; Barrett and others 2010). The Dahurian larches often prune their branches, so ladder fuels in Chinese boreal forests are not well developed (Xu 1998). However, the black spruces often grow low crown base height with branches growing to the ground, so ladder fuels are abundantly developed (Steve 2003). Climate is usually considered as the dominate factor of fire regimes in boreal forests. This is widely reported from studies in North American boreal forests, which often burn with high intensity fires (e.g., crown fires) (Bessie and Johnson 1995; Schoennagel and others 2004). However, fires in Chinese boreal forests are characterized with low and moderate intensity surface fires (Liu and others 2012), in which vegetation and topography are more influential than those under climate-driven crown fire conditions. Therefore, we focused our study on the relative importance of vegetation and topography in determining burn severity. The relationships between burn severity and vegetation and topography derived in our study can provide a reference to studies in other similar regions. Managers can 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.

Historically, fires in the Chinese boreal forests were characterized by frequent, low intensity surface fires mixed with sparse, stand-replacing fires on relatively small areas. However, fires that occur in Chinese boreal forests are often more severe and intensity than fires that occurred before the 1950s (Xu and others 1997; Tian and others 2005; Chang and others 2007). For example, on 6 May 1987, a catastrophic fire occurred in this region burned 1.3×10^6 ha, which had drastic effects on the forest and environment (Xiao and others 1988; Cahoon and others 1994; Xu and others 1997; Wang and others 2007). However, the relative importance of vegetation and topography

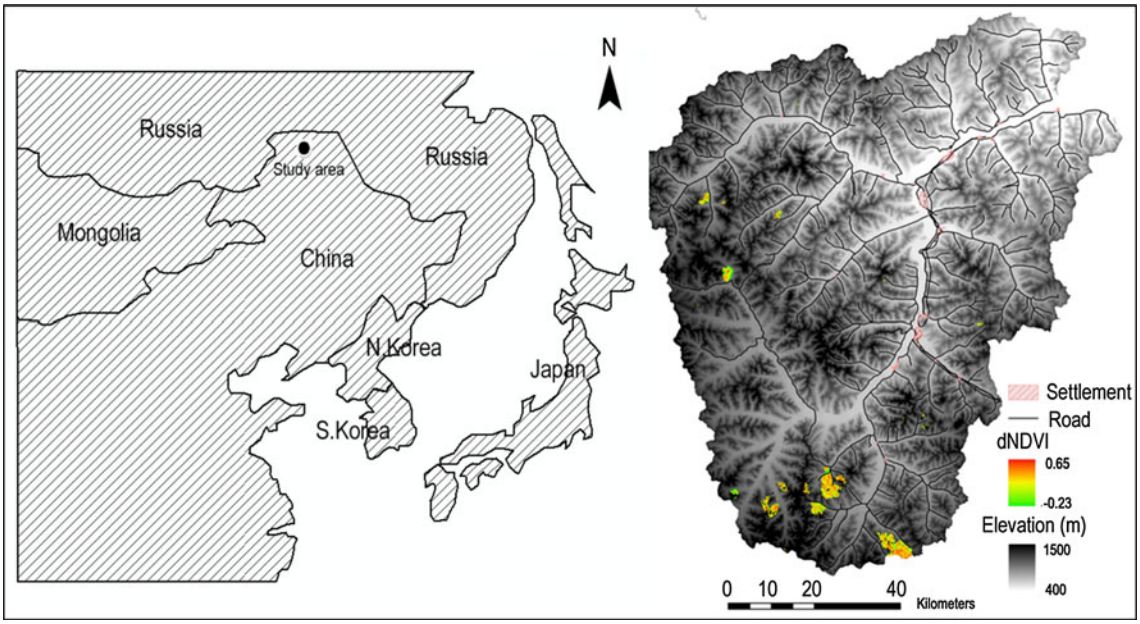

Fig. 1 The geographic location of the study area and locations of 24 fire patches in 2010 overlaid on a digital elevation model of the Huzhong Forest Bureau

remains poorly understood in this region. As climate has become warmer and drier in recent decades, understanding how and why fires burn more severely has become a major concern in fire management of this region.

The objective of this study was to improve our understanding of the relative importance of vegetation and topography in determining burn severity using pre- and post-fire NDVI from 24 fire patches in northeastern China. The following questions were addressed: (1) What is the relative importance of vegetation and topography factors in determining burn severity? (2) Do these patterns of relative importance differ among small (<100 ha), moderate (100–1,000 ha), and large fires (>1,000 ha)? (3) If so, then how do the relative importance patterns transition across fire sizes? We hypothesized that relationships of vegetation and topography to burn severity vary with fire size. This knowledge is essential for fire managers to effectively allocate resources among various terrains or forests to mediate the effects of high severity fires (Epting and others 2005; Duffy and others 2007).

Materials and Methods

Study Area

The study area, the Huzhong Forest Bureau, is 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). It covers 937,244 ha, ranging in elevations from 440 to 1,500 m (Fig. 1). Climatically, the study area falls within the cool temperature zone, which is affected by the Siberian cold air mass and has a typical terrestrial monsoon climate. Mean annual temperature for the study area 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 about 500 mm, of which more than 60 % occurs between June and August.

Most of the study area is forested. The primarily trees are 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*). Birch is an early successional pioneer species, and larch is a late climax species in this region. With the exception of wetlands near rivers, larch is widely distributed over 65 % of the study area. Birch and pine are mixed with larch in most areas owing to fire disturbance and timber harvesting. Pine covers only 1.8 % of the area. Aspen is confined to terraces along the rivers where water is plentiful. Spruce occurs mostly in valleys and high elevation areas, and dwarf Siberian Pine (*Pinus pumila*) occurs mostly in elevations >800 m (Xu 1998) (Fig. 2).

The primary carrier of wildfire for the broadleaf forests (birch and aspen) is broadleaf litter and herbaceous plants, which produce the least severe fires (Wu and others 2011). Nevertheless, under high wind speed conditions, fire spread rates can be high in broadleaf forests when fueled by high accumulation of leaf mass (Anderson 1982). The primary carrier of wildfire for the coniferous forests (larch, pine,

