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# THE EFFECT OF RANDOM AND SPATIALLY EXPLICIT LIGHTNING AND HUMAN-CAUSED IGNITIONS ON SIMULATED BURN PROBABILITIES AT SMALL SCALES

By

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The effect of random and spatially explicit lightning and human-caused ignitions on simulated burn probabilities at small scales

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# The effect of random and spatially explicit lightning and human-caused ignitions on simulated burn probabilities at small scales

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## Abstract

Our overall goal was to assess the difference between annual wildfire burn probability (BP) generated from simulation models using random ignitions versus spatially explicit ignitions for wildland urban interface (WUI) areas and designated wilderness in the Rocky Mountain West, and infer whether one may be more useful than the other at small scales. We collected all available ignition data from logbooks, spreadsheets and the internet for a 1282 km$^2$ study area within a 10 km buffer of the Rattlesnake National Recreation Area (RNRA) and Rattlesnake Wilderness (RW), Montana, which also included WUI. These ignitions were on small private landholdings, as well as on public land, for the years 2000-2010, and enabled the identification of specific wildfire ignition zones, that facilitated the parameterization of wildfire simulation models to more closely reflect where ignitions occur. The wildfire ignition model Randig was used to create BP maps for our focus area (the Rattlesnake Valley, the RNRA and RW) under eight ignition scenarios: two types of ignitions (human-caused and lightning-caused), two spatial patterns of ignition (random and spatially explicit), and two levels of wildfire ignition frequency (average and high). Spatially explicit ignition scenarios based on actual human-caused and lightning ignition locations generated higher BP in the WUI and Wilderness in our focus area relative to random ignition scenarios. Our results indicate that spatially explicit ignition data should be used whenever possible to estimate BP at small scales, to support placement of fuel treatments, deployment of wildfire suppression resources, and for WUI preparedness including prevention programs and homeowner education.

**Additional Keywords:** burn probability, bushfire, spatially explicit ignitions, wilderness, wildfire risk, wildfire simulation model, wildland urban interface

## Introduction

Beginning with the year 2000, wildland fire activity increased in the United States resulting in substantial ecological damage and financial cost to private and public resources (Calkin *et al*. 2011). There has been a trend toward larger fires and increased exposure of structures to significant wildfire events. In the Rocky Mountain states, for example, there were 30% more fires over 40,500 ha (100,000 acres) from 2000-2009, than during the previous two decades (1980-1999) combined (Table 1; USGS 2010). In Montana where fires are generally smaller, there were twice as many fires over 4,000 ha (10,000 acres) from 2000-2009 than during the previous two decades combined.

A number of factors have been implicated as causes for the increase in the number of large fires. For example, the length of the average fire season (the time between the reported first wildfire discovery date and the last wildfire control date) in the Western United States was 78 days (64%) longer between 1987 and 2003, relative to the period 1970 to 1986, due to the increasing warming trends (Westerling *et al*. 2006). Since the global climate system is warming (ACIA 2004; Kolbert 2006; IPCC 2007:), it is not surprising that climate in western Montana is warming also (Pederson *et al*. 2010). The rise in annual average temperature in Western Montana between 1900 and 2005 is 1.8 times greater than the rise in global annual average temperatures over the same period (Lugina *et al*. 2005). Furthermore, drought and an increase in fuel quantities due to past successful fire suppression (Taylor and Skinner 2003; Hessburg *et al*. 2005; Naficy *et al*. 2010) has added to the incendiary nature of these long hot dry fire seasons, producing larger, more severe wildfires (Finney and Cohen 2003, Cohen 2008).

Of particular concern are areas where communities abut or are in close proximity to forest areas. The area where homes and public infrastructure meet wildland fuels is defined as the wildland urban interface (WUI) (Theobald and Romme 2007). In the fire-prone areas of the western Rocky Mountains, 1.57 million homes fall within the WUI, and this number is expected to increase to 2.2 million by the year 2030. (OIG 2006). New residents are attracted by amenities, such as living in areas rich with scenery, wildlife, clean water and recreational opportunities (Power and Barrett 2001, Swanson *et al*. 2003, OIG 2006). As more people move to be near forested areas, the likelihood of structures being lost to wildfire will increase due in part to the larger numbers of homes at risk, but also due to increased likelihood of human-caused ignitions.

Numerous studies conducted in different areas of the world have shown that proximity to roads, population, and forest-based recreation activities can substantially increase the likelihood of human-caused ignitions. In the U.S., designated wilderness areas are to be managed to preserve their wilderness character, including allowing or restoring a “natural” fire regime [1]. Non-management ignited, human-caused wildfires may threaten wilderness values, and not be for resource benefit (Watson 2012). Contemporary human-caused ignitions can occur in places and at a frequency unlikely to mimic “natural” ignitions, and cause fire patterns on the landscape unlike those caused by lightning, which can be of special concern in designated wilderness areas.

Wildfire simulation models, such as FARSITE (Finney 1998) and FSim (Finney *et al*. 2011), are used to estimate annual wildfire burn probability (BP), using ignitions, vegetation, weather and topography as inputs. Historic information about human-caused and lightning ignitions, and subsequent spread of wildfire, has been used to parameterize these wildfire simulation models to facilitate evaluation of land and fire management opportunities for mitigating wildfire risk. Nevertheless, spatially explicit ignition data is not always readily available, and many studies, have used random ignition locations to simulate wildfire on the landscape (Lacroix *et al*. 2006, Ager *et al*. 2007, Parisien *et al*. 2007, Schmidt *et al*. 2008, Suffling *et al*. 2008, Bar Massada *et al*. 2009, Carmel *et al*. 2009). While random ignitions may be acceptable for wildfire simulations to determine BP over large areas (Finney *et al*. 2011), recent research suggests that the inclusion of ignition location in simulation models influences wildfire risk patterns (Parisien *et al*. 2011; Parks *et al* 2012). Because a large percentage of human-caused ignitions can occur in the WUI and other areas frequented by people, replacing them with random ignitions could substantially underestimate BP near the WUI. Similarly, since lightning ignitions increase with elevation (Parks *et al*. 2012; van Wagtendonk and Cayan 2008), random placement of lightning ignitions could substantially affect BP estimates. While random human-caused and lightning ignitions can be useful for simulation modeling, especially at larger scales, they may introduce substantial error at smaller scales, because human-caused and lightning ignitions are not random. Poor accuracy in local burn BP estimates may promote an inefficient distribution of fire management resources and fuel treatments, thus putting people, property and natural resources at risk.

The objective of the current study is to assess the extent to which using random ignitions to estimate BP could misinform wildfire managers at the local scale relative to using spatially explicit wildfire ignitions. We consider the alternative BP estimates in the context of two resources at risk: WUI and wilderness. If a large proportion of human-caused ignitions occur in or near the WUI, then it is likely that BP estimates based on random ignitions will underestimate wildfire risk to the WUI and adjacent forest. The paper proceeds with a review of wildfire ignition literature. This is followed by a description of the study area wildfire ignition data and wildfire simulation procedures. Results from the different ignition scenarios are then reported and discussed.

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[1] In the wildfire season of 2012, there was a temporary exception to this. Due to limited funding, all fires were to be suppressed, even in wilderness, unless approval was granted by the regional forester for an exception.

