Influences of forest roads on the spatial patterns of human- and lightning-caused wildfire ignitions

Article *in* Applied Geography · March 2012

DOI: 10.1016/j.apgeog.2011.09.004

2 authors:

Ganapathy Narayanaraj
Swarthmore College

Michael Wimberly
University of Oklahoma

Applied Geography 32 (2012) 878–888

Contents lists available at SciVerse ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Influences of forest roads on the spatial patterns of human- and lightning-caused wildfire ignitions

Ganapathy Narayanaraj*, Michael C. Wimberly

Geographic Information Science Center of Excellence, Wecota Hall, 1021 Medary Avenue S, South Dakota State University, Brookings, South Dakota 57007-3510, USA

Keywords:
Forest roads
Wildfire
Human ignition
Lightning
East Cascades
Geographical information systems
Case-control logistic regression

ABSTRACT

Understanding the spatial patterns of fire ignitions and fire sizes is essential for understanding fire regimes. Although previous studies have documented associations of human-caused fire ignitions with road corridors, less consideration has been given to understanding the multiple influences of roads on the fire regime at a broader landscape-scale. Therefore, we examined the difference between lightning- and human-caused fire ignitions in relation to forest road corridors and other anthropogenic and biophysical factors in the eastern Cascade Mountains of Washington State. We used geographical information systems and case-control logistic regression models to assess the relative importance of these explanatory variables that influence the locations of lightning versus human-caused ignitions.

We found that human-caused ignitions were concentrated close to roads, in high road density areas, and near the wildland–urban interface (WUI). In contrast, lightning-caused ignitions were concentrated in low road density areas, away from WUI, and in low population density areas. Lightning-caused ignitions were also associated with fuels and climatic and topographic factors. A weak but significant relationship between lightning-caused fire and proximity to gravel roads may be related to fuels near roads or to bias in detection and reporting of lightning-caused fires near roads. Although most small fires occurred in roaded areas, they accounted for only a small proportion of the total burned area. In contrast, the large fires in roadless and wilderness areas accounted for most of the burned area. Thus, from the standpoint of the total area burned, the effect of forest roads on restricting fire size is likely greater than the impact of roads on increasing fire ignitions. The results of our study suggest that roads and their edge effect area should be more widely acknowledged as a unique type of landscape effect in fire research and management.

Introduction

The spatial patterns of forest fire ignitions are gaining attention due to the important role these ignitions play in structuring the spatial pattern of fire regimes (Guyette, Muzika, & Dey, 2002; Kernan & Hessl, 2010; Sibold, Veblen, & González, 2006; Syphard et al., 2008; Yang, He, Sturtevant, Miranda, & Gustafson, 2008). The spatial pattern of different-sized fires at varying levels of severity generates a mosaic of burned and unburned areas that affects plant species composition and forest age classes, creating spatially heterogeneous fuel conditions (Hessburg & Agee, 2003; Perry et al., 2011). Fuel heterogeneity consequently has an effect on the spatial pattern of subsequent wildfires (Hessburg & Agee, 2003; Perry et al., 2011). Important environmental factors affecting wildfire patterns include climate, weather, topography, fuel loads, vegetation types, and natural- and human-caused ignition sources (Hessl, 2011; Hessl, McKenzie, & Schellhaas, 2004; Kernan & Hessl, 2010; Kellogg, McKenzie, Peterson, & Hessl, 2008; Lutz, van Wagtendonk, Thode, Miller, & Franklin, 2009; Perry et al., 2011; Syphard et al., 2008).

Forest roads may constrain fire spread because they can serve as fire breaks and provide access for fire suppression activities (Price & Bradstock, 2010; Narayanaraj & Wimberly, 2011). However, increasing road access also elevates the frequency of human-caused fire ignitions (Syphard et al., 2007). Given the complex and multi-faceted nature of road effects, there is a need to explore the broader landscape-scale implications of roads for fire management. As debate over forest roads increases, there is controversy about whether roads increase the risk for unwanted human-caused fires or reduce fire hazard by providing access for fire suppression and fuel treatments (Gucinski, Furniss, Ziemer, & Brookes, 2001; USFS, 2000). This ongoing debate necessitates research to address the influences of forest roads on fire regimes (Gucinski et al., 2001;

* Corresponding author.
E-mail address: ganapathy.narayana@sdstate.edu (G. Narayanaraj).

0143-6228/$ – see front matter
doi:10.1016/j.apgeog.2011.09.004

USFS, 2000). Therefore, the major objective of this study was to identify the influences of roads on the spatial patterns of fire ignitions.

Human- and lightning-caused fires

Human-caused fires are not randomly distributed events. Studies have demonstrated human-caused fires are located in proximity to human settlements and road corridors (Brosofske, Cleland, & Saunders, 2007; Maingi & Henry, 2007; Syphard et al., 2007; 2008; Syphard, Radeloff, Hawbaker, & Stewart, 2009; Vega Garcia, Woodard, Titus, Adamowicz, & Lee, 1995; Yang, He, Shifley, & Gustafson, 2007, 2008). Human-caused fires result from a combination of factors, either accidental or deliberate, and environmental conditions that are conducive to fire. The range of direct human-caused fire ignitions includes release of burning carbon particles from automobile exhaust pipes, throwing of improperly extinguished cigarette butts, and recreational activities such as inappropriately put out campfires. The extent and location of road access limits the number and distribution of humans as possible ignition sources. Previous studies have focused on the location of fires in relation to roads, trails, towns, vegetation, rivers, topography (elevation, slope, and aspect), forestry operation sites and other geographic variables (Chou, 1992; Turner & Romme, 1994; Vega Garcia et al., 1995). All of these biophysical factors affect the probability of human-caused fire ignitions. Some of these biophysical factors, such as topography and fine fuel load (Arienti, Cumming, Krawchuk, & Boutin, 2009); also affect the probability of lightning-caused fire ignitions.

Lightning-caused fires depend on cloud to ground lightning strikes and also on the availability of dry fine fuel on the forest floor (surface litter) or beneath the forest floor (duff layer) where fire can smolder for several days (Latham & Williams, 2001). For a lightning strike to cause an ignition, it must carry sufficient current for a long enough time to ignite fine fuels on the forest floor. When a tree is struck by lightning, a lightning flash (cloud to ground) is conducted downwards through either the cambium layer or along the bark of a tree (Latham & Williams, 2001). Ignitions can occur in the fine fuel on the top of the forest floor, or the charge can ignite the duff layer below the forest floor. Such ignitions below the forest floor have been observed to smolder for more than ten days prior to the arrival of flaming combustion (Flannigan &Wotton, 1991). There can also be a lag between the fire ignition and its subsequent detection. As a result, lightning-caused fires may have time to spread before they are noticed and subsequently extinguished and tend to be larger than human-caused fires (Arienti et al., 2009). However, if lightning fires occur close to developed areas, they may be quickly detected and suppressed, resulting in smaller fires.

Spatial patterns of forest roads and fires

The road network in the United States includes over 6.5 million km of travel corridors, which comprise the largest man-made structure on the US landscape (Forman & Alexander, 1998; Watts et al., 2007). The spatial patterns of forest roads are an important legacy of anthropogenic disturbance (Forman & Alexander, 1998). Forest roads provide essential access for logging and fire management activities such as fuel treatment and fire suppression and may also act as fuel breaks. At the same time, forest roads have adverse effects on ecosystems. Forest roads contribute significantly to the degradation of water quality and aquatic habitat. They are associated with enhanced erosion and can be a major source of sediment delivery to streams (Forman & Alexander, 1998; Lugo & Gucinski 2000).

Roads segregate the landscape with artificial linear gaps and create abrupt edges (Forman & Alexander, 1998). Forest edge habitat created by roads is more extensive than edge habitat created by clear-cuts (Reed, Johnson-Barnard, & Baker, 1996). One of the important effects of road edge habitat on the forested environment is the alteration of the microclimate, particularly changes in sun light penetration, temperature levels, wind speed and humidity (Spellerberg, 1998). Changes in microclimate affect the flora and fauna at forest edges but also extend into forest stands (Chen, Franklin, & Spies, 1992, 1993). For example, Chen et al. (1992) have shown that a greater amount of snags and fallen trees are located near the edge rather than the forest interior. Most of these fallen trees were uprooted or broken off by wind. Another study by Chen et al. (1993) observed that daily averages of soil and air temperature are consistently higher, and humidity is lower at the edge of the forest compared to the interior. Hence, the combined effects of higher mortality of trees near forest edges and the change in temperature and humidity would have an important impact on patterns of fuels and fuel moisture from the edge to the interior of forests.