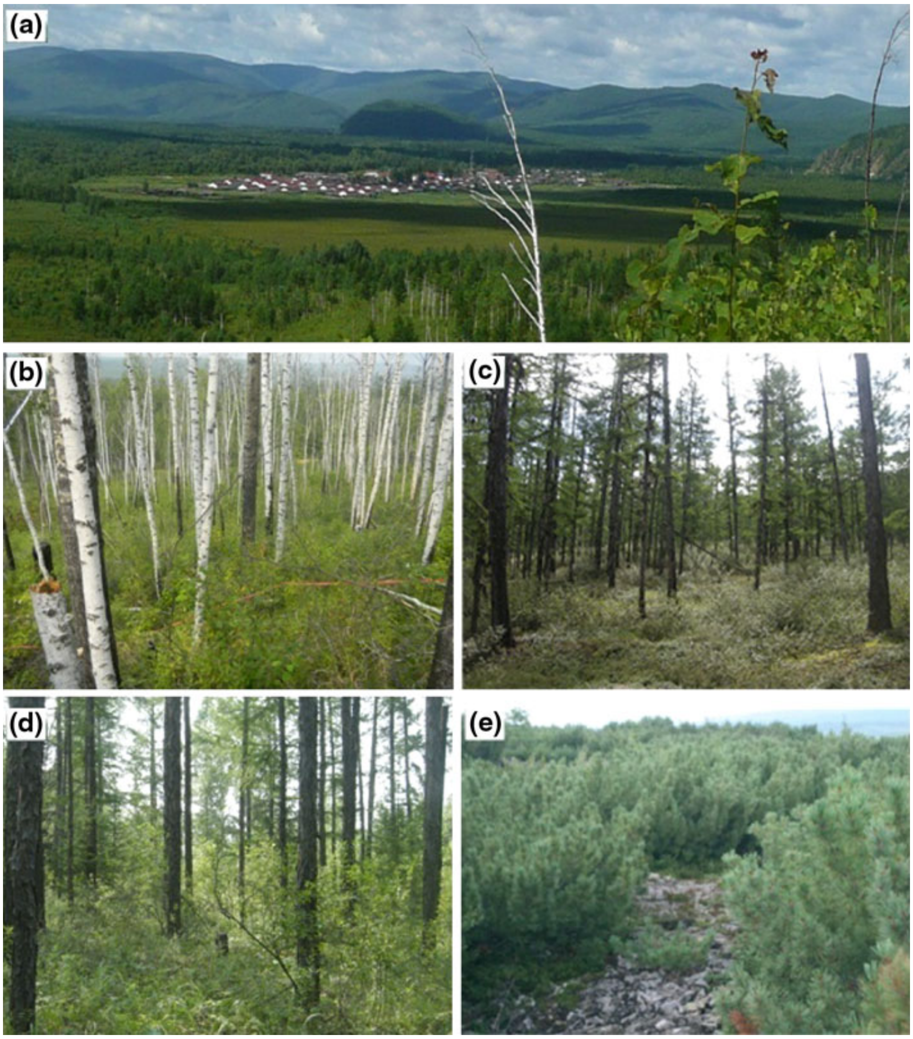

Fig. 2 Example photos of **a** landscape characteristics of the study area, **b** fuel characteristics on the hills or lower mountains, **c** fuel characteristics on the north aspect, **d** fuel characteristics on the south aspect, and **e** fuel characteristics on the ridge top

and spruce) is coniferous litter interspersed with grass and shrubs. Although these typically produce surface fires, under drought conditions they may cause crown fires and spot fires that sometimes torch individual trees (Shu and others 2003; Wang and others 2004). The primary carriers of wildfire for the shrublands of dwarf Siberian pine (*P. pumila*) are live and dead shrub twigs and foliage in combination with dead and down shrub litter. The influence of this fine fuel depends largely on its moisture content. These shrublands usually do not produce crown fires because of absence of a tree layer sufficient to carry one (Wu and others 2011, 2013).

Fire Characteristics

We selected 24 fire patches that burned in 2010 to study the relative contributions of vegetation and topography to burn severity (Fig. 1). The fire patches occurred simultaneously on June 26 and June 28, 2010 and continued to burn for 8 days from 26 June to 3 July in 2010 according to the Chinese governmental report (http://www.slfh.gov.cn). The fires were ignited by lightning and were suppressed by the combination of creating fire breaks through removing unburned trees and direct suppression. The 24 fire patches burned a total area of 9,021.9 ha, with patches ranging from 3.6 to 2,486.0 ha with an average size of 375.9 ha. We classified the fire patches into three fire size classes: small (<100 ha, $n = 12$), moderate (100–1,000 ha, $n = 9$), and large fires (>1,000 ha, $n = 3$). The criteria for classifying fire size were based on the “Regulations for forest fire prevention” (2008) in China (http://www.gov.cn/gongbao/content/2008/content_1175820.htm). The criterion was designed based on the area of damaged forests, number of deaths, and number of serious injuries (Table 1).

There were 7 consecutive days with no precipitation before the fires started. The days during the fires were characterized by extremely high temperature and no precipitation. Maximum daily air temperatures were 27–38 °C, with an average maximum temperature of 33.2 °C. Minimum daily temperatures were 15–19 °C, with average minimum temperatures of 16.4 °C. Wind speeds were 16–20 km/h, with an average wind speed of 17 km/h during the burning days.

Table 1 The criterion that used to define fire size class according to the "Regulations for forest fire prevention" (2008) in China

Fire categorized in this study	Area of damaged forests	Number of deaths	Number of seriously injuries	Classification of fire
Small fire	Less than 1 ha	1–3	1–10	Warning fire
	1–100 ha	3–10	10–50	Small fire
Moderate fire	100–1,000 ha	10–30	50–100	Big fire
Large fire	1,000 ha or larger	30 or more	100 or more	Huge fire