## Wildfire Ignition Literature

There is a growing body of literature on factors that are correlated with human-caused and lightning ignitions. Research on human-caused wildfire ignitions has revealed that proximity to roads, population and recreation are often statistically significant explanatory variables. Early research by Chuvieco and Congalton (1989) used proximity to roads and recreation areas in their assessment of wildfire risk on the Mediterranean coast of Spain. Morrison (2007) found that 88% of all wildfires in the United States are caused by humans, and that 95% of these fires occurred within 800 m of roads. Yang *et al*. (2007, 2008) found that proximity to roads increased the probability of fire occurrence in the Missouri Ozark Highlands in the United States. Scott *et al.* (2012) determined that, on the Bridger-Teton National Forest in Wyoming, United States, as distance to roads increased anthropogenic ignitions decreased. Romero-Calcerrada *et al*. (2010) found that in the southwest of Madrid (central Spain), the spatial pattern of ignition risk is mainly defined by distances from roads. Other studies in North America, Europe, China and India have found that wildfire ignitions are negatively correlated with increased distance to roads, population centers, and WUI (Vega-Garcia *et al*. 1993, Badarinath *et al*. 2004, XU Dong *et al*. 2005, Catry *et al*. 2007, Maingi and Henry 2007, Syphard *et al*. 2008), and positively correlated with population density and recreation activities (Cardille *et al*. 2001, Pew and Larsen 2001, Chapin *et al*. 2003, Romero-Calcerrada *et al*. 2008). Most of the cited studies adopted spatial buffers of between 50 m and 1000 m around roads to explain human-caused ignition probability, although some studies also examined buffers of between 2 km and 300 km (Vega-Garcia *et al*. 1995, Kovacs *et al*. 2004, Calef *et al*. 2007, Catry *et al*. 2007, Loboda and Csiszar 2007, Morrison 2007, Catry *et al*. 2009).

Spatially explicit wildfire ignition frequency data, both human-caused and lightning-caused, is used to model probability of ignition in order to estimate BP and risk. Often the wildfire ignition frequency data is limited to public lands and large private landholdings, and is gathered by a national, state or regional government agency. Data describing ignitions on small private landholdings in or adjacent to residential development are often lacking. Nevertheless, local ignitions on small private landholdings are important because of the immediate threat to life, property and infrastructure. Hence, not accounting for human-caused ignitions on small private landholdings may generate misleading estimates of probability of ignition, BP and fire risk.

A review of studies that estimate probability of ignition, BP and risk using spatially-explicit ignitions, found only 22 that used local human-caused ignition data: *13 in Europe*, specifically Spain (Amatulli *et al*. 2007, Benavent-Corai *et al*. 2007, Romero-Calcerrada *et al*. 2008, Romero-Calcerrada *et al*. 2010, Vilar *et al*. 2010, Badia *et al*. 2011, Gonzales-Olabarria *et al*. 2011, Vilar del Hoyo *et al*. 2011), Portugal (Catry *et al*. 2007, Catry *et al*. 2009, Costa *et al*. 2010), France (Lampin-Maillet *et al*. 2009), and Greece (Vasilakos *et al*. 2009); and *9 in the*

*United States*, specifically California (Keeley *et al*. 1999, Keeley and Fotheringham 2003, Syphard *et al*. 2008, Bar Massada *et al*. 2011), Alaska (DeWilde and Chapin 2006, Calef *et al*. 2007), Montana (Close 1995), Florida (Genton *et al*. 2006), and Wyoming (Scott *et al*. 2012). Statistical methods were used by 17 of these studies to estimate human-caused ignition probability; most of these were regression models using socioeconomic and environmental variables. In five studies, graphic displays of information (maps, charts and graphs) were used to summarize probability of human ignition (2), the size of human-caused fires (2), or how human ignitions are affected by housing density (1).

In the above 22 studies, there were a wide range of sizes of study areas and of human-caused ignition density. For the 8 studies in Spain, 4 were in the region of Madrid (central Spain), 2 in the region of Catalonia (northeast Spain), 1 in the region of Aragon (northeast Spain), and 1 in the Mediterranean region of Valencia, with ignition densities ranging from 0.00005/ha/year to 0.00081/ha/year. In Portugal, which has the highest density of wildfire ignitions among southern European countries (since 2000 averaging 28,500/year with 97% being human caused, Catry *et al* (2009)), 2 studies used the entire country as the study area finding an ignition density of 0.00275/ha/year, while the third study found a range of 0.001 to 0.02 ignitions/ha/year only within individual mainland government districts which had complete fire statistics for their counties. The French study found 0.00029 ignitions/ha/year for a study area in south-eastern France, while the Greek study found 0.00008 ignitions/ha/year on the island of Lesvos in the northeastern Aegean Sea. There were 6 studies (of the 9 in the United States) that found the following ignition densities: 3 in California ranging from 0.00009 to 0.00429 ignitions/ha/year, 1 in the St Johns River Water Management District in Florida with 0.00037 ignitions/ha/year, and 1 on the Bridger-Teton National Forest in Wyoming with 0.00001 ignitions/ha/year. Since our study area is located in Missoula County, it is important to note that there was 1 study in Missoula County, Montana that estimated 0.00025 ignitions/ha/year,

Of the above 22 studies, 6 estimated spatially explicit human-caused ignition density grids or zones (Genton *et al*. 2006, Amatulli *et al.* 2007, Syphard *et* al. 2008, Costa *et al.* 2010, Bar Masada *et al*. 2011, Scott *et al*. 2012). Only two studies (Bar Massada *et al*. (2011); Scott *et al*. (2012)) used a fire simulation model with local human-caused ignitions to estimate BP.

Bar Massada *et al*. (2011) used FARSITE simulations with random and spatially explicit ignitions to quantify the influence of ignition locations on BP in the Santa Monica Mountains in California, United States, under normal and extreme weather conditions. Their results indicate that the spatial predictions of fire spread patterns may be substantially influenced by the location of ignitions used in fire simulation models. However, when fire simulations are conducted under extreme weather conditions (when fire spread is greatest), the substantial bias toward larger fires which is introduced by using a random ignition location model may be reduced (Bar Massada *et al*. 2011).

Scott *et al*. (2012) used FSIM with spatially explicit human-caused and lightning ignitions to assess what effect the timing and location of ignitions had on whether an unsuppressed wildfire reached the WUI on the Bridger-Teton National Forest in Wyoming, United States. They found that fires reaching the WUI defense zone started near it, and came from all directions. They also found that early season (May) wildfires were several times more likely to reach the WUI defense zone than those starting later.

## 3.0 METHODS

### 3.1 Study Area

Western Montana has experienced several severe fire seasons since 2000, and the growing city of Missoula (pop. 62,923, U.S. Census Bureau 2010) is proximate to the USDA Forest Service Rattlesnake National Recreation Area (RNRA, 11,300 ha) and Rattlesnake Wilderness (RW, 13,400 ha). As illustrated in Figure 1, a 1282 km$^2$ study area within a 10 km buffer of the RNRA and RW, which also included WUI, was selected to examine the effect of spatially explicit ignitions versus random ignitions on wildfire burn probabilities. The vegetation in the study area, which ranges in elevation from 1067 m to 2627 m, can be characterized as low to high-elevation forest, shrubland and grassland (Figure 2). With successful wildfire suppression since 1919, the year of the last major wildfire in the area which burned 18,200 ha (Anon. 1919), forest fuels have accumulated, increasing the likelihood that future fires will be more severe and will threaten homes.