It is recognized that road edges are habitat for ruderal species (Spellerberg, 1998; Stoner & Adams, 2004) and serve as corridors for the spread of exotic plant species (Parendes & Jones, 2000; Trombulak & Frissell, 2000). Such species can result in more combustible live and dead fine fuels that are more easily ignited than within the forest interior (Arienti et al., 2009; D'Antonio & Vitousek, 1992), and these fuels may contribute to the greater likelihood of human- and lightning-caused ignitions near roads (Arienti et al., 2009; Syphard et al., 2007, 2008; Yang et al., 2007, 2008). Although previous studies have demonstrated that road corridors promote fire ignitions, most have focused on human-caused fire ignitions. The distribution of both human- and lightning-caused ignitions in relation to multiple anthropogenic and biophysical factors has not been explored as thoroughly. Recent studies have demonstrated that although terrain and vegetation are important determinants of fire boundary locations, forest roads have a stronger influence in stopping fires (Narayanaraj & Wimberly, 2011; Price & Bradstock, 2010). This result may reflect the fact that fire suppression activities are more effective close to roads because of ease of access and, the fact that roads act as a physical barrier for slowing or halting the rate of fire spread. It is also possible that fires are detected quickly near roads. For all these reasons, forest roads are likely to contribute to smaller fire sizes.

Research significance and questions

Understanding the spatial patterns of fire ignition and fire size is essential for analyzing wildland fire risk (Chuvieco, Allgöwer, & Salas, 2003; Finney, 2005; Miyanishi & Johnson, 2001; Vasconcelos, Silva, Tome, Alvim, & JMC, 2001; Vasilakos, Kalabokidis, Hatzopoulos, Kallos, & Matsinos, 2007). Most studies, however, have been focused primarily on government-owned lands. The federal fire occurrence database is virtually the only national information source (Brown, Hall, Mohrle, & Reinbold, 2002) and may partly explain this emphasis on public lands. Our study extends the research to include non-public lands. Consequently, our current study makes an important contribution to fire science research by focusing on a large geographic region with a broad range of ecological characteristics, comparing human- and lightning-caused fires within this landscape, and comparing the effects of different roads types (gravel versus paved). We addressed following questions: (1) Is the spatial pattern of human-caused wildfire ignitions associated with road networks?, (2) Is the spatial pattern of lightning-caused wildfire ignitions associated with road networks?, (3) Do road effects on wildfire ignitions differ for paved versus gravel roads? and (4) Do fire regimes differ in landscapes with high densities versus low densities of roads?

We conducted spatial statistical analyses to address these questions and elucidate the relative importance of human, biophysical and climate variables that influence human- versus lightning-caused ignitions.

Methods

Study area

The 20,304 km^2 study area encompassed most of the Okanogan-Wenatchee National Forest and its neighboring forested lands on the eastern slope of the Cascade Mountain range in Central Washington State (Fig. 1). The study area extends from the Cascade crest in the west to the foothills as they flatten into the Columbia River Plateau in the east, and extends from the US–Canada border in the north to the Goat Rocks wilderness area adjacent to the Yakama Indian Reservation in the south. The majority of the area is publicly owned, (79% by the US Forest Service), and includes the Alpine Lakes, Norse Peak, Goat Rocks, and Mount Adams Wilderness Areas. Major highways cross the study area at five locations. The largest roads are in the major valley bottoms, where they collect feeder roads that branch out to access the land in smaller drainages. Winthrop, Chelan, Leavenworth, Cashmere, Wenatchee, and Cle Elum are the major towns.

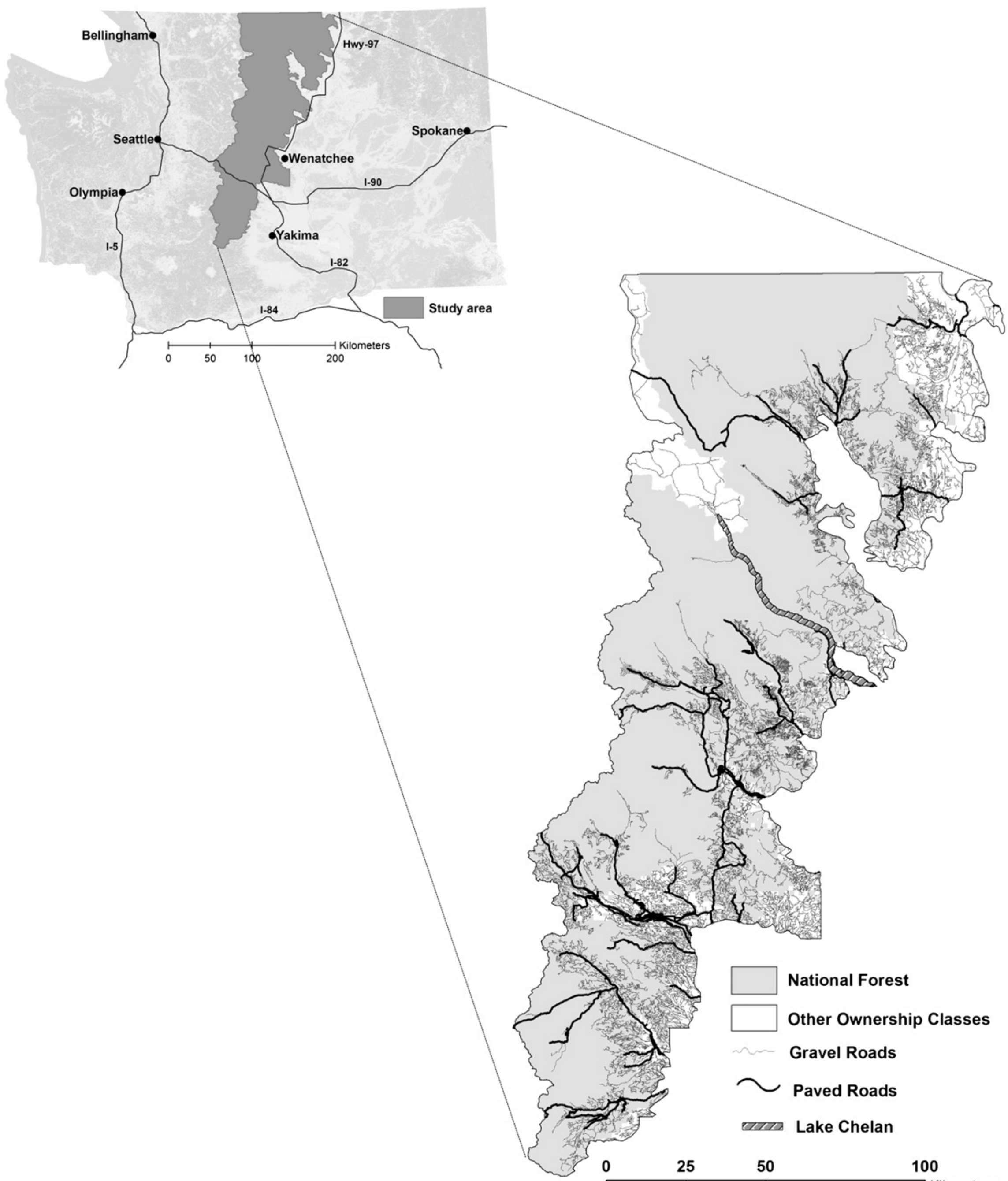

Fig. 1. The study area of the Okanogan-Wenatchee National Forest and other ownership classes on the eastern slope of the Cascade Mountain Range in Washington State with paved and gravel roads.