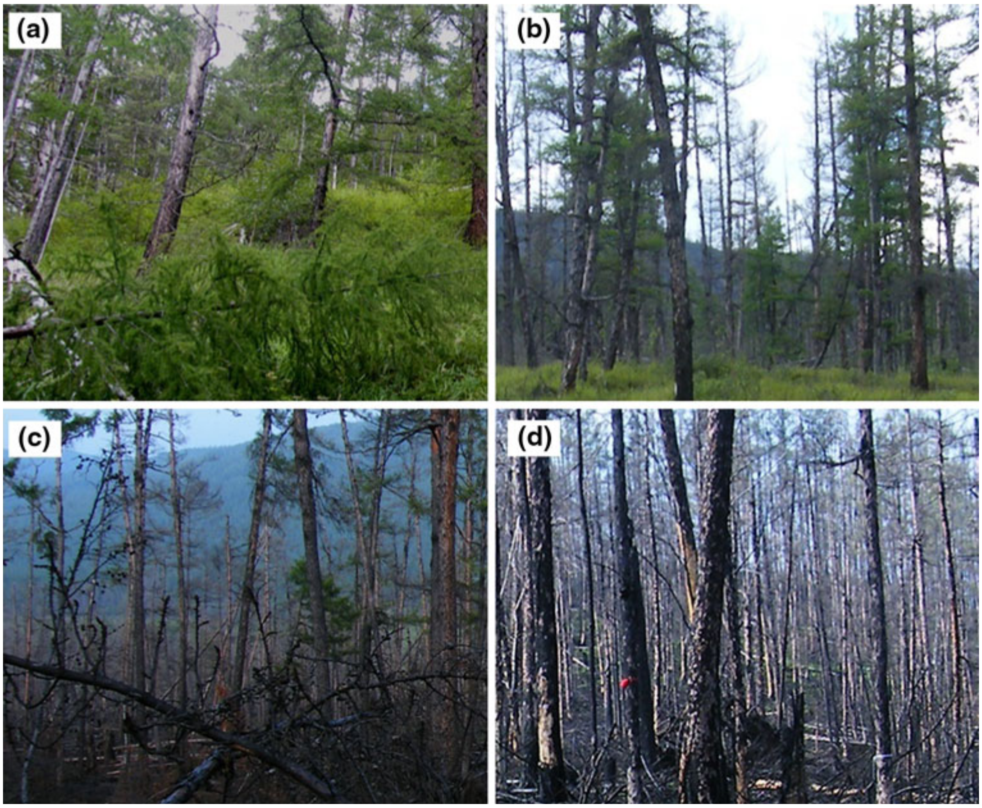

Fig. 3 Example photos of forests after the 2010 fires: **a** unburned, **b** low severity, **c** moderate severity, and **d** high severity

The fires burned with mixed of ground, surface, and crown fires (Fig. 3). The average length of fire fronts reached approximately 3 m, with highest length of 10 m according to visual estimations of local fire fighters on site. The amount of estimated carbon emissions from all fires was approximately 10.04 t/ha (Hu and others 2012). The fuel loadings and carbon emissions of each fuel category (e.g., tree, shrub, herb, litter, duff, and coarse woody debris) under different fire intensities are presented in Table 2.

Burn Severity Map

The difference Normalized Burn Ratio (dNBR) and the differenced Normalized Difference Vegetation Index (dNDVI) are widely used to map burn severity (Epting and others 2005; Lee and others 2008; Miller and others 2009; Oliveras and others 2009). In this study, we conducted correlation analysis of dNBR and dNDVI to vegetation and topography factors through analyzing the 24 fire patches. We found that dNDVI generally correlated more strongly than dNBR. Moreover, previous studies conducted in or nearby our study area showed that NDVI had good correlations to burn severity (Tian and others 2009; Feng 2012) and post-fire vegetation recovery (Xie and others 2005). For example, Feng (2012) found there was a significant correlation between NDVI and burn severity ($R^2 = 0.6, p < 0.0001$). Tian and others (2009) used NDVI to classify burn severities and found the classification accuracy was 94 %. Xie and others (2005) used NDVI to analyze relationship between forest restoration and burn severity and found that the relationship between vegetation restoration and burn severity was strong. Therefore, our burn severity was assessed based on the dNDVI between the images before and after fires (Fig. 1).

Table 2 Fuel loadings and carbon emissions of each fuel category (tree, shrub, herb, litter, duff, and coarse woody debris)

Fuel category	Fuel loading per unit (t/ha)	Fire intensity	Carbon emissions (t)
Tree	404.8	Low	5,230.7
		Moderate	12,828.7
		High	17,192.2
Shrub	45.0	Low	201.4
		Moderate	1,183.5
		High	13,671.6
Herb	5.6	Low	585.1
		Moderate	1,086.6
		High	1,936.9
Litter	57.4	Low	3,126.5
		Moderate	7,639.4
		High	18,684.2
Duff	82.8	Low	1,203.4
		Moderate	4,353.3
		High	18,253.8
Coarse woody debris	76.3	Low	1,033.6
		Moderate	2,862.0
		High	6,798.8
Total	671.9	–	117,870.62

The information in this table was compiled from Hu and others (2012) conducted in the Huzhong Forest Bureau after the 2010 fire

Notes (1) low fire intensity: less than 30 % canopy trees were killed; char height was less than 2 m; less than 50 % shrubs were killed; less than 50 % litter and duff were consumed. (2) Moderate fire intensity: 30–70 % canopy trees were killed; char height was 2–5 m; more than 50 % shrubs were killed; more than 50 % litter and duff were consumed. (3) High fire intensity: more than 70 % canopy trees were killed; char height was more than 5 m; all of the litter and duff was consumed

Two geometrically corrected and cloud-free Landsat TM images on the path 121-024 covering the burned area were used: one pre-fire image from 19 September 2007 and another post-fire image from 11 September 2010. The NDVI was calculated using the equation:

$$(\mathrm{TM4} - \mathrm{TM7})/(\mathrm{TM4} + \mathrm{TM7}),$$

where TM4 is the near-infrared band and TM7 is the visible red band. The dNDVI was computed as:

$$\mathrm{dNDVI} = \mathrm{NDVI}_{\mathrm{pre-fire}} - \mathrm{NDVI}_{\mathrm{post-fire}},$$

Higher dNDVI values correspond to higher burn severity. The ERDAS Imagine 9.3 software was used to perform all image processing.

Vegetation and Topography Factors

We used nine variables to assess the relative importance of vegetation and topography factors in determining burn severity (Table 3). Vegetation variables ($n = 5$), including canopy cover (%), tree height (m), tree diameter (cm), stand age (year), and understory cover (%), were derived from a forest management planning inventory (FMPI) database in 2000. In the FMPI database, the canopy cover and understory cover were estimates of the percentage of tree canopy and understory cover. Tree height (m) was measured as average heights of three dominant tree species. Tree diameter at breast height (cm) was computed as average diameter of each sample trees. Stand age was also measured as average age of dominant trees. The five vegetation variables are proxies for development conditions (e.g., stand age and tree diameter) and structure (e.g., canopy cover, tree height, and understory cover) of vegetation. Previous studies have shown that these five vegetation variables can affect burn severity greatly (Alexander and others 2006; Lentile and others 2006a; Oliveras and others 2009). For example, tree height and

Table 3 Descriptive statistics for vegetation and topography factors under small (<100 ha), moderate (100–1,000 ha), and large fires (>1,000 ha) in 2010

Factors	Small fires (<100 ha, $n = 12$)		Moderate fires (100–1,000 ha, $n = 9$)		Large fires (>1,000 ha, $n = 3$)	
	Mean	SD	Mean	SD	Mean	SD
Canopy cover (%)	43.2	11.6	52.1	10.5	47.8	9.8
Tree diameter (cm)	14.2	3.0	15.0	4.0	15.4	3.6
Tree height (m)	13.9	2.3	14.3	3.0	13.6	2.6
Understory cover (%)	53.7	21.2	50.8	22.1	51.1	16.8
Stand age	97.5	39.1	112.4	33.1	115.8	37.1
Elevation (m)	1,015.0	108.4	1,011.7	94.8	1,027.2	92.9
Slope (%)	14.5	7.4	12.8	7.4	14.1	7.7
Aspect index	−0.4	0.6	−0.2	0.7	−0.2	0.7
Topographic position index	0.3	1.3	0.1	1.3	0.0	1.6