Fire regimes vary throughout the study area (Hann and Bunnell 2001; Rollins 2009; Barrett *et al*. 2010). The low elevation ponderosa pine (*Pinus ponderosa*)-Douglas fir (*Psuedotsuga menziesii*) forest in the study area was historically characterized by frequent (0-35 years) low-severity fire (Arno and Allison-Bunnell 2002; Arno and Fiedler 2005), or less frequent (35-100 years) mixed-severity fire. This fire regime characterizes the majority of the RNRA. The mid-elevation Engelmann spruce (*Picea engelmannii*)-subalpine fir (Abies lasiocarpa) -lodgepole pine (*Pinus contorta*) forest has historically experienced less frequent (35-200 years) mixed severity to stand replacement fires. The high elevation whitebark pine (*Pinus albicaulis)* -lodgepole pine forest historically has experienced infrequent (200-500 years) stand replacement fires. This fire regime characterizes the majority of the northern half of the Rattlesnake Wilderness, and the area immediately to the north and west of the Wilderness (Rollins 2009). The low elevation forest has experienced moderate departure from the historic fire regime due to fire suppression (Pyne 1982; Arno *et al*. 1995; Keane *et al*. 2002; Keeling *et al*. 2006; Rollins 2009; Barrett *et al*. 2010). The past 80-100 years of fire suppression (Arno

1980; Pyne 1982; Arno and Allison-Bunnnell 2002), would not have caused a significant departure from the historic fire regime in the mid to upper elevation forests, because these forests historically have less frequent (35-200 years) or infrequent (200-500 years) fire return intervals (Rollins 2009).

The focus area within the study area is the Rattlesnake Valley, the RNRA and RW. The WUI focus area is the Rattlesnake Valley, a residential area of Missoula that is highlighted in Figure 1 and characterized by hundreds of homes interspersed within 2 km of Rattlesnake creek for a distance of about 5.5 km north of Interstate Highway 90 to the RNRA boundary. Missoula County, where the population has increased by more than 14% (U.S. Census Bureau 2000 & 2010) since 2000, is no exception to the trend toward more homes in the WUI. The WUI focus area has trees interspersed along the Rattlesnake Creek and hillsides, which become denser with proximity to the RNRA. There has not been a major wildfire in the Rattlesnake residential area since the fire of 1919 (Anon. 1919) which started in the Grant Creek drainage, directly to the west, and burned out almost all the homes and vegetation in three smaller drainages on the west side of the Rattlesnake Valley, before burning most of the RNRA, and a small area in the RW, and continuing northeast for approximately 17 km to Placid Lake (Poe and Poe 1991).

The focus area is well suited to this research because of the presence of both WUI and wilderness values at risk. An escaped wildfire ignition in the WUI of the Rattlesnake Valley (or one of the zones immediately to the south of or adjacent to the Rattlesnake Valley) could burn into the Wilderness, which is as little as 5.5 km from homes. A good example of this possibility was the human-caused West Riverside Fire (perimeter illustrated in Figure 2) in 2011, which started at low elevation in the WUI, threatened houses, cost $5.5 million to suppress (MT DNRC 2011A), was the number one fire in the nation for six days (NICC 2011), and threatened to burn the RNRA. The energy release component (ERC[2]) for the start date (August 22, 2011) was only at the 83rd percentile value of 66, but 1 hour to 100 hour fuel moistures were at only 4-7% (Missoula Remote Automatic Weather Station (RAWS) 10-24-2012), and 30-40 mph winds were occurring during a frontal passage (MT DNRC 2011B). The fire started on a steep south facing slope in the dry fine fuels. The fire was eventually contained at 1540 ha (3800 acres) (MT DNRC 2011B), about 1.5 km from the RNRA boundary. But if it had defied all suppression efforts and escaped control, it could have gone into the RNRA, and eventually the RW. Human-caused fires coming from the WUI could produce significantly different BP patterns than lightning-caused fires that start in the wilderness or an adjacent forested area, which could threaten wilderness values. Given that prevailing summer winds are from the southwest, the

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[2] ERC is an indicator of fire danger which combines weather conditions (temperature and relative humidity, but not including wind) and fuel moisture conditions (dead 1 to 100 hour fuels and 1000 hour fuels, and live herbaceous and woody fuels) as they influence fuel availability for ignition. The ERC is based on the estimated potential available energy released per unit area of a fire's propagating flame zone (Cohen 2012: Deeming *et al*. 1977).

Rattlesnake Valley WUI and the drainages to the west of the Rattlesnake Valley are of particular concern regarding ignitions that could impact the RW. Additionally, a fire could burn out of the RNRA or RW and threaten homes in the Rattlesnake Valley WUI. During severe fire behavior conditions, the wind in the study area is often from the northwest (Ryan 2012).

### 3.2 Wildfire Ignition Data

All available data on human-caused and lightning ignitions for the study area were compiled for the years 2000 to 2010 from all five fire management agencies that operate in the study area, namely the Missoula City Fire Department, the Missoula Rural Fire District, the US Forest Service (Forest Service), the Montana Department of Natural Resources and Conservation (DNRC), and the Bureau of Indian Affairs (BIA) for the Confederated Salish & Kootenai Tribes (CSKT). This period was chosen because wildfire activity in the U.S. has changed dramatically since 2000 (Calkin *et al*. 2011), and also because there has been better record keeping since 2000.

DNRC wildfire ignitions data was obtained from the MT DNRC Fire and Aviation Bureau Website (MT DNRC 2010). The USFS and BIA for the CSKT wildfire ignition data for the study area were obtained from the Federal Fire Occurrence Website (USGS 2010). Fire start data from the Missoula City Fire Department and Missoula Rural Fire District was carefully compiled over many months from hand-written logbooks, as well as spreadsheet programs and digitized information storage sites. To the best of our knowledge, this level of fire ignition data collection had not been conducted to estimate wildfire ignition probability and parameterize wildfire simulation models in the Western United States before.

The Missoula Rural Fire District and the Missoula City Fire Department data were filtered to include only classes of fires that were deemed “not under the control of humans”, which meant that they were considered to pose a threat to people and resources because the fire was not being managed. These fires were primarily natural vegetation fires (forest fires, grass fires or brush fires), but also included outside storage fires (sheds, barns, play houses) and cultivated vegetation or crop fires. The outside storage fires were included because they often set vegetation on fire (Colwell 2011). Fire starts in the Missoula downtown area were removed from the dataset as fire starts in this area were not expected to have any chance of starting wildfires in the study area. Missoula Rural Fire District and the Missoula City Fire Department ignitions were geocoded with Missoula County Roads spatial data obtained from the Missoula County GIS Office. Approximately 10% of the recorded fire starts had an address which was vague or nonexistent, and were deleted from our dataset. Three fire starts on hill or mountain sides had to be located on the map by hand with assistance from Missoula Rural Fire District, because they did not have a street address.

All of the datasets were filtered to separate lightning from human-caused fire starts, and to include only fires that occurred during the fire season, defined in western Montana to be July 1st to September 30th. Fires that were duplicated in at least two fire management agency datasets were identified manually by comparing ignition locations, dates, times and fire names. Further assistance from the Missoula Rural Fire District Chief or Fire Management Officer at the appropriate agency was sometimes required to make the final determination on duplicate fires. After all duplicates were eliminated, the final dataset included 307 human-caused and 113 lightning ignition fires within the study area for the period 2000-2010. The fire ignitions from our study are illustrated in Figure 2, and some summary statistics are reported in Table 2.