At the Cascade crest, 200–300 cm of precipitation falls annually, much of it as snow. At lower elevations, in the rain shadow of the Cascade Mountains, approximately 50 cm falls in a year. Most precipitation occurs during autumn and winter (Franklin & Dyrness, 1973). Vegetation composition of ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and subalpine fir (*Abies lasiocarpa*) varies along an elevation gradient (Camp, Oliver, Hessburg, & Everett, 1997; Franklin & Dyrness, 1973). For example, ponderosa pine forests occur at relatively low elevations between 600 and 1200 m, Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) dominate at higher elevations between 600 and 1300 m, and subalpine fir is dominant at elevations between 1500 and 1700 m (Franklin & Dyrness, 1973). Overall, the fire regimes in our study area vary along a gradient from a high-frequency low severity fire regime at lower elevations (e.g. ponderosa pine), to a low-frequency high severity fire regime at the higher elevations (e.g. subalpine fir) (Everett, Schellhaas, Keenum, & Spurbeck, 2000; Hessburg & Agee, 2003, Hessl et al., 2004, Kellogg et al., 2008; Kernan & Hessl, 2010).

In addition to vegetation changes along the elevation gradient, landscapes range from wilderness lacking any roads at higher elevations to a mixture of roaded and roadless areas at mid-elevation to heavily roaded areas at lower elevations. The wilderness areas are protected under one of the oldest environmental laws in the US, The Wilderness Act of 1964 (Rohrman, 2008). All wilderness areas designated by this law must not contain active roads. “Roadless” areas are different from wilderness areas. Under roadless conservation rules, certain activities such as limited timber harvesting, off-highway vehicle uses, livestock grazing and oil and gas development which do not requiring the construction of new roads are permitted in roadless areas (Rohrman, 2008). Roaded areas are more developed than roadless areas and have higher concentrations of human activities.

A policy of aggressive fire suppression in the Okanogan-Wenatchee National Forest began in 1910 (Agee, 1994) with early efforts concentrating on fires near settled areas (Camp et al., 1997; Everett et al., 2000). As a result, the reduced fire occurrence has caused significant increases in tree densities and changes in species composition in ponderosa pine/Douglas-fir stands in the East Cascades (Everett, Schellhas, Spurbeck, Ohlson, & Keenum, 1997) particularly in the zones dominated by ponderosa pine forests and Douglas/grand fir forests. These altered forests are, therefore, increasingly susceptible to large stand-replacement fires. Fire suppression is still widely implemented; however, some natural ignitions in wilderness areas are monitored and not actively suppressed (wildland fire use) unless they threaten adjacent non-wilderness areas or recreational sites.

Data source and geoprocessing

The dependent variables (fire ignition locations and fire sizes) and independent variables such as roads (paved and gravel), distance to wildland urban interface, streams, terrain, climate and fuels were calculated using data obtained from various agencies (Table 1). Data were geoprocessed using a Geographic Information System (GIS). Fire ignitions and non-fire ignition locations were generated and were intersected with the geoprocessed independent variables. We conducted a case-control logistic regression analysis to identify the environmental characteristics associated with fire ignitions.

Dependent variables

We used records of fire ignitions and fire sizes for the study period from 1997 through 2007. For the purpose of our study, we define fire ignition as the location of the origin of the fire. The fire ignition coordinates and fire sizes for lightning- and human-caused fires were downloaded separately for the Okanogan-Wenatchee National Forest and Cascade National Park from The Fire and Aviation Management Web Applications (FAMWEB). Additional records of fire ignitions and fire size were obtained from the Washington Department of Natural Resources (WDNR) for non-federal lands. The WDNR fire point locations were centroids of quarter-quarter sections from the Public Land Survey System (PLSS), which represents a spatial resolution of 0.16 km^2. The point location data for ignitions included total area burned as an attribute.

We evaluated the fire ignition coordinates overlaid with the mask layer of the study area. The mask layer was generated from the 30 m gridded National Land Cover Data (2001) to exclude non-burnable areas: open water, perennial ice and snow, developed medium and high intensity areas, barren land: rock, clay, and sand. We also cross-checked the data between WDNR and FAMWEB data to ensure that there were no duplicate ignitions. We retained 1106 lightning- and 874 human-caused fire ignitions (Fig. 2a, c) and used the fire size and cause of the fire for our analysis.

Table 1
Landscape predictor variables used for this study.

Variables	Units	Descriptions and data source
Distance to nearest road	Meters	Distance from raster cell to the nearest road. Calculated from vector road layers from Okanogan – Wenatchee National Forest and Washington Department of Natural Resource.
Road density	km/km^2	Total length of roads per square kilometer. Calculated from vector road layers from Okanogan – Wenatchee National Forest and Washington State Department of Natural Resource.
Distance to Wildland Urban Interface (WUI)	Meters	Distance from each point to the nearest Wildland Urban Interface (WUI).: Locations obtained from SILVIS (http://silvis.forest.wisc.edu/).
Population density	Persons/km^2	2000 census block-scale population density: number of person per square kilometers obtained from SILVIS (http://silvis.forest.wisc.edu/).
Precipitation	mm	June–August precipitation climate normals (1971–2000) from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, http://www.prism.oregonstate.edu/)
Temperature	°C	Maximum June–August temperature of climate normals 1971–2000 from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, http://www.prism.oregonstate.edu/).
Slope	Percent	Angular position relative to horizontal reference derived from Digital Elevation Model from LANDFIRE (http://www.landfire.gov/).
Heat load index	Index ranging from 0 (Cold – 45°) to 1 (Warm – 225°).	Measure of the solar exposure of a location using a cosine transformation (McCune & Keon, 2002).
Terrain shape index	Index with negative values for concave to positive values for convex	Represents concave to convex shapes of terrain, with negative values representing a concave terrain shape (cove) and positive values representing a convex terrain shape (ridge) (McNab, 1989).
Fuel Model	Discrete classes	Based on amount and distribution of vegetation and live and dead fuels. Classes include short grass, grass/timber, brush, dormant brush, and short and long needle timbers. Fuel model obtained from US Forest Service Okanogan – Wenatchee National Forest.

