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Influences of forest roads and their edge effects on the spatial pattern of burn severity

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ABSTRACT

Previous research has shown that forest roads are an important feature in many landscapes and have significant effects on wildfire ignition and cessation. However, forest road effects on burn severity have not been studied at the landscape level. Therefore, the overarching goal of our study is to identify the influences of road edge effects on the spatial patterns of burn severity. We analyzed six fires within the Okanogan–Wenatchee National Forest on the eastern slope of the Cascades mountain range of central Washington.

We generated two categories for assessing road variables: (1) Primary Road Effect Zone (area within 150 m of the nearest road) and (2) Secondary Road Effect Zone (area from 150 m to 300 m to the nearest road). A regular sampling grid including one out of every 9 cells was created for each fire.

These grids were intersected with burn severity data in the form of the Relative Differenced Normalized Burn Ratio (RdNBR), road distance category, stream distance, elevation, slope, terrain shape index, heat load index, canopy cover, and fuel type. We fit spatial regression models with RdNBR as the dependent variable.

We found that high burn severity is less likely to occur in the Primary Road Effect Zone for most fires, although one fire exhibited the opposite relationship. Forest road edge effects were hypothesized to be an important determinant of burn severity because fragmentation created by roads alters the roadside fuel profile and environment and because road corridors create barriers to fire spread. Recognizing roadside effects on burn severity patterns highlights the need for further study of the range of effects that roads have on fuels and the fire environment and the potential for incorporating road effects into landscape-level assessments of fire risk.

1. Introduction

Wildfires are one of the most important disturbances shaping forest ecosystems (Agee, 1993). Varying levels of burn severity strongly increase the spatial heterogeneity of landscape mosaics (Turner and Romme, 1994) and have an important influence on forest stand and landscape structural diversity (Weatherspoon and Skinner, 1995; Taylor and Skinner, 1998). Multiple definitions of burn severity are used by researchers and by the general public as discussed elsewhere (Jain, 2004; Lentile et al., 2006). For the purpose of this study, burn severity is defined as the magnitude of wildfire-caused vegetation mortality after approximately one year. Various environmental conditions such as weather, topography, vegetation structure, fire breaks (Agee, 1993) and their interactions lead to varying levels of burn severity (Turner and Romme, 1994). These burn severity patterns and their ecological effects can vary significantly among wildfires and within a single wildfire event.

Roads are a predominant feature across many forested landscapes and play a significant role in influencing wildfire ignition and cessation. Forest roads increase human fire ignition probability by providing road accessibility (Narayanaraj and Wimberly, 2012; Syphard et al., 2007, 2008) and fire boundaries tend to occur near roads because roads facilitate fire suppression and act as physical barriers (Narayanaraj and Wimberly, 2011; Price and Bradstock, 2010). Furthermore, forest roads create linear gaps that result in edge effects (Spellerberg, 2002) which alter microclimates from the road edge extending into the neighboring forests (Chen et al., 1992, 1993). As a result, the area influenced by forest roads and their edge effects is markedly larger than the area covered by roads themselves (Forman and Alexander, 1998). To date, the effects of forest roads and their edge effects on burn severity have not been adequately analyzed at the landscape level. Therefore, the major objective of this study was to determine the influences of road effects on the spatial patterns of burn severity.

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1.1. Forest roads and their edge effects

Road edge effects are defined as the alteration of habitat quality influenced by proximity to the road edge. Road edge effects are different from those caused by natural disturbances and anthropogenic edges created by timber harvesting. Reed et al. (1996) point out that gradual vegetation succession progressively diminishes natural and clear-cut forest edges. In contrast, road edges tend to last over a longer period of time and are disturbed more frequently by human activities. The invasion of exotic plant species initiated by forest roads frequently becomes a source of combustible fuels (Arienti et al., 2009; D'Antonio and Vitousek, 1992; Parendes and Jones, 2000; Trombulak and Frissell, 2000). Subsequently, these fuels may contribute to a greater incidence of human- and lightning-caused ignitions near roads (Arienti et al., 2009; Syphard et al., 2007, 2008; Yang et al., 2007, 2008). Changes in microclimatic conditions such as solar radiation, temperature levels, wind speed and humidity are caused by forest roads (Spellerberg, 1998) and can influence the flora and fauna at forest edges and also extend into the interior forest (Chen et al., 1992, 1993; Haskell, 2000). Forest edge environments are usually drier and warmer than interior forests with more solar radiation and higher windspeeds.

These edge environments also change vegetation structure and composition. For example, in western conifer forests, canopy cover, tree density and basal area tend to be lower near the edge (Chen et al., 1992). Also, shade intolerant species, as well as disturbance-adapted and exotic species, often have their highest abundances near forest edges. Conversely, shade tolerant species and those sensitive to disturbance are often restricted to the forest interior (Ranney et al., 1981). Changes in species composition in relation to forest edges have been reported for both woody and herbaceous species in eastern deciduous and western coniferous forests of North America (Palik and Murphy, 1990). These vegetation gradients from road edge to interior can influence the spatial patterns of fuel characteristics such as total amount, horizontal and vertical continuity, and fuel moisture dynamics. Ultimately, varying levels of burn severity may occur from road edge to interior forests as a result.