Between 2000 and 2010, eight wildfires escaped initial attack in the study area, defined as wildfires exceeding 50 ha. Five were lightning ignitions in 2003 that together burned 10,145 ha. The other three were human-caused wildfires that together burned only 470 ha due in part to increased fire-fighter access at lower elevations. Table 2 indicates that the mean escape rate for the study area was 1% for human-caused ignitions and 4% for lightning ignitions over the period 2000 to 2010.

In the study area, the Fourth of July holiday and celebration is important in explaining how and when fires ignite. The Missoula Rural Fire District and Missoula City Fire Department data indicate that 41% of their human-caused fire starts for the years 2000-2010 occurred within one week of July 4th. Many of these starts were most likely caused by fireworks. Of the three human-caused fires that grew to greater than 50 ha, two were during the week of the Fourth of July holiday. The DNRC, which does not respond to fires close to Missoula as frequently as Missoula Rural Fire District, still reported that 21% of their human-caused fires started within one week of July 4th. On the CSKT Reservation, 74% of human-caused fires started within one week of July 4th. The BIA included over 80% of these in the category of campfire starts, but in actuality many of them were bonfires, or fires of suspicious origin (Steele 2011).

### 3.3 Wildfire burn probability modeling

BP maps were generated for the focus area using eight ignition scenarios: two types of ignitions (human-caused and lightning-caused), two spatial patterns of ignition (random and spatially explicit), and two levels of wildfire ignition frequency (average and high). Burn probability maps were created for the focus area using a modified version of FlamMap (Finney 2006), called Randig (Ager *et al*. 2007), which simulates fire growth using the minimum travel time algorithm (Finney 2002). We used Randig instead of FlamMap because Randig allows for non-random ignitions[3] (i.e. a spatially-explicit burn probability ignition grid) and variable wind directions and wind speeds. Randig models the ignition and spread of a large number of fires and counts how many times each pixel burns, thereby creating a map depicting the likelihood of burning, or BP; these values were converted to *annual* probability of burning (see below). The Randig model does not account for changes in fuels due to vegetation succession or disturbance; therefore, Randig estimates BP for a static landscape.

For each ignition scenario, we simulated 50,000 fires. The pixel size of all spatial inputs, and therefore the resulting BP grids, was 30 x 30 m (0.09 ha). Each human-caused fire was simulated for two eight-hour burning periods (i.e. days) and each lightning-caused fire was simulated for five eight-hour burning periods. These differences in burning duration account for disparities in fire-suppression accessibility. The RNRA and RW were buffered by 10 km to eliminate edge effects by allowing fires to start outside, and spread into, the focus area. Inputs to Randig include spatial layers depicting topography, fuels, and ignition density, and aspatial information such as wind speed, wind direction, and fuel moisture data.

### *3.3.1 Spatial Inputs: Topography, Fuels, and Spatially-explicit Wildfire Ignition Grids*

The topographic inputs consisted of elevation, slope, and aspect. These were created using standard GIS methods from a digital elevation model obtained from the National Elevation Dataset (USGS 2011A). The fuels data were obtained from LANDFIRE (Rollins 2009, USGS 2011B); we used the "refresh 2008" version, which is an updated version of the original data that incorporates recent disturbance events and modifications that improved the product.

The spatially-explicit lightning ignition density grid was developed by slightly modifying an ignition density model generated for the Selway-Bitterroot Wilderness (SBW) area (Parks *et al*. 2012), which is approximately 30 km southwest of our study area. This is a classification and regression tree (CART) model with ignition location as the dependent variable and generalized vegetation type and elevation as the independent variables (Parks *et al*. 2011). The ignition density model was parameterized by Parks *et al*. (2012) with ignitions that burned at least 50 ha and therefore represents ignitions that lead to "large" fires. An independent ignition density grid was not created for our study area because of the close proximity to SBW and because of data limitations due to the relatively small size of the study area. Nevertheless, the lightning ignition density grid produced for the study area did correlate well with observed lightning ignition datraset for the period 2000 to 2010. The values in the CART model were converted to number of ignitions/ha/year so that they could be directly integrated with and compared to the ignition grid representing human-caused ignitions (described below).

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[3] The version of FlamMap used for our research did not allow for non-random ignitions, whereas the new version does.

Spatial examination of the human-caused wildfire ignitions revealed that almost all of the human-caused ignitions were in close proximity to public access roads (Figure3). However, human-caused ignition patterns vary substantially throughout the study area. Therefore 13 unique human-caused ignition zones were defined following discussions with the Missoula Rural Fire Chief, the FMO for the CSKT, the FMO for the USFS, and the Fire Program Manager for the DNRC. These zones, which are illustrated in Figure 3 and described in Table 3, collectively define the human-caused spatially explicit wildfire ignition density grid used in Randig. The spatial buffers around public access roads that define each zone are consistent with actual ignition locations and the current literature relating human-caused ignitions to roads. For the three rural zones: Gold Creek, Firestone Flats, and the BIA Zone, 500 m was used as the buffer because the fires tended to be from campfires, bonfires and other fires of unknown or suspicious origin that were located further from roads. For the more suburban zones, namely Rattlesnake, Grant Creek, West Zone, Mount Sentinel, Pattee Canyon, East Missoula and West Riverside, 200 m was selected as the buffer, since observed fires ignited close to roads. In the more industrialized Broadway to I90 Zone, all observed fires ignited within 100 m of roads, and a 100 m buffer was adopted for this zone. For the two Interstate 90 (I90) Zones: I90 East and I90 West; 40 m was the buffer for analysis purposes. Only two out of 307 human-caused fires between 2000 and 2010 were far outside these buffers, and were deleted from the dataset for analysis purposes.

From the historical evidence reported in Table 3, there is a wide range of ignition probability per ha per year, ranging from 28 fires in 15,033 ha in the Gold Creek Zone (0.02% chance of ignition/ha/y), to 13 fires in 147 ha in the I90 East Zone (0.80% chance of ignition/ha/y). The zones also present a wide range of probability of burning into the Rattlesnake WUI or the Rattlesnake Wilderness based on location, fuels and weather. Zones to the southwest, immediately to the south and southeast of the Rattlesnake, as well as the Rattlesnake Zone itself, pose the most significant threat.

### *3.3.2 Aspatial Inputs: Wind and Fuel Moisture*

Randig utilizes wind data that are represented by a probability distribution depicting wind speed and direction. For each burning period for each fire, wind data are randomly selected from this probability distribution and are variable throughout each fire. That is, for those days that met or exceeded the 90th percentile ERC value, we generated the joint probability of wind speed and direction. Wind speed and wind direction are coupled in the frequency distribution, therefore avoiding non-existent combinations of speed and direction. This probability distribution was generated using data for the 90th percentile ERC[4] value of 70 for the fire season (7/1 – 9/30) from the Missoula RAWS which is located 4 km southwest of the study area boundary. Fuel model G,

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[4] When the ERC is greater than the 90th percentile, the fire danger is very high (Andrews and Bradshaw 1997).

which is closed, short-needle conifer (heavy dead) (Andrews and Bradshaw 1997) was used. Moisture values of live fuels (herbaceous and woody) and of 1-hour, 10-hour, and 100-hour time lag dead fuels (Cohen and Deeming 1985) were also generated using the values for those days that met or exceeded the 90th percentile ERC using FireFamily Plus (Bradshaw and McCormick 2000).