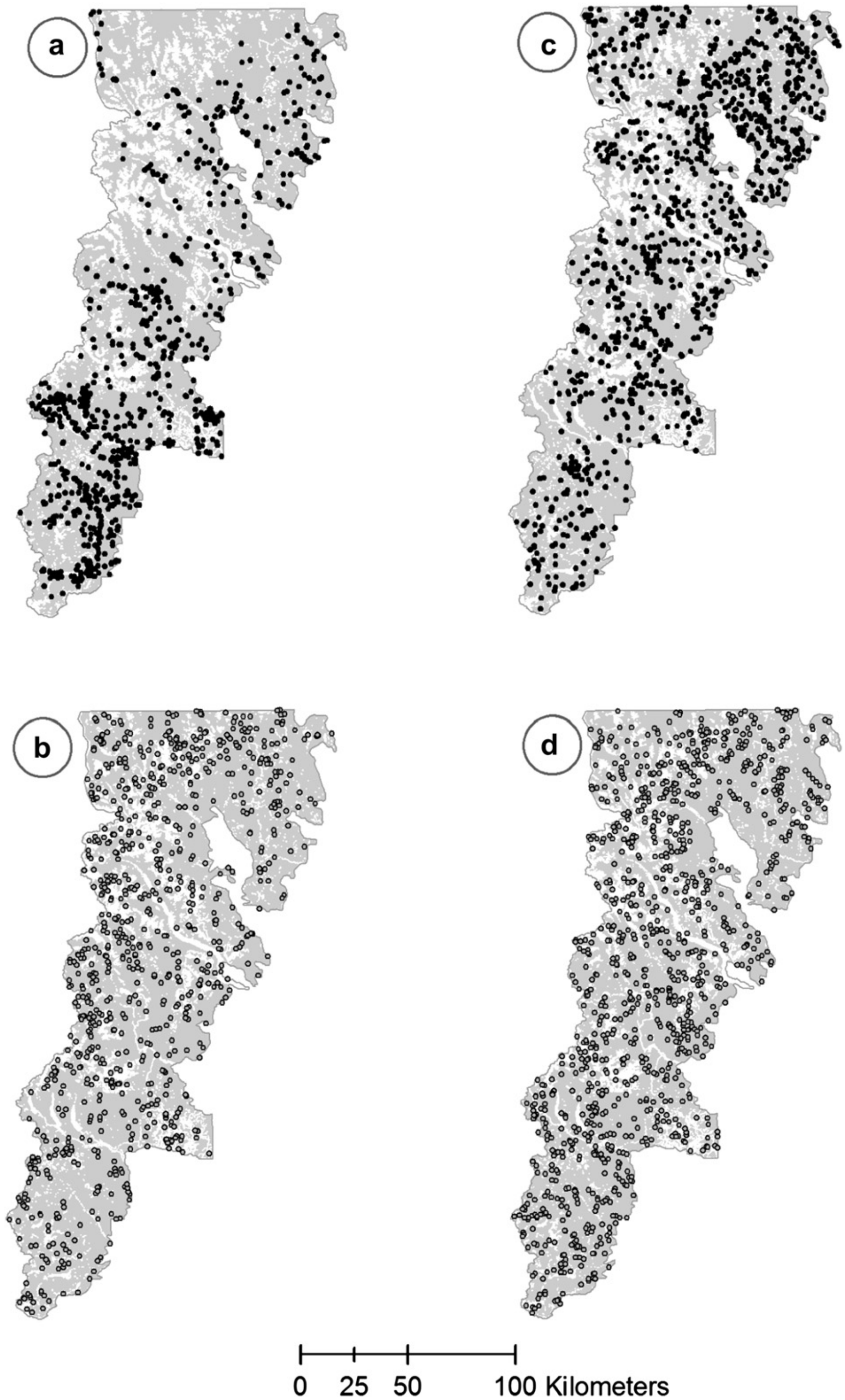

Fig. 2. (a) Human-caused case locations; (b) Human-caused control locations; (c) Lightning-caused case locations and (d) Lightning-caused control locations. Background gray indicates burnable areas and white indicates unburnable areas derived from NLCD 2001: Unburnable areas included open water, perennial ice and snow, developed medium and high intensity areas, barren land and rock.

Independent variables

Geographical information system (GIS) data were gathered from multiple sources. Data on roads and fire behavior fuel models were obtained from the US Forest Service Okanogan-Wenatchee National Forest (Table 1). Additional road data for private land ownerships were acquired from the Washington Department of Natural Resources. Data on population density (2000 block-scale population density) and distances to wildland urban interface (WUI) were obtained through the wildland urban interface national mapping project (Radeloff et al., 2005). There are two different types of WUI: interface and intermix. The interface WUI locations are where development and wildland fuel meet at a clearly defined boundary. The intermix WUI locations are where development and wildland fuel meet with no clear boundary. Because our region had a relatively small portion of intermix and interface compared to other landscape variables we combined these two classes and we used WUI as a single variable. Distances to WUI from fire ignition were included to capture the effects of rural development on fire ignition probabilities and the size of the fires.

Road and WUI datasets were converted from vector to raster datasets (30 m) of distance to nearest gravel road, distance to nearest low paved road, and distance to nearest WUI. These distances were calculated from the center of each raster cell to the nearest paved road, gravel road and WUI using the Distance function from Spatial Analyst in ArcGIS 9.3 (ESRI, 2008). We also calculated paved road density and gravel road density using the Kernel Density function with a 1000 m bandwidth in ArcGIS 9.3 (ESRI, 2008). The road densities were expressed as kilometers of road per square kilometers of area.

Spatial climate grids of precipitation (mm) and temperature (°C) were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset, Climate Normals 1971–2000. We used the June–August averages because the months of June–August have the highest number of fire ignitions and greatest area burned. Temperature and precipitation were included in our model to capture their broad-scale effects on spatial patterns of forest vegetation, fuels, and fuel moisture (Syphard et al., 2008).

A digital elevation model (DEM) was obtained from the USGS LANDFIRE project. Slope, terrain shape index, and heat load index were generated from the 30 m DEM. Terrain shape index was calculated using McNab's (1989) procedure with a modified Arc Macro Language script that calculates convex to concave shapes, with negative values representing a convex terrain shape (ridge), and positive values representing a concave terrain shape (cove). The heat load index was calculated from raw aspect values that were converted using a cosine transformation and rescaled to reflect a gradient from north-east (low values) to south-west (high values) aspects (McCune & Keon, 2002). The calculated topographic indices were used in our model as a hydrological indicator of places on the landscape that tend to disperse or collect water. Our assumption was that the topographic indices reflect the spatial pattern of moisture and its effects on fire ignition probability.

The fire behavior fuel model map was a 30 m-raster dataset consisting of 10 categories (Short grass, Grass/Timber, Brush, Dormant brush, Short needle timber, Long needle timber, mature timber, Snow/Ice, Water, and Rocks). Fuels were mapped in 2001 and 2007 using the Pacific Meridian Resource (PMR) vegetation classification and Dr. Ken Neiman's Cascade vegetation mapping information. This fuel model dataset was used because it incorporated local expert knowledge, was field checked, and incorporated more site-specific data than national level datasets (Dr. Richy Harrod, Okanogan-Wenatchee National Forest, personal communication). We used a 2001 fuel model for the fire ignition and fire size data for the period of 1997–2001 and we used a 2007 fuel model for the fire ignition and fire size data for the period of 2002–2007. The landscape pattern of fuels did not change significantly between these two different time periods; however, since the fuel model data were readily available for different time periods, we chose to use both fuel models for our analysis. Since short needle timber occurred most commonly, we selected short needle timber as the base class and represented other fire behavior fuel models as indicator variables.

Descriptive statistics

Descriptive statistics for the wilderness, roadless and roaded areas were computed accounting for masked non-burnable areas. Fire density (number of ignitions per unit area), fire size (area of fire in km^2 [burned area of individual fires reported by fire management agency]) and burned areas (the total area burned per unit area in a given time, which is a function of fire size as well as fire density) were calculated for these different landscape types. Within these landscapes, we grouped fire size into four classes: (1) human-caused small fires that are less than 200 ha, (2) human-caused large fires that are greater than 200 ha, (3) lightning-caused small fires that are less than 200 ha, and (4) lightning-caused large fires that are greater than 200 ha. We chose the 200 ha size threshold because, for severity mapping by Monitoring Trends in Burn Severity (MTBS), this size is considered large enough for severity mapping.

Ignition models

We carried out statistical analyses for fire ignition using a case-control multiple logistic regression in which all fire ignition locations (cases) were assigned values of 1 and the non-fire ignition locations (controls) were assigned values of zero. Similar case-control multiple logistic regressions have been used in previous wildfire occurrence studies (Chou, Minnich, & Chase, 1993; Kalabokidis et al., 2007; Vasconcelos et al., 2001). In this method, the case locations and control locations were compared to determine whether the environmental characteristics of the ignitions were different from the environmental characteristics of the set of random control points. We standardized the model coefficients to determine the relative importance of explanatory variables.

We generated 200 m buffers around human- and lightning-caused ignitions using ArcGIS 9.3. The same number of control locations were used as fire ignitions (1106 for lightning-caused and 874 for human-caused) and were generated by randomly selecting points outside of the fire ignition buffers and mask layer (Fig. 2b, d). This method avoided control points being in the same locations as case points and in non-burnable land cover types such as water and rock (Fig. 2). Both the case and control locations were intersected with the geoprocessed explanatory anthropogenic and biophysical variables (Table 1, Fig. 3) and values were extracted. All the distance variables were square root transformed and population density was log10 transformed to achieve normality and linearize the relationships with the dependent variables. We then tested for multicollinearity among the landscape explanatory variables by using as a cut-off criterion variation inflation factor (VIF) values greater than 10 (SAS Institute, 2010). Values of VIF did not exceeded 5, indicating that was no multicollinearity among the predictor variables. Thus, all variables were retained in the subsequent analysis. Furthermore, we generated correlograms of the model's deviance residuals to ensure there was no evidence of serious spatial autocorrelation.

We fitted full models including all independent variables, as well as reduced models based on stepwise selection. We found that the coefficients that were statistically significant in the full models were the same ones that were statistically significant in the stepwise models (with the selection of the best independent variables). Consequently, our conclusions about the influence of landscape predictor variables (including roads) would be similar whether we were working with the full or the stepwise models. We chose to report the stepwise model in our paper because they provide a more parsimonious characterization of key environmental drivers compared to the full models. All statistical analyses were done using SAS version 9.2 (SAS Institute, 2010).