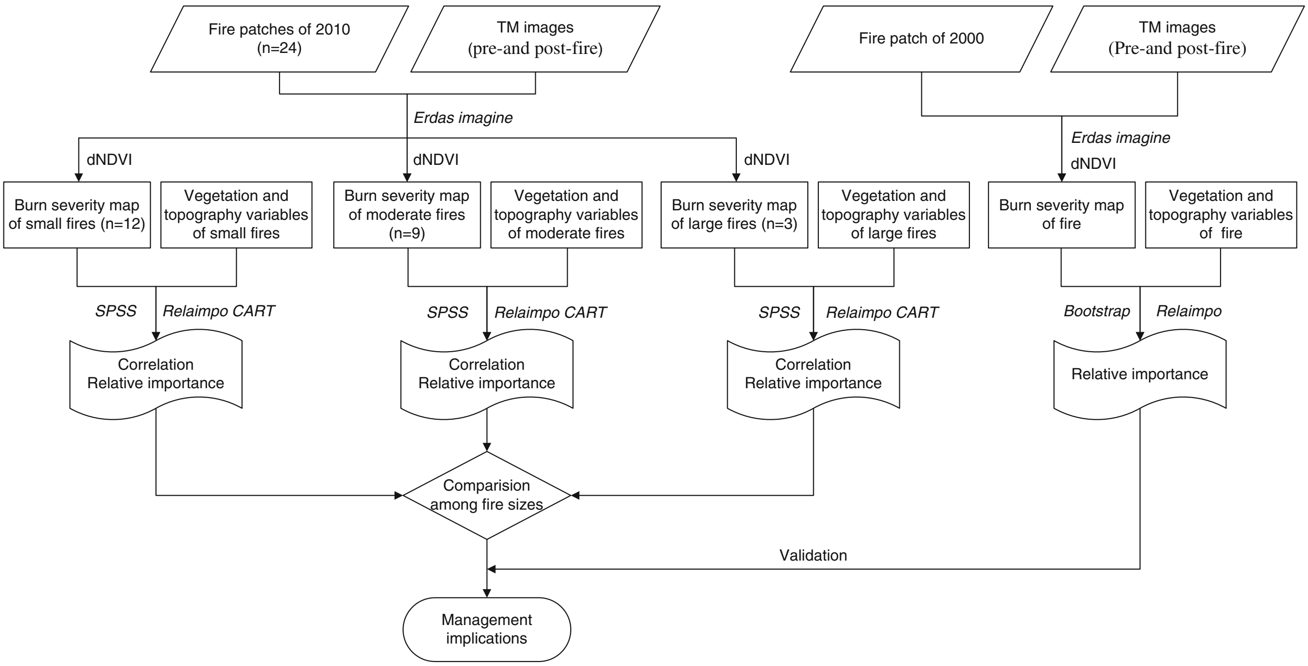

Fig. 4 The steps used to compare the relative contribution of vegetation and topography to burn severity among fire sizes

understory cover can determine vertical continuity of fuels that consequently affect the probability of a surface fire to transition to a crown fire.

Topography factors ($n = 4$), including elevation (m), slope (degree), aspect, and topographic position index (TPI), were extracted from a Digital Elevation Model (DEM) with 30 m spatial resolution. The degree of slope was ranged from 0 to 90. The aspect was converted into an aspect index using formula:

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

where θ was the aspect derived from the ArcGIS "aspect" function, which ranged from 0 to 360. The aspect index ranged from -1 to 1, with higher value indicating higher potential solar radiation. The TPI was derived by ArcGIS 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). Positive values of TPI represent the cells that are higher than their surroundings, while negative values represent cells that are lower. The four topography variables mainly affect moisture content of fuels and spread pattern of a fire (Falk and others 2011). For example, the elevation and aspect strongly affect solar radiation which controls the amount and moisture content of fuels to burn. The slope and topographic position mainly affect the spread rate and direction of a fire. In this study, the only categorical variable, aspect was converted into a continuous index, ranging from -1 to 1.

Statistical Analysis

Statistical analyses were performed using R and SPSS statistical software. There were number of 2,616, 28,944, and 53,215 samples (occurred in forested land) used to conduct the statistical analysis for small, moderate, and large fires, respectively. Steps used to explore the burn severity and vegetation and topography relationships among fire sizes were illustrated in Fig. 4.

The Duncan test with the "laercio" package in R was used to examine differences of burn severity among small, moderate, and large fires. The Duncan multiple comparison test can effectively identify significant differences among multiple treatments and was often used to determine whether three or more means differ significantly in an analysis of burn severity (Lee and others 2008).

The Pearson correlation coefficient matrix in SPSS was used to determine the correlation between individual vegetation and topography factor and burn severity (Lee and others 2009). The stepwise linear regression in SPSS was used to examine how the burn severity relates to topography and vegetation factors. This analysis was used to detect whether there is a linear relationship between burn severity and factors of topography and vegetation ($p < 0.05$). These two statistics methods are effective in deriving relationships between variables and also widely used to analyze relationships between burn severity and environment factors (Lee and others 2009).

The “lmg” metric in the “Relaimpo” package in R was used to assess the relative importance of vegetation and topography factors. The relative importance of factors 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. Considering the samples used in the analysis may not be independent spatially, that is spatial autocorrelation problem may present in the dataset. Therefore, to avoid effects of autocorrelation in the dataset, we further used the classification and regression tree (CART) to quantify the relative importance of vegetation and topography factors in determining burn severity and partition distributions of burn severity response to factors (Lentile and others 2006a; Lee and others 2009). The CART is non-parametric and allows spatially autocorrelated data (Calbk and others 2002; Collins and others 2007). The CART tree was constructed with the “rpart” package in R. We used the tenfold cross-validation method to prune trees and then derived the smallest trees using an error was within 1 standard error of the minimum error.

Validation Relative Importance Patterns of Vegetation and Topography Factors

We used a fire patch (2,950.1 ha) burned in 2000 (between 17 and 23 June 2000) of our study area to test the relative importance patterns of vegetation and topography derived from the fire patches burned in 2010. The burn severity map of 2000 was derived by calculating the difference between pre- and post-fire Normalized Difference Vegetation Index (dNDVI) of two Landsat Thematic Mapper images (5 September 1999 and 13 September 2002). The vegetation factors (canopy cover, tree height, tree diameter, stand age, and understory cover) were derived from the FMPI database of 1990. The topography factors (elevation, slope, aspect, and topographic position index) were also extracted from the Digital Elevation Model (DEM) with 30 m spatial resolution.

The “lmg” metric in the “Relaimpo” package in R was also used to assess the relative importance of vegetation and topography factors. The bootstrap resampling method, bootstrapping regression model, was employed while conducting the relative importance analysis. Bootstrapping in the “Relaimpo” package was done using the “boot.relimp” function with 1,000 bootstrap replications.