### 3.4 Modeling and analyzing the lightning-caused and human-caused ignition scenarios

Spatially explicit ignitions scenarios are represented in Randig by the spatially explicit lightning and human-caused wildfire ignition density grids described above. The Randig random ignitions feature was used for the random ignitions alternative. Randig does not directly estimate the *annual* probability of burning (Randig essentially assumes one fire per year), hence, we converted the raw Randig BP estimates to annual probability of burning by multiplying the raw Randig BP estimates by the number of fires that occur per year under ‘average’ and ‘high’ ignition frequency conditions. This conversion was necessary to ensure valid comparison among ignition scenarios and to provide more-interpretable and realistic burn probability estimates.

The ‘average’ number of lightning-caused fires in the study area is 0.25 fires/year, which is based on the observed number of lightning-caused wildfires that burned at least 50 ha between 1985 and 2008. The ‘high’ lightning-caused ignition frequency adapted for this study is 0.55 fires/y, which is the observed number of fires that burned at least 50 ha between 1998 and 2008 - a period of high fire activity in the vicinity of the study area. ‘Average’ and ‘high’ human-caused ignition frequencies adopted for this study that cause wildfires that burn at least 50 ha are 0.277 fires/year and 0.832 fires/year, respectively. These frequencies represent 1% and 3% human-caused wildfire escape rates, respectively, and are based on ignition data from 2000-10 reported in Table 2. The 1% wildfire escape rate is the “average” human-caused wildfire escape rate for the period 2000-10. The 3% wildfire escape rate is reflective of the maximum human-caused wildfire escape rate for a single year over the period 2000-10, which means that 3% of the fires in a given year defy initial attack and grow to at least 50 ha.

The human and lightning-caused burn probability estimates for both ‘average’ and ‘high’ ignition frequency conditions were spatially summed to provide a clear picture of the combined effect of both ignition types. To facilitate comparison between ignition sources (human vs. lightning) for the different conditions (average vs. high), we generated “ratio maps” using equation 3 from Parks *et al*. (2012):

$$ratio_{\mathrm{i}} = \begin{cases} -(BP.random_{\mathrm{i}} \div BP.non.random_{\mathrm{i}}) + 1, & BP.random_{\mathrm{i}} > BP.non.random_{\mathrm{i}} \\ (BP.non.random_{\mathrm{i}} \div BP.random_{\mathrm{i}}) - 1, & BP.non.random_{\mathrm{i}} < BP.random_{\mathrm{i}} \end{cases}$$

Where $BP.non.random_i$ represents the BP generated using spatially structured ignitions at the *i*th pixel and $BP.random_i$ is the BP generated using random ignitions at the *i*th pixel. The resulting ratios appropriately quantified the differences between the BP maps generated using spatially structured vs. random ignitions; those pixels with a higher BP using spatially structured ignitions vs. the BP generated using random ignitions had a positive ratio,  and those pixels with a higher BP using random ignitions vs. the BP generated using spatially-explicit ignitions had a negative ratio.

## Results

### *Burn Probability Maps*

BP estimated from spatially explicit lightning and human-caused ignitions for the focus area is shown in Figure 4, while BP from random lightning and human-caused ignitions is shown in Figure 5.   There are four rows of BP maps in each figure, each row representing one of four ignition scenarios.  Ignition scenarios are defined by ignition frequency (“average” and “high”) and ignition source ( human and lightning).  Column 1 in each figure illustrates BP from human-caused ignitions, and column 2 illustrates BP from lightning ignitions.  Simulated ignition frequency of fires grown to at least 50 ha (“average” and “high”) is reported beside each BP map in columns 1 and 2.  As one would expect, a higher level of ignitions leads to higher BP.  The third column in each figure reports the aggregate BP arising from human-caused and lightning ignitions.  This is what wildfire managers are interested in seeing, as these maps purport to show areas more or less likely to be burned by wildfire in any given wildfire season.

The four ignition scenarios in Figures 4 and 5 each represent plausible ignition frequency combinations for a wildfire season in the study area.  Lightning ignition frequency is largely dependent on the number of lightning storms sweeping through the study area during the wildfire season.  The number of human-caused ignitions is largely dependent on fuel moisture in the lower elevations and more easily accessible forests.  This in turn is dependent largely on the level of winter snow pack, the time of the onset of spring, and spring rains.  It is certainly possible to have average lightning ignition years coupled with high human-caused ignition years, and high lightning ignition years coupled with average human-caused ignition years.

There is a visible substantial difference in column one between spatially explicit and random human-caused ignitions (Figures 4 and 5).   The spatially explicit human-caused ignition maps show areas of positive BP closer to populated (southwest) and recreation (east and northwest) areas , and zero BP elsewhere,   However, the random human-caused ignition maps show a fairly uniform BP across most of the focus area, which is not consistent with historical evidence of where human-caused fires start. Therefore, random human-caused ignitions may not accurately reflect the fire exposure in these areas.

As illustrated in Figure 2, lightning-caused ignitions in the Rattlesnake WUI are uncommon (indeed there were no lightning ignitions between 2000-2010). This is reflected in low lightning-caused BP in Figure 4 for this area. Figure 4 does indicate relatively high BP from spatially explicit lightning ignitions in the high elevation Rattlesnake Wilderness, which is consistent with historic lightning ignitions. In contrast, BP generated by random lightning-caused ignitions illustrated in Figure 5 is relatively high on the west side of the Rattlesnake WUI and low in the Rattlesnake Wilderness, which appears to be inconsistent with historical evidence.

Column 3 is an aggregate of column 1, which illustrates BP from human-caused ignitions, and column 2 which illustrates BP from lightning ignitions. Thus fire managers are provided with four combinations of ignitions, thereby duplicating the BP scenarios that are possible during any given fire season, which are always a combination of human-caused and lightning ignitions (“average” or “high”).

### *Ratio Maps*

Ratio maps A to D represent the relative difference in aggregate BP for rows 1 to 4 respectively of Figure 4 and Figure 5. The charts accompanying each ratio map plots proportion of 30 x 30 m pixels in the focus area (y-axis) by simulated burn probability (x-axis) for random and spatially explicit ignitions. The frequency distributions show that there is more heterogeneity in the BP maps produced with spatially explicit ignitions. All ratio maps highlight that spatially explicit ignitions led to simulation of higher BP in the wilderness and the southeast of the recreation area than did random ignitions. All ratio maps also show large parts of the RNRA have higher BP simulated from random wildfire ignitions compared with spatially explicit ignitions. Reference to Figures 4 and 5 reveals that the high spatially explicit ignition BP in the wilderness is due to lightning ignitions, and that the relatively high random ignition BP in the RNRA is also due to lightning ignitions. Historic lightning ignition data illustrated in Figure 2, which shows few lightning ignitions west and south of the RNRA, and many west and south of the RW, suggests that the spatially explicit lightning ignitions are generating BP maps that more closely reflect local lightning caused wildfire risk.

The most variation between ratio maps A to D exists around the Rattlesnake WUI. Ratio maps A and C illustrate scenarios with average levels of human-caused ignitions, and show higher BP from random ignitions. Inspection of Figures 4 and 5 reveals that this is, in fact, due to relatively high BP caused by random lightning ignitions. Indeed, column 2 of Figure 5 suggests that the Rattlesnake WUI has the highest BP due to lightning ignitions in the entire focus area. Historic evidence in the study area (including Figure 2) does not support this.