Results

The mean size of human-caused wildfires was 16.7 ha and the range was 6646 ha. Human-caused wildfires accounted for 8% of total acres burned (222003 ha). The mean size of lightning-caused

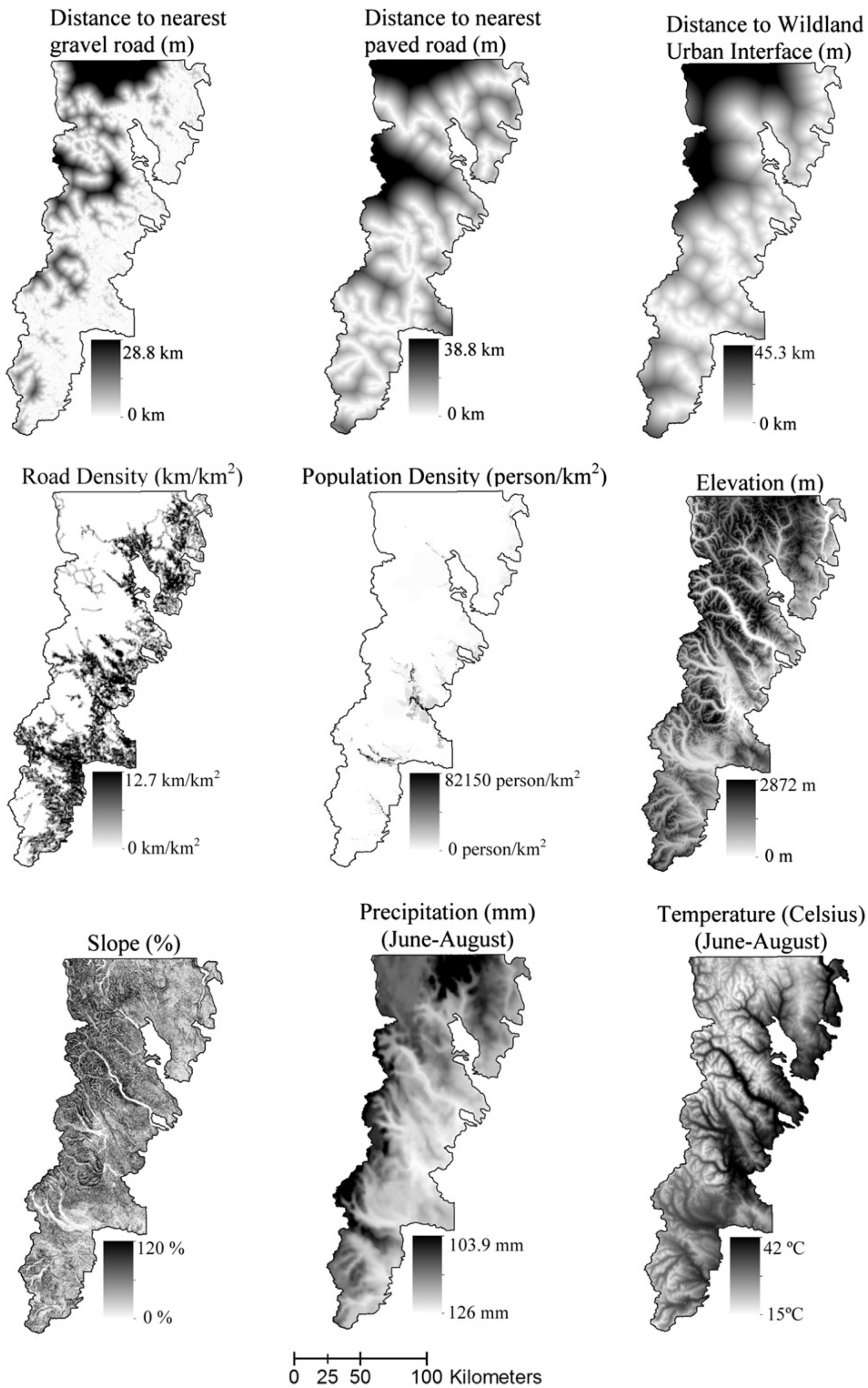

Fig. 3. Maps of selected independent variables.

wildfires was 187.7 ha and the range was 45,734 ha. Lightning-caused wildfires accounted for 92% of total acres burned. The highest number of wildfire ignitions was during the month of July for human-caused and during August for lightning-caused fires. The largest area burned was in July for both human- and lightning-caused fires. We found that human-caused wildfire ignitions were concentrated in roaded areas with high accessibility (Figs. 4 and 5). In contrast, lightning-caused fire ignitions occurred in both roadless and roaded areas. The majority of the total area burned was in roadless and wilderness areas, and was burned by a few lightning-caused fires greater than 200 ha in size (Fig. 5). The majority of the area burned by human-caused fires was in roadless and roaded areas, and was also burned by fires greater than 200 ha in size.

Human-caused fire ignitions

Distance to gravel roads was negatively associated with human-caused ignitions (Table 2), which indicated that human-caused fires

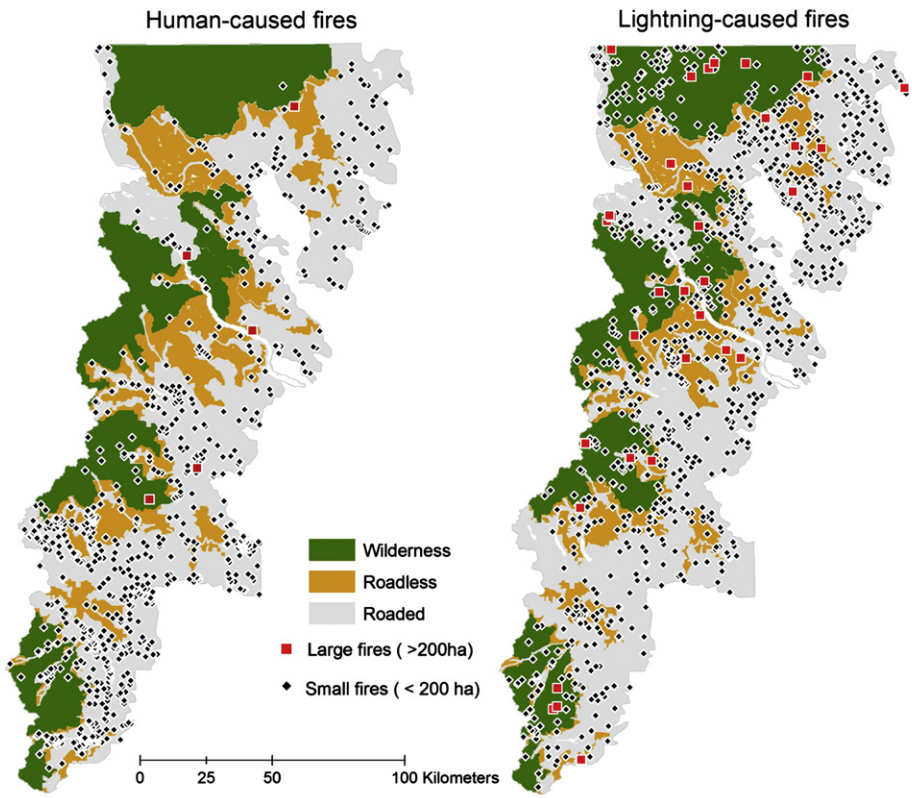

Fig. 4. Human- and lightning-caused small and large fires in the wilderness, roadless and roaded areas.

tended to start near roads. Gravel and paved road density were positively associated with human-caused fire ignitions. Distance to WUI was negatively associated with human-caused fire ignitions, indicating that fire ignitions tended to be near the WUI. Population density was negatively associated with human-caused fire ignitions. Elevation and slope were negatively associated with human-caused fire ignitions. Fire was less likely to start in the brush fuel type than in others.