Results

Variation of Burn Severities Among Fire Sizes

Burn severities (characterized by dNDVI) in our study area ranged from −0.1 to 0.57 (mean = 0.22), −0.23 to 0.63 (mean = 0.25), and −0.19 to 0.65 (mean = 0.32) for small, moderate, and large fires, respectively. The burn severities varied significantly among fire size and generally increased with fire size (Fig. 5). The spatial variation of burn severity was ranked in the order of small (CV = 0.77), moderate (CV = 0.68), and large (CV = 0.49) fires.

Relationships Between Vegetation and Topography Factors and Burn Severities Among Fire Sizes

Correlations between vegetation and topography factors and burn severities presented relatively similar patterns among small, moderate, and large fires (Table 4). According to linear regression analysis results, relationships between burn severity and factors were linear ($p < 0.05$) except for canopy cover and tree diameter ($p > 0.05$) for large fires (Table 4). However, it is important to note that the linear relationships between burn severity and vegetation and topography factors are weak. This weak relationship was also reported by previous studies (Lee and others 2009; Finney and others 2011; Parks and others 2012; Zumbrunnen and others 2012). This indicates that relationships between burn severity and vegetation and topography factors were complex and a single factor may not be enough in explaining burn severity.

Of the topography factors that were examined, elevation and topographic position index were positively corrected with burn severity, and aspect index was negatively correlated with burn severity. Relationships between factors of elevation, topographic position index, and burn severity increased with increasing fire size. The relationship between aspect and burn severity decreased with increasing fire size. The slope was significantly negatively correlated with burn severity. The relationship between slope and burn severity

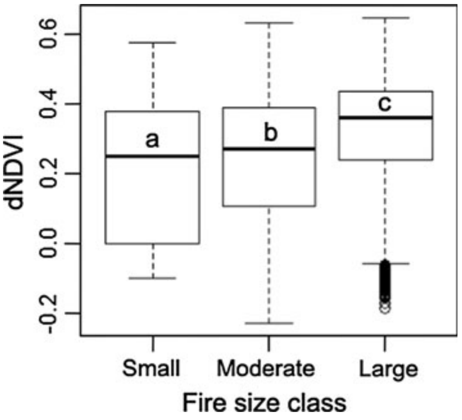

Fig. 5 Burn severities (dNDVI) for small (<100 ha, $n = 12$), moderate (100–1,000 ha, $n = 9$), and large (>1,000 ha, $n = 3$) fires in 2010. *Letters* (*a*, *b*, and *c*) indicate the significance difference ($\alpha = 0.05$) among fire sizes

Table 4 The relationships between burn severity and vegetation and topography factors of fires in 2010

Factors	Small fires (<100 ha, $n = 12$)		Moderate fires (100–1,000 ha, $n = 9$)		Large fires (>1,000 ha, $n = 3$)	
	Correlation	Regression model	Correlation	Regression model	Correlation	Regression model
Canopy cover (%)	$r = -0.09$	$y = 0.338–0.001x^{a}$	$r = -0.05$	$y = 0.328–0.001x^{a}$	$r = -0.003$	$y = 0.347–0.0001x^{a}$
	$p < 0.001$	$R^2 = 0.07, p < 0.001$	$p < 0.001$	$R^2 = 0.02, p < 0.001$	$p > 0.05$	$R^2 = 0.001, p = 0.524$
Tree diameter (cm)	$r = 0.14$	$y = 0.203 + 0.006x^{b}$	$r = -0.08$	$y = 0.335–0.003x^{b}$	$r = 0.002$	$y = 0.344 + 0.0001x^{b}$
	$p < 0.001$	$R^2 = 0.20, p < 0.001$	$p < 0.001$	$R^2 = 0.06, p < 0.001$	$p > 0.05$	$R^2 = 0.001, p = 0.622$
Tree height (m)	$r = 0.05$	$y = 0.255 + 0.003x^{c}$	$r = -0.06$	$y = 0.331–0.003x^{c}$	$r = -0.04$	$y = 0.371–0.002x^{c}$
	$p = 0.05$	$R^2 = 0.002, p < 0.001$	$p = 0.05$	$R^2 = 0.03, p < 0.001$	$p < 0.001$	$R^2 = 0.002, p < 0.001$
Understory cover (%)	$r = 0.31$	$y = 0.190 + 0.002x^{d}$	$r = 0.24$	$y = 0.212 + 0.002x^{d}$	$r = 0.20$	$y = 0.268 + 0.002x^{d}$
	$p < 0.001$	$R^2 = 0.093, p < 0.001$	$p < 0.001$	$R^2 = 0.057, p < 0.001$	$p < 0.001$	$R^2 = 0.037, p < 0.001$
Stand age	$r = 0.19$	$y = 0.229 + 0.001x^{e}$	$r = 0.16$	$y = 0.214 + 0.001x^{e}$	$r = 0.10$	$y = 0.304 + 0.0001x^{e}$
	$p < 0.001$	$R^2 = 0.037, p < 0.001$	$p < 0.001$	$R^2 = 0.024, p < 0.001$	$p < 0.001$	$R^2 = 0.010, p < 0.001$
Elevation (m)	$r = 0.31$	$y = -0.91 + 0.00001x^{f}$	$r = 0.26$	$y = -0.116 + 0.0001x^{f}$	$r = 0.34$	$y = -0.150 + 0.0001x^{f}$
	$p < 0.001$	$R^2 = 0.092, p < 0.01$	$p < 0.001$	$R^2 = 0.068, p < 0.001$	$p < 0.001$	$R^2 = 0.115, p < 0.001$
Slope (%)	$r = -0.04$	$y = 0.305–0.001x^{g}$	$r = -0.26$	$y = 0.299–0.001x^{g}$	$r = -0.04$	$y = 0.353–0.001x^{g}$
	$p = 0.05$	$R^2 = 0.001, p = 0.05$	$p < 0.001$	$R^2 = 0.001, p < 0.001$	$p < 0.001$	$R^2 = 0.001, p < 0.001$
Aspect index	$r = -0.23$	$y = 0.276–0.054x^{h}$	$r = -0.11$	$y = 0.286–0.025x^{h}$	$r = -0.02$	$y = 0.344–0.004x^{h}$
	$p < 0.001$	$R^2 = 0.054, p < 0.001$	$p < 0.001$	$R^2 = 0.012, p < 0.001$	$p < 0.001$	$R^2 = 0.001, p < 0.001$
Topographic position index	$r = 0.13$	$y = 0.290 + 0.014x^{i}$	$r = 0.14$	$y = 0.291 + 0.016x^{i}$	$r = 0.16$	$y = 0.344 + 0.013x^{i}$
	$p < 0.001$	$R^2 = 0.017, p < 0.001$	$p < 0.001$	$R^2 = 0.019, p < 0.001$	$p < 0.001$	$R^2 = 0.024, p < 0.001$

y Burn severity

[a] Canopy cover, [b] tree diameter, [c] tree height, [d] understory cover, [e] stand age, [f] elevation, [g] slope, [h] aspect index, [i] topographic position index

was stronger for moderate fires than that for small and large fires.