Ratio maps B and D in Figure 6 illustrate scenarios with high human-caused ignitions and higher BP in the Rattlesnake WUI due to spatially explicit wildfire ignitions. Rows 2 and 4 of Figure 4 reveal that this is due to human-caused ignitions, not lightning, which is more plausible given the historic evidence.

## Discussion

In the United States, considerable effort has been expended developing wildfire simulation models, including Randig (Ager *et al*. 2007) and FSim (Finney *et al.* 2011) to estimate wildfire risk across the landscape. Typically, these models are used to estimate BP on large landscapes assuming random wildfire ignition locations and wildfire ignition frequencies that are based on historic records from public lands. The literature suggests this approach is reasonable for large-scale analyses (Finney *et al*. 2011). Of course, lightning and human-caused wildfires do not ignite at random locations on the landscape and ignitions are not limited to public lands. The effect on simulated BP of not accounting for this reality is likely to become increasingly apparent the smaller the scale of analysis. This study aimed to explore the effect that utilizing random versus spatially explicit wildfire ignitions can have on simulated BP at a scale that is relevant for local wildfire management planning. Human-caused and lightning ignition probability grids were developed for the study area around Missoula, Montana, from spatially explicit wildfire ignition data for small private landholdings and public land, to be compared to randomly generated ignitions.

Regardless of simulated human and lightning ignition frequency level, substantial and relatively consistent spatial differences between the BPs generated by random and spatially explicit ignitions were observed. Relative to BP estimated from random ignitions, spatially explicit lightning ignitions generated higher BP for the RW, and spatially explicit human-caused ignitions generated higher BP for the Rattlesnake Valley WUI. In contrast, BP generated by random lightning-caused ignitions is relatively high on the west side of the Rattlesnake Valley WUI and low in the Rattlesnake Wilderness, which appears to be inconsistent with historical evidence. Thus, local fire managers using BP maps produced by random wildfire ignition simulations to support pre-season planning and allocation of management resources, including fuel treatments, could conceivably come up with very different strategies than managers supported by BP maps produced from spatially explicit wildfire ignitions, potentially putting WUI and Wilderness values at risk. This suggests that spatially explicit ignition data is beneficial for wildfire simulation modeling at small scales, for fuel treatments, deployment of resources and WUI preparedness including prevention programs and homeowner education. Spatially explicit ignition data, especially ignitions on small private landholdings, are essential for producing accurate BP maps for small landscapes. Inaccurate BP maps could lead to increased financial, social and environmental costs. In the future, we would recommend further research in other local areas to test the results of this study, as our study area and database were small.

As more people move to Missoula County and recreate in the RNRA, which has high fuel levels due to past successful fire suppression, the likelihood of wildfire ignitions will increase. A widening of the range of conditions in western Montana, with an increase in the seasonal window for and number of extremely hot days, and a decrease in the seasonal window for and number of extremely cold days (Pederson *et al.* 2010) suggests the need to be prepared for higher fire season danger in the future (Cohen 2012). Given the temperature and precipitation gradient with elevation in Montana, the ERC tends to be higher at lower elevations[5] where the majority of the population lives. Therefore, spatially explicit information about human-caused wildfire ignitions will become increasingly important to wildfire managers for the protection of people, property and natural resources at risk in western Montana.

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[5] Missoula RAWS – elevation 3200 ft & Point Six RAWS – elevation 7920 ft.

Figure 1. Land ownership within the study area.