Lightning-caused fire ignitions

Distance to nearest gravel roads was negatively associated with lightning-caused fire ignitions (Table 2), which indicated that ignitions tended to be near gravel roads. However, this effect size was considerably smaller than the road effect for human-caused fires. Gravel and paved road density were negatively associated with lightning-caused fire ignitions. Distance to WUI was positively associated with lightning-caused fire ignitions, indicating that ignitions tended to be far away from the WUI. Elevation was positively associated with lightning-caused fire ignitions. Precipitation was negatively associated with lightning-caused fire ignitions. Temperature was positively associated with lightning-caused fire ignitions. Lightning-caused fires were more likely to start in the long needle fuel type than in others.

Discussion

As we anticipated, road corridors significantly influenced the spatial pattern of human-caused fire ignitions. The locations of human-caused ignitions were concentrated in close proximity to gravel roads and were located where there were high densities of both gravel and paved roads. The exception was that human-caused fire ignitions were not more common closer to paved roads. Constant maintenance in paved roadsides (verges) likely reduces combustible fuels. Furthermore, paved roads are generally used for passage through forested areas, whereas gravel roads are more often used for a spectrum of human activities such as fishing, hunting and camping. These activities can involve the use of fire and therefore greater fire potential exists near gravel roads than paved roads. Our findings are generally consistent with previous studies of human-caused fire ignition in various regions of the United States, supporting the idea that human-caused fire ignitions are spatially clustered, and that road accessibility is one of the most important determinants of spatial locations of human-caused ignitions (Maingi & Henry, 2007; Syphard et al., 2007, 2008; Yang et al., 2007, 2008).

Other influences on the likelihood of human-caused fire ignitions were also consistent with previous studies. Lower slopes and lower elevation (Syphard et al., 2007; Yang et al., 2007), proximity to the WUI (Syphard et al., 2007), and high population density (Cardille, Ventura, & Turner, 2001; Maingi & Henry, 2007) are associated with human activities. However, our finding of a negative relationship between human-caused fire ignition and population density contradicted findings of previous studies by Cardille et al. (2001) in the Upper Midwest and Maingi and Henry (2007) in eastern Kentucky. In these areas dominated by deciduous hardwoods, they found more fires in high population density areas. In both of these study regions the vast majorities (over 90%) of fire ignitions are caused by humans, the percentage of private lands is higher, and population densities are higher than in our study region. The negative influence of population density on fire ignition in the east Cascades might also depend on the types and spatial patterns of human activities. For example, we would expect recreational activities such as hiking, camping and hunting on public lands to increase accidental and arson fire ignition probabilities far away from highly populated areas.

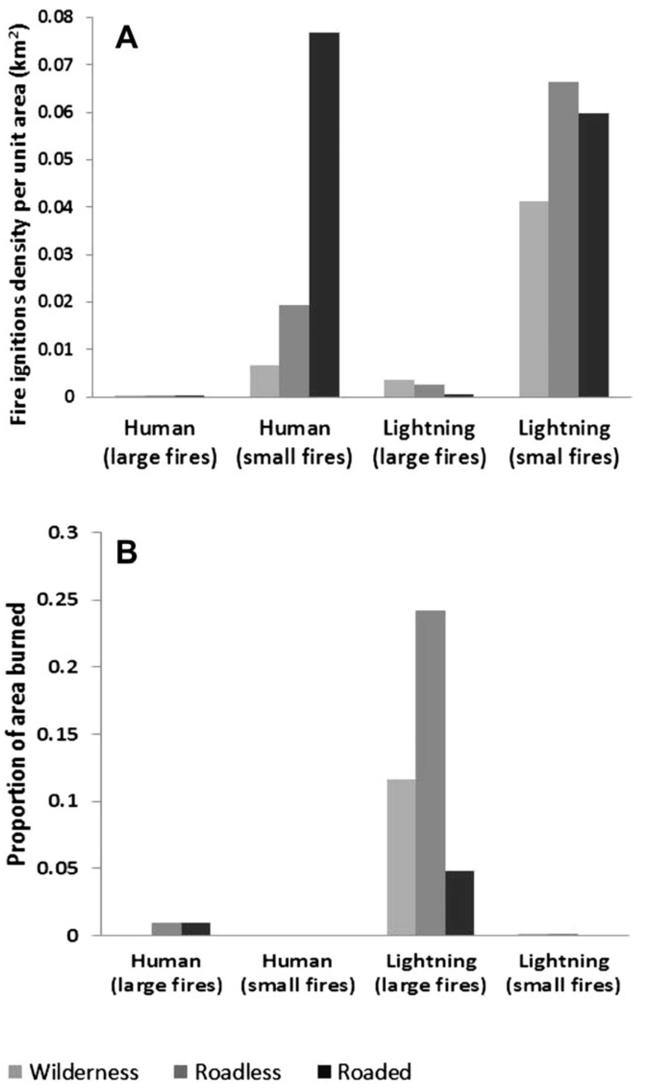

Fig. 5. (A) Fire ignitions density and (B) proportion of area burned from 1997 to 2007 in different landscape types: wilderness (5429 km^2), roadless (3904 km^2) and roaded (9882 km^2) areas.

The weak but statistically significant influence of distance to gravel roads on lightning-caused fire ignitions may be related to two different processes. First, as mentioned in the introduction, Arienti et al. (2009) hypothesized that higher availability of fine fuels along roadsides may contribute to an association between roads and lightning ignitions. More generally, forest roads create linear edge by opening canopies. These canopy openings create edge effects (Spellerberg, 2002) that can influence fuels by modifying microclimate and canopy structure (Chen et al., 1992, 1993; Spellerberg, 2002). These combined influences of changes in microclimate and forest stand dynamics extend into the neighboring interior forests (Chen et al., 1992, 1993). Road effects on fire ignitions and fire size are therefore not solely along the road edges, but extends across a broader zone over which fuels and microenvironments are altered.

Fire detection rates are higher and lightning-caused fires are more likely to be reported in human-dominated areas (Podur, Martell, & Csillag, 2003). We recognize that the relationship between road corridors and lightning-caused fires needs to be explored more thoroughly and may provide insight into spatial patterns of lightning-caused ignitions. For example, analysis of field measurements of the variability in fuels with distance to road, analysis of lightning strike data relative to actual lightning ignitions, and validation of the fire ignition data to determine if there is a detection bias related to roads (Podur et al., 2003) would be potential follow-up studies.

In contrast to human-caused ignitions, the spatial locations of lightning-caused ignitions are concentrated in areas of low gravel and paved road density and low population density. These factors are indicative of more remote locations, and these remote areas are more common at mid-to high-elevations (Van Wagtendonk & Cayan, 2008). In our study area, most mid-elevation mixed conifer forests are long needle timber fuel types. We found that this fuel type tended to be more prevalent in starting lightning-caused fires in our study region than other fuel types. The characteristics of the long needle timber fuel model structural stage and size are considered to be large trees with saplings, and canopy closure is usually greater than 70%. The vegetation size class is greater than 0.6 m diameter at breast height (DBH). Thus, long needle timber is generally mature forest with a high canopy fuel load and crown fires can occur in this fuel model under extreme fire weather conditions.

Table 2
Multivariate case-control logistic regression analyses for all variables with model coefficients (Standardized), standard errors (S.E.), and *p*-values for human- and lightning-caused fire ignitions in the East Cascades Mountains.

Cause	Variables	Estimate	S.E	*p*-Value	Standardized estimate
Human	Intercept	1.4236	0.6091	0.0194	
	Distance to nearest gravel road (meters)[a]	−0.0293	0.00534	<0.0001	−0.4660
	Gravel road density (km/km^2)[a]	0.4762	0.2037	0.0194	0.1165
	Paved road density (km/km^2)[a]	1.3674	0.2641	<0.0001	0.2703
	Distance to WUI (meters)[a]	−0.0121	0.00212	<0.0001	−0.3147
	Population density ($person/km^2$)[b]	−0.9015	0.2253	<0.0001	−0.1565
	Elevation (meters)	−0.00108	0.000203	<0.0001	−0.2596
	Slope (%)	−0.0139	0.00311	<0.0001	−0.1928
	Brush (fuel model)	−0.6587	0.1836	0.0003	−0.1308
Lightning	Intercept	−3.1251	0.8083	0.0001	
	Distance to nearest gravel road (meters)[a]	−0.00596	0.00213	0.0052	−0.1000
	Gravel road density (km/km^2)[a]	−0.3922	0.1357	0.0039	−0.0902
	Paved road density (km/km^2)[a]	−0.5119	0.2400	0.0329	−0.0581
	Distance to WUI (meters)[a]	0.00462	0.00150	0.0021	0.1137
	Elevation (meters)	0.00118	0.000198	<0.0001	0.2826
	Precipitation (June–August maximum)	−0.00019	0.000045	<0.0001	−0.1475
	Temperature (June–August maximum)	0.00107	0.000160	<0.0001	0.3492
	Long needle timber (fuel model)	0.7077	0.2485	0.0044	0.0742

[a] Square root transformed.
[b] log_{10} transformed.