Of the vegetation factors examined, understory cover and stand age were positively correlated with burn severity, and canopy cover was negatively correlated with burn severity. Relationships between factors of understory cover, stand age, canopy cover, and burn severity decreased with increasing fire size. The tree height was significantly positively correlated with burn severity for small fires but negatively correlated for moderate and large fires. The tree diameter was significantly positively correlated for small fires and significantly negatively correlated for moderate fires. There was no correlation ($r = 0.002$, $p > 0.05$) for large fires.

Relative Importance Patterns of Vegetation and Topography Factors Among Fire Sizes

The "lmg" metric in the "Relaimpo" package presented a quantificational evaluation of relative importance of vegetation and topography factors (Table 5). The CART analysis showed the hierarchical importance of vegetation and topography factors from top to bottom (Fig. 6, 7, 8). Topography factors, ranked in order of relative importance, were elevation, topographical position index, slope, and aspect index. Vegetation factors, ranked in order of relative importance, were understory cover, stand age, tree diameter, tree height, and canopy cover.

Relative importance of vegetation and topography varied with fire sizes (Fig. 6, 7, 8). Generally, the importance of topography increased with increasing fire size and the vegetation presented opposite trend. Specifically, the burn severity of small fires was primary controlled by vegetation, and the burn severity of large fires was primary controlled by topography. The relative importance of vegetation and topography was complex and indistinguishable for moderate fires.

Spatial distribution of burn severities partitioned by vegetation and topography factors varied with fire sizes (Fig. 6, 7, 8). For example, the elevation factor separated

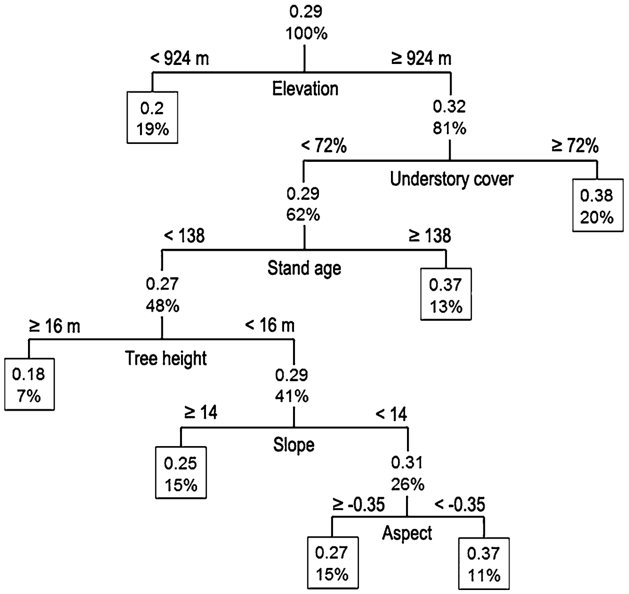

Fig. 6 Classification and regression tree (CART) partition of burn severity of the small (<100 ha, $n = 12$) fires in 2010. Each node (including the terminal nodes in the *boxes*) shows the percent of area (*bottom*) and the mean burn severity (*top*). Variance of burn severity explained (R^2) by the CART is 0.34

Table 5 The relative contribution (%) of vegetation and topography factors to burn severity of fires burned in 2000 and 2010

Factors	Fires of 2010			Fire of 2000
	Small fires (<100 ha)	Moderate fires (100–1,000 ha)	Large fires (>1,000 ha)	Large fire (2,950.1 ha)
Canopy cover (%)	3	1	1	14
Tree diameter (cm)	6	3	2	10
Tree height (m)	5	2	5	9
Understory cover (%)	22	24	13	1
Stand age	6	12	6	3
Elevation (m)	30	38	61	39
Slope (%)	5	6	2	1
Aspect index	16	5	1	21
Topographic position index	7	9	9	2

Note The fires of 2000 and 2010 burned with different weather conditions and their burn severities were derived from different timing of Landsat TM images. Therefore, one only comparing the relative importance values of vegetation and topography factors between these 2 years is meaningless. However, the relative importance pattern of topography and vegetation in the 2000 fire can support our finding (the burn severity of large fire was primary controlled by topographic conditions) derived from the 2010 fires

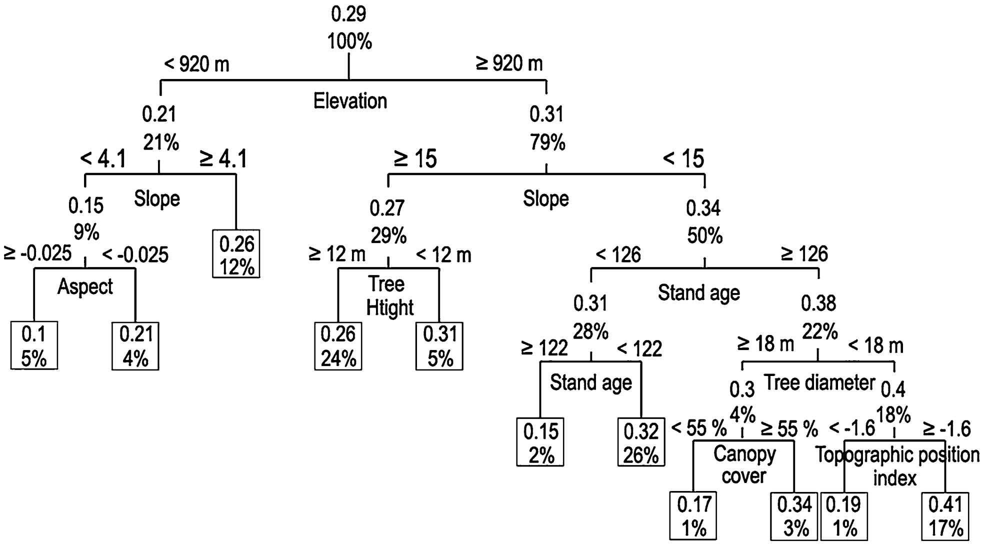

Fig. 7 Classification and regression tree (CART) partition of burn severity of the moderate (100–1,000 ha, $n = 9$) fires in 2010. Each node (including the terminal nodes in the *boxes*) shows the percent of area (*bottom*) and the mean burn severity (*top*). Variance of burn severity explained (R^2) by the CART is 0.26