1.2. Burn severity and burn ratio indices

Burn severity depends on the vegetation structure, fuel characteristics, and the environmental conditions under which a wildfire occurs. For example, thinning followed by prescribed burning typically decreases burn severity, whereas thinning without subsequent surface fuel treatment may lead to increased burn severity (Wimberly et al., 2009). Several studies have found increased burn severity in conifer plantations compared to unmanged forest stands (Odion et al., 2004; Weatherspoon and Skinner, 1995), particularly when the plantation is younger than 12 years old (Stephens and Moghaddas, 2005). Steeper slopes and higher topographic positions have been associated with higher burn severity (Kushla and Ripple, 1997; Lentile et al., 2006; Taylor and Skinner, 1998).

The Differenced Normalized Burn Ratio (dNBR) index (Key and Benson, 2006) and the relative version of the dNBR (RdNBR) index (Miller and Thode, 2007) are commonly used to assess post-fire burn severity effects. Both of these indices are derived from the NBR calculation (Eq. (1)) using two spectral bands in the near infrared (NIR) and shortwave infrared (SWIR) wavelengths.

$$\mathrm{NBR} = \frac{\mathrm{NIR} - \mathrm{SWIR}}{\mathrm{NIR} + \mathrm{SWIR}} \tag{1}$$

where NIR and SWIR are the spectral reflectance values for Landsat Thematic Mapper NIR (0.76–0.90 μm) and SWIR (2.08–2.35 μm) respectively. NIR is sensitive to green vegetation and SWIR is sensitive to dry vegetation and non-organic land surface cover (Key and Benson, 2006). Differenced NBR (dNBR, Eq. (2)) is based on calculating NBR on pre- and post-fire images and then subtracting post fire NBR from pre-fire NBR

$$\mathrm{dNBR} = \mathrm{NBR}_{\text{pre-fire}} - \mathrm{NBR}_{\text{post-fire}} \tag{2}$$

With the dNBR, the timing of the pre-fire and post-fire dates are very important as differences in vegetation moisture content and phenology can significantly influence the results (Key and Benson, 2006). After the fire, reflectance in NIR decreases while reflectance in SWIR increases, highlighting changes created by the fire. The algorithm assumes that the NBR in the unburned areas remains unchanged and that climatic conditions are similar for the pre - and post-fire images (Key and Benson, 2006; Miller and Thode, 2007). The dNBR is positive for fire-damaged areas and negative for regions experiencing enhanced re-growth (Key and Benson, 2006).

Recently Miller and Thode (2007) developed a relative version of the dNBR (RdNBR). The concept behind this index is to determine what proportion of vegetation has been killed or removed in a fixed area (pixel) by the fire. RdNBR (Eq. (3)) measures this relative change on a pixel by pixel basis. The index is computed as the difference between pre- and post-fire NBR divided by the square root of the absolute value of pre-fire NBR

$$\mathrm{RdNBR} = \frac{\mathrm{dNBR}}{\mathrm{Sqrt}(\mathrm{Abs}(\mathrm{NBR}_{\text{pre-fire}}/1000))} \tag{3}$$

The Trends in Burn Severity (MTBS) project utilizes dNBR and RdNBR to provide long-term fire severity data based on Landsat imagery from 1984 to the present for various regions of the United States. These burn severity indices have been used in a wide range of scientific research activities. For example, the indices have been used to assess burn severity effects on plant species diversity (Wimberly and Reilly, 2007), fuel treatment effectiveness (Wimberly et al., 2009), and water quality and stream flow (Robichaud et al., 2007). In addition, there are numerous other studies that have used the indices for assessing burn severity at the landscape-scale (Odion et al., 2004; Collins et al., 2007; Kulakowski and Veblen, 2007; Thompson et al., 2007).

Despite widespread interest in both the ecological effects of roads and landscape patterns of fire severity, there have been no studies investigating forest roads and their edge effects on the spatial pattern of burn severity. Our primary objective was to assess the relative importance of forest road effects on burn severity (RdNBR) while controlling for the influence of confounding factors such as streams, terrain, and vegetation variables in our multivariate model. We addressed the following research questions: (1) Are streams, topographic indices, fuels and vegetation cover associated with burn severity patterns? and (2) After controlling for the influences of these variables, do forest roads and their edge effects influence burn severity patterns?

2. Methods

2.1. Study site

We studied six fires, Rex Creek, Deep Harbor, Deer Point, Pot Peak, Icicle, and Fischer, in the Okanogan–Wenatchee National Forest in eastern Washington State (Fig. 1). The six fires chosen for this study reflect a range of landscape characteristics which is important for sampling burn severity locations under variable environmental conditions (Table 1). The selection criteria were fires that occurred between 2000 and 2007, a time period during which site specific data on roads and fire behavior fuel models were available. In addition, only fires that were larger than 2000 ha and burned over some roaded areas were included in the analysis. All fires occurred during the summer months (July–August).