Larger fires tended to occur in remote, low road density areas that were primarily located at higher elevations. One explanation for this finding is that fewer roads increases fuel continuity and results in a less fragmented landscape. As a result, there were larger fire sizes particularly in the roadless and wilderness areas. Smaller size fires tended to be located in roaded areas, presumably because of reduced fuel connectivity. In addition, high priority is given to fire suppression near populated areas. Our previous study (Narayanaraj & Wimberly, 2011) and Price and Bradstock (2010) demonstrated that roads have a strong influence on the locations of fire boundaries. Smaller fires also occured at higher elevations where unburnable areas (ice, rocks and sparse vegetation) along with mesic conditions may have limited fire spread. These areas tended to be located in wilderness areas in the eastern part of the study area (Fig. 4).

Lightning usually ignites multiple fires in the same time frame and area which increases the probability of fire growth. When lightning-caused fires occur in less populated areas, they are less likely to be noticed immediately when they are still a small extinguishable size (Podur et al., 2003). As a result, lightning-caused fires have time to spread before they are noticed and subsequently extinguished and tend to be larger than human-caused fires (Arienti et al., 2009). It is important to note that when wildland fire use is practiced, this practice tends to result in larger fires.

In summary, larger size fires tended to be in more remote areas where landscapes are less accessible to humans (ground based fire suppression tactics are difficult), less fragmented by roads, and where there is more continuous fuel connectivity. However, these fire size differences likely also partially environmental variability in vegetation and fuels along the elevation gradient. We also recognize the importance of weather and its interactions with fuel and topography on the fire environment and resulting fire behavior (Countryman, 1972; Pyne, Andrews, & Laven, 1996). For example, in situations of extreme weather (e.g., high winds), high flame lengths and high fire line intensity may facilitate fire spread across forest roads. However, we restricted our focus to relatively static landscape features and to looking at the average conditions that allow us to determine where fire ignition and fire size differences are most likely to occur on the landscape.

Conclusions

The importance of roads as transportation corridors and their access associated with human-caused fire ignitions are well-known, but less consideration has been paid to understanding the multiple influences of roads on the fire regime at a broader landscape-scale.

In our study, we compared the factors influencing lightning and human ignitions. Distance from gravel roads had a significant influence on the human-caused ignitions, whereas distance from paved roads did not. We also found an intriguing relationship between lightning-caused fire ignition and gravel roads, suggesting a broader suite of road effects on vegetation structure, microenvironments, fuels and ignition potential that may have implications for fire management and prediction of the spatial patterns of fires.

Although, human-caused fire ignitions are much more frequent in roaded areas compared to roadless areas, it can be argued that the high rate of ignition is counterbalanced by road effects on fire size. Although most fires occur in the heavily roaded areas, the total area burned by these fires is miniscule. In contrast, large fires in roadless and wilderness areas burn the greatest area. Thus, from the standpoint of the overall fire return interval, the impact of forest roads on limiting fire spread seems to be greater than the impact of roads on increasing fire ignitions. These differences are at least partially due to the direct and indirect effects of roads on fire boundary locations, but also likely reflect the greater application of wildland fire use in roadless and wilderness areas and differences in vegetation and fuels along the elevation gradient.

Our landscape-level analysis documents key spatial relationships and provides a framework to help structure future investigations. Several other papers (Chou et al., 1993; Kalabokidis et al., 2007; Vasconcelos et al., 2001) using similar methodology have made valuable contributions to our ability to understand and predict where in the landscape large and small fires are most likely to occur. Our work makes a further contribution by focusing on a new geographic region with a broad range of ecological characteristics, demonstrating the roads influence both human- and lightning-caused fire. Furthermore, our study suggests that roads and their edge effects should be acknowledged as a unique type of landscape component with fuel characteristics different from neighboring interior areas. Road edges influence fuels through various environmental factors such as reduced canopy closure, increased temperature, wind, and forest management activities. Roads and their edge effects influence fire regimes and should be more rigorously studied and incorporated into wildland fire management and planning.

Acknowledgments

We would like to acknowledge support from the Geographic Information Science Center of Excellence, South Dakota State University for research funding. We thank Patrick Murphy and Dr. Richy Harrod with the Supervisor's Office of the Okanogan-Wenatchee National Forest for making the GIS data available and for their help during my field visit to the Wenatchee National Forest.

References

Agee, J. (1994). Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. In *General technical report USDA forest service*. Pacific Northwest Research Station.

Arienti, M. C., Cumming, S. G., Krawchuk, M. A., & Boutin, S. (2009). Road network density correlated with increased lightning fire incidence in the Canadian western boreal forest. *International Journal of Wildland Fire, 18*, 970–982.

Brosofske, K. D., Cleland, D. T., & Saunders, S. (2007). Factors influencing modern wildfire occurrence in the Mark Twain National Forest, Missouri. *Southern Journal of Applied Forestry, 31*, 73–84.

Brown, T. J., Hall, B. L., Mohrle, C. R..Reinbold, H. J. (2002). Coarse assessment of federal wildland fire occurrence data. Unpublished Report for the National Wildfire Coordinating Group. In. Desert Research Institute, Division of Atmospheric Sciences, Program for Climate, Ecosystem and Fire Applications.

Camp, A., Oliver, C., Hessburg, P., & Everett, R. (1997). Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. *Forest Ecology and Management, 95*, 63–77.

Cardille, J. A., Ventura, S. J., & Turner, M. G. (2001). Environmental and social factors influencing wildfires in the Upper Midwest, United States. *Ecological Applications, 11*, 111–127.

Chen, J., Franklin, J. F., & Spies, T. A. (1992). Vegetation responses to edge environments in old-growth Douglas-fir forests. *Ecological Applications, 2*, 387–396.

Chen, J., Franklin, J. F., & Spies, T. A. (1993). Contrasting microclimates among clearcut, edge, and interior old growth Douglas-fir forest. *Agricultural and Forest Meteorology, 63*, 219–237.

Chou, Y. (1992). Management of wildfires with a Geographical Information System. *International Journal of Geographic Information Systems, 6*, 123–140.

Chou, Y. H., Minnich, R. A., & Chase, R. A. (1993). Mapping probability of fire occurrence in San-Jacinto Mountains, California, USA. *Environmental Management, 17*, 129–140.

Chuvieco, E., Allgöwer, B., & Salas, F. J. (2003). Wildland fire danger estimation and mapping. The role of remote sensing data. In *Series in remote sensing* (pp. 197–218). Singapore: World Scientific Publishing.

Countryman, C. (1972). The fire environment concept. In *Pacific southwest forest and ranger experiment station*. Berkeley, CA: U.S. Forest Service.

D'Antonio, C. M., & Vitousek, P. M. (1992). Biological invasions by exotic grasses, the grass fire cycle, and global change. *Annual Review of Ecology and Systematics, 23*, 63–87.

ESRI. (2008). *Environmental systems research institute, ArcGIS desktop*. [Computer Program]. Redlands, California.

Everett, R., Schellhas, D., Spurbeck, D., Ohlson, P., & Keenum, D. T. A. (1997). Structure of northern spotted owl nest stands and their historical conditions on the eastern slope of the Pacific Northwest Cascades, USA. *Forest Ecology and Management, 94*, 1–14.

Everett, R., Schellhaas, R., Keenum, D., & Spurbeck, D. P. O. (2000). Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. *Forest Ecology and Management, 129*, 207–225.