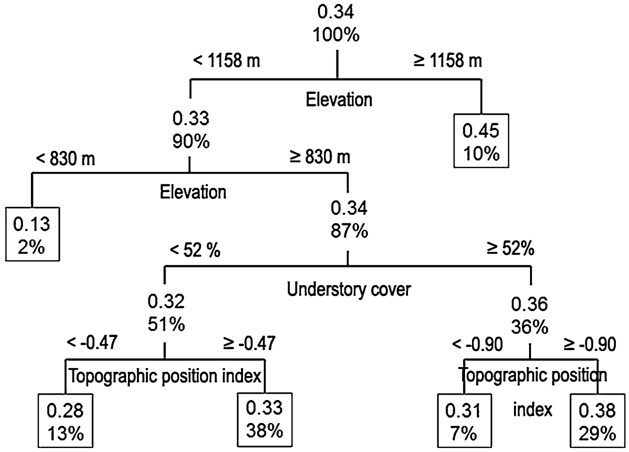

Fig. 8 Classification and regression tree (CART) partition of burn severity of the large (>1,000 ha, $n = 3$) fires in 2010. Each node (including the terminal nodes in the *boxes*) shows the percent of area (*bottom*) and the mean burn severity (*top*). Variance of burn severity explained (R^2) by the CART is 0.18

approximately 80 % of the landscape with an elevation of 920 m into a relative homogeneous group under small and moderate fires. The primary factor was also elevation for large fires; however, the threshold that separated the landscape into a relative homogeneous group was 1,158 m. This indicated that as fire size increases, the more likely severe fires were located in areas with higher elevations.

Validation Results of the Relative Importance Patterns of Vegetation and Topography Factors

Information from Table 5 showed that topography was slightly more important than vegetation in determining burn severity for the large fire burned in 2000. This result did not change the relative importance patterns of vegetation and topography (the more important of topography in large fires) observed from fires burned in 2010.

Discussion

Relative Importance of Vegetation and Topography Factors in Determining Burn Severity

Our study demonstrated that small and large fires analyzed may lead to different relationships between burn severity and vegetation and topography. The relative importance of vegetation and topography driving patterns of burn severity differed greatly among fire sizes (Fig. 6, 7, 8). The different relationships (relative importance) could be attributed to differences in fire burning schemes of small and large fires. Fire ignition is largely dependent on local vegetation characteristics (e.g., fuel type, moisture, and continuity) (Falk and others 2011). Locations with flammable fuels are easily ignited but do not necessarily spread to become large and severe fires (Finney 2005). Once a fire has ignited, its severity is further controlled by topography conditions (Falk and others 2007). Small fires are generally ignited and spread within a homogeneous topographic condition. Fuel conditions within or between forests stands can effectively limit fire size and then control burn severity (Rollins and others 2002). Associated with favorable weather conditions (e.g., high wind speed and temperate), larger fires are commonly severe in many forests (Bergeron and others 2002; Turetsky and others 2010). Large, weather-driven fires can consume vegetation/fuel types and ages without preference such as the 1988 Yellowstone fire (Turner and Romme 1994), whereas they can also burn at low severity. In the latter case, burn direction and spread rate of a fire are primary affected by topography (e.g., slope).

Our results indicated that patterns of relative importance of both vegetation and topography factors did not vary with increasing fire size (with implications for not fire size independence) (Table 5). The elevation and topographical position index were always most important. Some studies support our result that elevation is always important in determining burn severity (Wimberly and Reilly 2007; Barrett and others 2010; Carlson and others 2011). They found that coniferous species–dominated forests often distributed at higher elevations. The coniferous forests often have flammable fuels (forest species such as pine with flammable compounds in the fuels), which consequently can burn severe fires. Moreover, these studies suggested that higher-elevation areas have higher levels of solar radiation and steeper slopes where fire may spread at higher speeds and, consequently, higher burn severity. However, some other studies found higher burn severities at lower elevations than those at higher elevations (Epting and Verbyla 2005; Alexander and others 2006), suggesting that this pattern is driven by changes in vegetation composition along elevation gradients and more flammable vegetation distribution at lower elevations. These studies demonstrated that elevation gradients can shape vegetation composition, fuel structure, and distribution pattern across a landscape, and consequently influence burn severity patterns. In this study, we found higher burn severity occurred at higher elevations (especially elevations >800 m) where plenty of dense and heavily branched shrubs of dwarf Siberian Pine (*P. pumila*) are common. These shrublands often do not produce a crown fire because of the limited and discontinuous crown foliage. However, shrublands may be more susceptible to crown fires under favorable weather conditions (e.g., high wind speed) (Wu and others 2011).

Our results showed that fires in north aspects burned more severely than those in south aspects, although many studies found converse results (Kane and others 2007; Barrett and others 2010). The aspect effect in this study seems counter-intuitive because south aspects receive more solar radiation than those north aspects in the northern hemisphere (Alexander and others 2006). However, some studies showed that north aspects also burned with severe fires (Rollins and others 2002; Bigler and others 2005). Higher severity in north aspects is typical of many forested systems because forests tend to be denser and may contain shade tolerant species and multi-layered canopies. This indicates that although the relationship between burn severity and aspect is strong, it does not exclusively control burn severity. We assume our relationship between burn severity and aspect is directly related to weather and fuel conditions (e.g., moisture content) that were not accounted for in this study. In this study, the days prior to the fires were characterized by hot and dry conditions causing the fuel moisture contents of the fuels to be similar between the north and south aspects. North aspects have more surface fuel continuity that are dominated by the understory shrub layers of the *Ledum palustre* and *Vaccinium uliginosum* (up to 0.4 m). Consequently, north aspects burned with more severe fires. Therefore, the relationship between aspect and burn severity may be altered by other factors, such as the weather conditions, spatial continuous biomass and fuel structure in different aspects (Parks and others 2011).

The understory cover and stand age were always important, which is somewhat expected because areas with increased understory cover have higher vertical fuel continuity and subsequently increased burn severity (e.g., crown fire) (Ryan 2002). This pattern is consistent with other studies (Thaxton and Platt 2006; Thompson and Spies 2009), including the 2002 Biscuit fire in the United States that found burn severity increased with increasing understory cover (Thompson and Spies 2009). Our study also found that older-aged stands presented higher burn severity, a pattern also observed in many other ecosystems (Lentile and others 2006a), suggesting that stands with older age had higher biomass accumulation and relatively lower decomposition of dead organic matters (Keeley and others 2008), and consequently burned with greater severity fires. In contrast, other studies showed that fires burned with greater severity in stands dominated by young forest (Thompson and Spies 2009; Thompson and others 2011). For example, the level of fire damage after the Biscuit fire peaked around age of 15 and stayed relatively high until age of 25 before declining (Thompson and others 2011). Generally, the young regeneration is often less apt to burn; especially if there is the lack of woody debris and other flammable materials in the understory. The findings of Thompson and others (2011) could be explained by young trees tending to have a low crown base height and a high degree of vertical continuity in fuel structure, which results in weak fire resistance. In this study, we found higher burn severity occurred at higher elevations where plenty of dense and heavily branched shrubs of dwarf Siberian Pine (*P. pumila*) are common. This indicates that locations with dense shrub understory may present high severity risks.