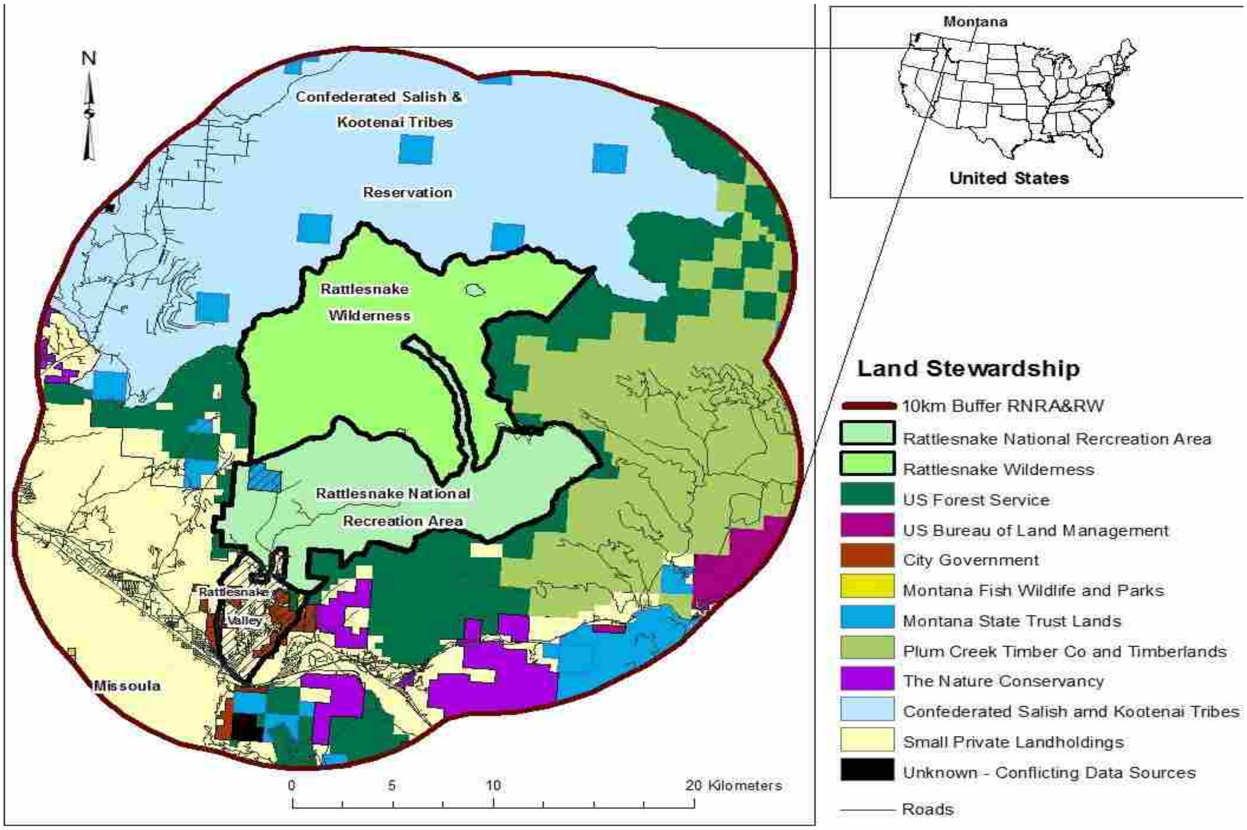


Figure 2. Vegetation within the study area**.**

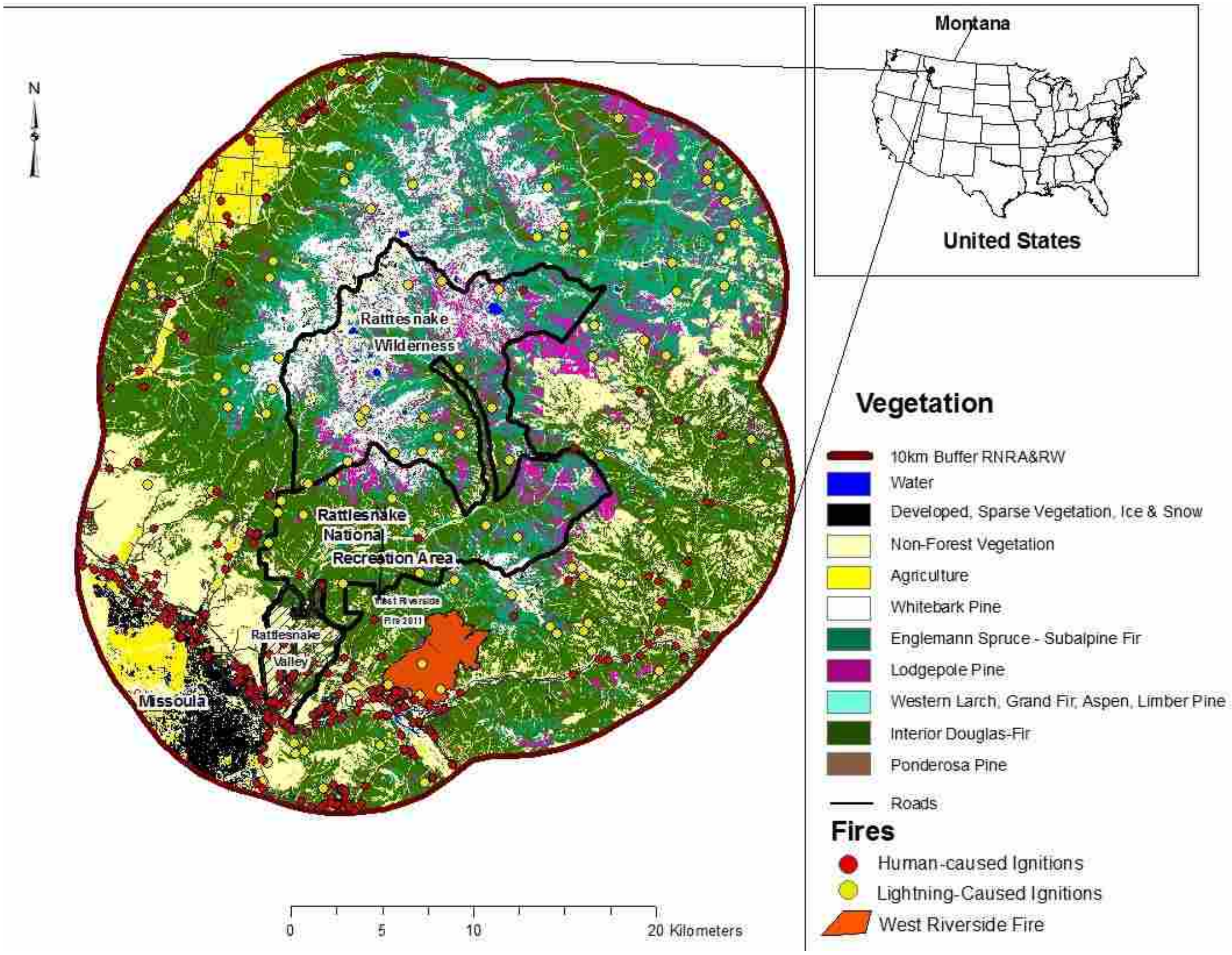


Figure 3. Human-caused ignition zones within the study area.

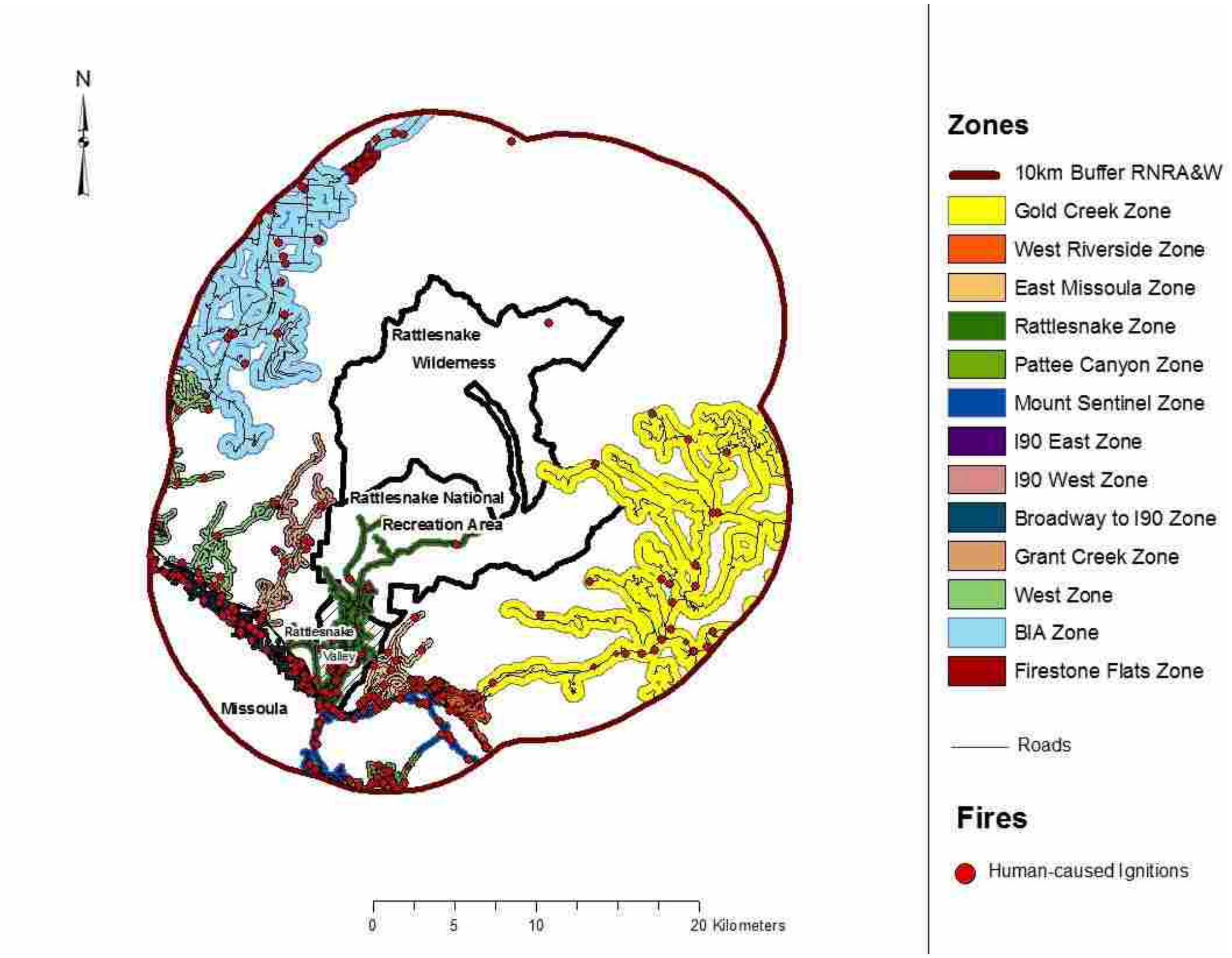


Figure 4. Burn Probability generated by ignition probability grids.