Finney, M. A. (2005). The challenge of quantitative risk analysis for wildland fire. *Forest Ecology and Management, 211*, 97–108.

Flannigan, M. D., & Wotton, B. M. (1991). Lightning ignited forest fires in Northwestern Ontario. *Canadian Journal of Forest Research, 21*, 277–287.

Forman, R. T. T., & Alexander, L. E. (1998). Roads and their major ecological effects. *Annual Review of Ecology and Systematics, 29*, 207–231.

Franklin, J., & Dyrness, C. (1973). Natural vegetation of Oregon and Washington. In *General technical report PNW*. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Gucinski, H., Furniss, M. J., Ziemer, R. R., & Brookes, M. H. (2001). *Forest roads: A synthesis of scientific information. General Technical Report PNW-GTR-509*. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Guyette, R. P., Muzika, R. M., & Dey, D. C. (2002). Dynamics of an anthropogenic fire regime. *Ecosystems, 5*, 472–486.

Hessburg, P. F., & Agee, J. K. (2003). An environmental narrative of Inland Northwest United States forests, 1800–2000. *Forest Ecology and Management, 178*, 23–59.

Hessl, A. E. (2011). Pathways for climate change effects on fire: models, data, and uncertainties. *Progress in Physical Geography, 35*, 393–407.

Hessl, A. E., McKenzie, D., & Schellhaas, R. (2004). Drought and pacific decadal oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications, 14*, 425–442.

Kalabokidis, K., Koutsias, N., & Konstantinidis, P. C. V. (2007). Multivariate analysis of landscape wildfire dynamics in a Mediterranean ecosystem of Greece. *Area, 39*, 392–402.

Kellogg, L. B., McKenzie, D., Peterson, D. L., & Hessl, A. E. (2008). Spatial models for inferring topographic controls on historical low-severity fire in the eastern cascade range of Washington, USA. *Landscape Ecology, 23*, 227–240.

Kernan, J. T., & Hessl, A. E. (2010). Spatially heterogeneous estimates of fire frequency in ponderosa pine forests of Washington, USA. *Fire Ecology, 6*(3), 117–135.

Latham, D., & Williams, E. (2001). Lightning and forest fires. In E. D. Johnson, & K. Miyanishi (Eds.), *Forest fires: Behavior and ecological effects* (pp. 376–413). San Diego, CA: Academic Press.

Lugo, A. E., & Gucinski, H. (2000). Function, effect, and management of forest roads. *Forest Ecology and Management, 133*, 249–262.

Lutz, J. A., van Wagtendonk, J. W., Thode, A. E., Miller, J. D., & Franklin, J. F. (2009). Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. *International Journal of Wildland Fire, 18*, 765–774.

McCune, B., & Keon, D. (2002). Equations for potential annual direct incident radiation and heat load. *Journal of Vegetation Science, 13*, 603–606.

McNab, W. H. (1989). Terrain shape index – quantifying effect of minor landforms on tree height. *Forest Science, 35*, 91–104.

Maingi, J. K., & Henry, M. C. (2007). Factors influencing wildlife occurrence and distribution in eastern Kentucky, USA. *International Journal of Wildland Fire, 16*, 23–33.

Miyanishi, K., & Johnson, E. A. (2001). A re-examination of the effects of fire suppression in the boreal forest. *Canadian Journal of Forest Research, 31*, 1462–1466.

Narayanaraj, G., & Wimberly, M. C. (2011). Influences of forest roads on the spatial pattern of wildfire boundaries. *International Journal of Wildland Fire, 20*, 792–803. doi:10.1071/WF10032.

Parendes, L. A., & Jones, J. A. (2000). Role of light availability and dispersal in exotic plant invasion along roads and streams in the H.J. Andrews Experimental Forest, Oregon. *Conservation Biology, 14*, 64–75.

Perry, D. A., Hessburg, P. F., Skinner, C. N., Spies, T. A., Stephens, S. L., Taylor, A. H., et al. (2011). The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management, 262*, 703–717.

Podur, J., Martell, D. L., & Csillag, F. (2003). Spatial patterns of lightning-caused forest fires in Ontario, 1976–1998. *Ecological Modelling, 164*, 1–20.

Price, O. F., & Bradstock, R. A. (2010). The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia. *International Journal of Wildland Fire, 19*, 35–45.

Pyne, S. J., Andrews, P. J., & Laven, R. D. (1996). *Introduction to wildland fire*. New York-Chichester, UK: John Wiley & Sons.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). The wildland–urban interface in the United States. *Ecological Applications, 15*, 799–805.

Reed, R. A., Johnson-Barnard, J., & Baker, W. L. (1996). Contribution of roads to forest fragmentation in the Rocky Mountains. *Conservation Biology, 10*, 1098–1106.

Rohrman, D. F. (2008). Road rules. *Frontiers in Ecology and the Environment, 6*, 162–163.

SAS Institute Inc. (2010). *SAS/STAT 9.2 user's guide*. Cary, North Carolina, USA.

Sibold, J. S., Veblen, T. T., & González, M. E. (2006). Spatial and temporal variation in historic fire regimes in subalpine forests across the Colorado Front Range. *Journal of Biogeography, 33*, 631–647.

Spellerberg, I. F. (2002). *Ecological effects of roads*. USA: Science Publisher, Inc.

Spellerberg, I. F. (1998). Ecological effects of roads and traffic: a literature review. *Global Ecology and Biogeography, 7*, 317–333.

Stoner, J., & Adams, R. D. S. (2004). Management implications of increased fuel loads following exotic grass invasion. *Ecological Management and Restoration, 5*, 68–69.

Syphard, A. D., Radeloff, V. C., Keeley, J. E., Hawbaker, T. J., Clayton, M. K., Stewart, S. I., et al. (2007). Human influence on California fire regimes. *Ecological Applications, 17*, 1388–1402.

Syphard, A. D., Radeloff, V. C., Keuler, N. S., Taylor, R. S., Hawbaker, T. J., Stewart, S. I., et al. (2008). Predicting spatial patterns of fire on a southern California landscape. *International Journal of Wildland Fire, 17*, 602–613.

Syphard, A. D., Radeloff, V. C., Hawbaker, T. J., & Stewart, S. I. (2009). Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. *Conservation Biology, 23*, 758–769.

Trombulak, S. C., & Frissell, C. A. (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology, 14*, 18–30.

Turner, M. G., & Romme, W. H. (1994). Landscape dynamics in crown fire ecosystems. *Landscape Ecology, 9*, 59–77.

USDA Forest Service. (2000). *Forest Service roadless area conservation. Final environmental impact statement, Vol. 1*, Washington, DC.

Van Wagtendonk, V., & Cayan, D. (2008). Temporal and Spatial Distribution of Lightning Strikes in California in relation to large-scale weather patterns. *Fire Ecology, 1*, 34–57.

Vasconcelos, M., Silva, S., Tome, M., Alvim, M., & Jmc, P. (2001). Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. *Photogrammetric Engineering Remote Sensing, 67*, 73–81.

Vasilakos, C., Kalabokidis, K., Hatzopoulos, J., Kallos, G., & Matsinos, Y. (2007). Integrating new methods and tools in fire danger rating. *International Journal of Wildland Fire, 16*, 306–316.

Vega Garcia, C., Woodard, P. M., Titus, S. J., Adamowicz, & Lee, B. S. (1995). A logit model for predicting the daily occurrence of human caused forest fires. *International Journal of Wildland Fire, 5*, 101–111.

Watts, R. D., Compton, R. W., McCammon, J. H., Rich, C. L., Wright, S. M., Owens, T., et al. (2007). Roadless space of the conterminous United States. *Science, 316*, 736–738.

Yang, J., He, H. S., Shifley, S. R., & Gustafson, E. J. (2007). Spatial patterns of modern period human-caused fire occurrence in the Missouri Ozark Highlands. *Forest Science, 53*, 1–15.

Yang, J., He, H. S., Sturtevant, B. R., Miranda, B. R., & Gustafson, E. J. (2008). Comparing effects of fire modeling methods on simulated fire patterns and succession: a case study in the Missouri Ozarks. *Canadian Journal of Forest Research, 38*, 1290–1302.