Our study showed that areas with large trees (especially tree diameter larger than 16 cm) often burned less severely than those with small trees. Alexander and others (2006) suggested that larger trees with more biomass and greater height could be resistant to fire-induced mortality. This pattern is consistent with some previous studies (Hely and others 2003; Alexander and others 2006; Lentile and others 2006a). These studies from North America were conducted in coniferous-dominated forest ecosystems (as was our study). In our study area, the higher burn severity fires mostly occurred in higher elevations where dominated by the dwarf Siberian Pine (*P. pumila*). The dwarf Siberian Pines often small in size (diameter and height) and relatively old (because of the difficulties of harvest at high elevations). Thus, dwarf Siberian pine forest can have high burn severity under extreme weather conditions (Wu and others 2011). This can explain why fires burned more severe in older-aged stands and why large trees often burned less severe than those with small trees in our study area. Therefore, the tree size to burn severity relationship is complex and may be further influenced by local forest composition, distribution or fire regimes of vegetation.

Management Implications

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.

(1) At high elevations, fires tend to be larger and burn more severe. The fires are commonly far away from roads and settlements, which makes them difficult to detect and suppress. Therefore, management activities should include more intensive monitoring in these areas. Aspects present negative correlations to burn severity suggest that the ability of fuel treatments focus on south aspects to achieve the desired results of reduced burn severity may be limited. Therefore, fuel treatments should pay more attention to north aspects where have higher fuel continuity of the understory shrub layers of the *L. palustre* and *V. uliginosum*.

(2) Older forests with a high cover of understory vegetation often will have larger and more severe fires since the understory cover in combination with ladder fuels will increase the likelihood of a surface fire transitioning into the crowns. Therefore, fuel treatments should be prioritized in mature stands with high understory cover. For example, thinning can reduce the likelihood of spreading fires from surface to crown by removing the ladder fuels, including large fire-susceptible trees.

(3) Because relationships between vegetation and topography and burn severity vary with fire sizes, different management activities should be adopted. For small fires, treatments of vegetation may be effectively control burn severity. For large fires, this vegetation based treatments may provide limited control of burn severity, and the spatial perspective should be employed. For example, landscape fuel management via fuel breaks can be designed based on the assumption that fires will be spread slower and burn less severity in adverse topographic conditions.

Study Limitations and Future Directions

Although results from this study could be used for a range of forest and fire management activities, they have limitations. The focus of this study is on the bottom-up controls (vegetation and topography) on burn severity. However, the effect of climate or weather (top-down controls) is not negligible and some previous studies showed that weather or climate factors is the primary factor in determining fire regimes (Bessie and Johnson 1995; McKenzie and others 2004; Thompson and Spies 2009; Bradstock and others 2010). For example, Thompson and Spies (2009) found the most important predictors of conifer damage were average daily temperature and burn period (an index of fire weather and fire suppression effort) of the 2002 Biscuit fire in southwestern Oregon and northwestern California. Moreover, some other studies showed that weather or climate factors can alter relationships between burn severity and environmental factors (e.g., vegetation and topography) (Turner and Romme 1994; Keeley and Fotheringham 2001; Oliveras and others 2009). For example, the weather conditions of fire in this study had been extremely dry, which produced the fuel moisture conditions between the north and south aspects were neutral. Consequently, the higher fuel continuity on the north aspects burned more severe fires. Therefore, fire is affected by a range of factors and is not simply related to topography and vegetation. In the future, we should combine bottom-up and top-down controls to explain burn severity across a forest landscape.

The major assumption that we implicitly used in this study was that we assumed the 24 fire patches burned with the same weather conditions. Our assumption was made based on (1) the 24 fire patches occurred almost simultaneously on June 26 and June 28, 2010 and (2) burned within similar time period (from 26 June to 3 July in 2010) and weather conditions that characterized as extremely high temperatures and dry conditions. However, it is important to note that this assumption may affect our conclusion on the relative contribution of vegetation and topography to burn severity. This is because fire weather conditions (especially wind speed) have huge spatial variability, which may produce burn severity of fires differ across a forest landscape and consequently make different relationships between burn severity and vegetation and topography. Therefore, exploring how weather conditions influence the relative contribution of vegetation and topography to burn severity is a study of future direction.

Our burn severity map was only characterized by determining differences of NDVI between pre- and post-fire TM images and was not validated with field sample data. Validating burn severity maps with field sample data (e.g., Composite Burn Index, CBI) is widely conducted by previous studies (Epting and others 2005; Miller and others 2009). Using field sample data is useful for selecting a most suitable remote sensing index to assessment burn severity (Miller and others 2009). Our justification of using of NDVI index to derive the burn severity was mainly based on previous studies conducted in or nearby our study area (Xie and others 2005; Tian and others 2009; Feng 2012). Therefore, calibration and validation of the dNDVI with field samples from the burned fires is a study of future direction.

In this study, the scale effects on vegetation and topography and burn severity relationships were explored by changing fire size but maintaining the same spatial grain size (30 m × 30 m). However, scaling is a function of both grain and extent. Multi-grain size analysis of relationships between environment and ecological processes is essential for the modern ecology (Wu 2004; Turner 2010), as well as in fire science (Falk and others 2007). The grain size can considerably affect our ability to identify the burn severity patterns and the relative importance of their determinants. Using a single grain size cannot adequately answer how scale-dependent relationships change with observations at varying grain sizes (Morgan and others 2001; Lentile and others 2006b). We therefore encourage similar examinations of other regions with different spatial grain sizes to explore the issues of scaling and controls on fire regimes such as burn severity.

Conclusions

Our results further support findings that effects of environments (e.g., vegetation and topography) on fire regimes are spatial scale-dependent (Cyr and others 2007; Parks and others 2011). The importance of topography increased with increasing fire size and the vegetation presented opposite trend. Burn severity of small fire is primary controlled by vegetation conditions. In contrast, burn severity of large fire is mostly determined by topographic conditions. Our results indicate that evaluating the effects of vegetation and topography with a single scale of fire size may not capture the effects from another scale of fire size (Parks and others 2011). Therefore, cross-scale analysis is important for quantifying the fire–environment relationships (Cyr and others 2007; Falk and others 2007, 2011).

These results provide a necessary step towards a more clearly understanding effects of vegetation and topography on burn severity across a landscape. Practically, exploring how vegetation and topography control burn severity across a fire-prone landscape is critical for strategic and effective placement of fire mitigation treatments (Turner and others 2003; Alexander and others 2006; Lee and others 2009; Metz and others 2011). For example, our results showed that areas with higher elevations would burn more severely; therefore, management activities should include more intensive monitoring in higher-elevation areas where fires tend to be larger and burn severely.

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