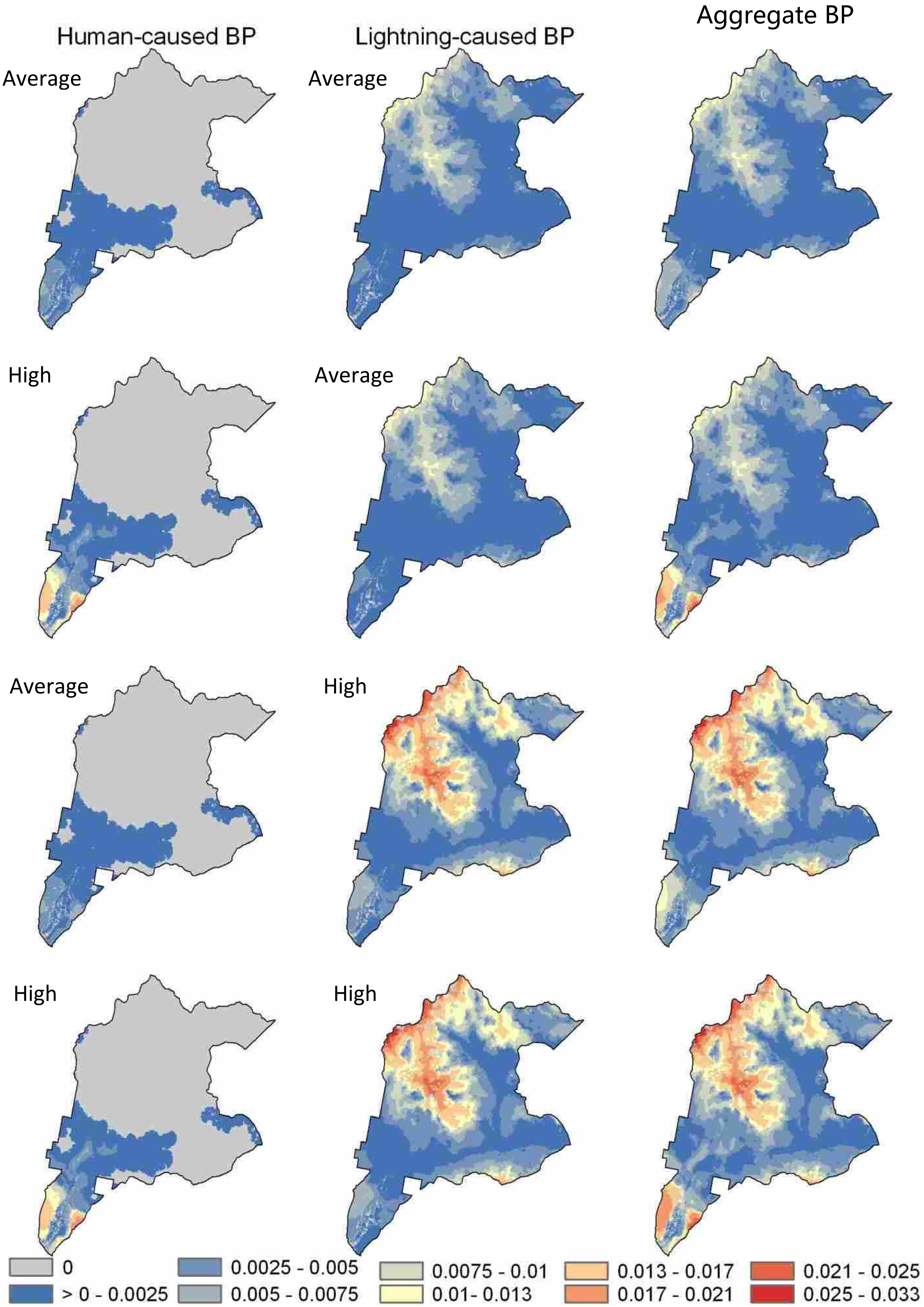


Figure 5. Burn Probability generated by random ignition locations.

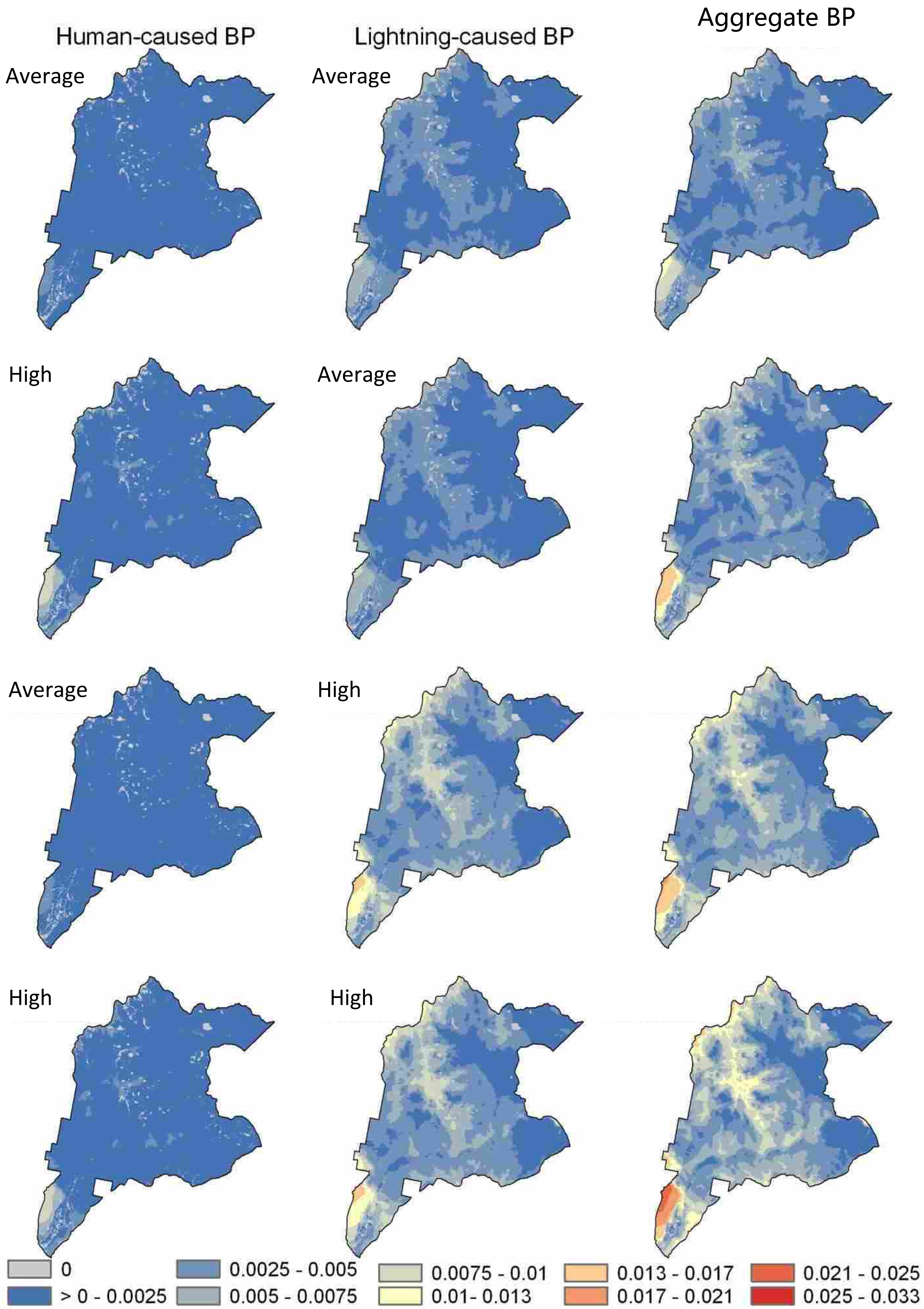
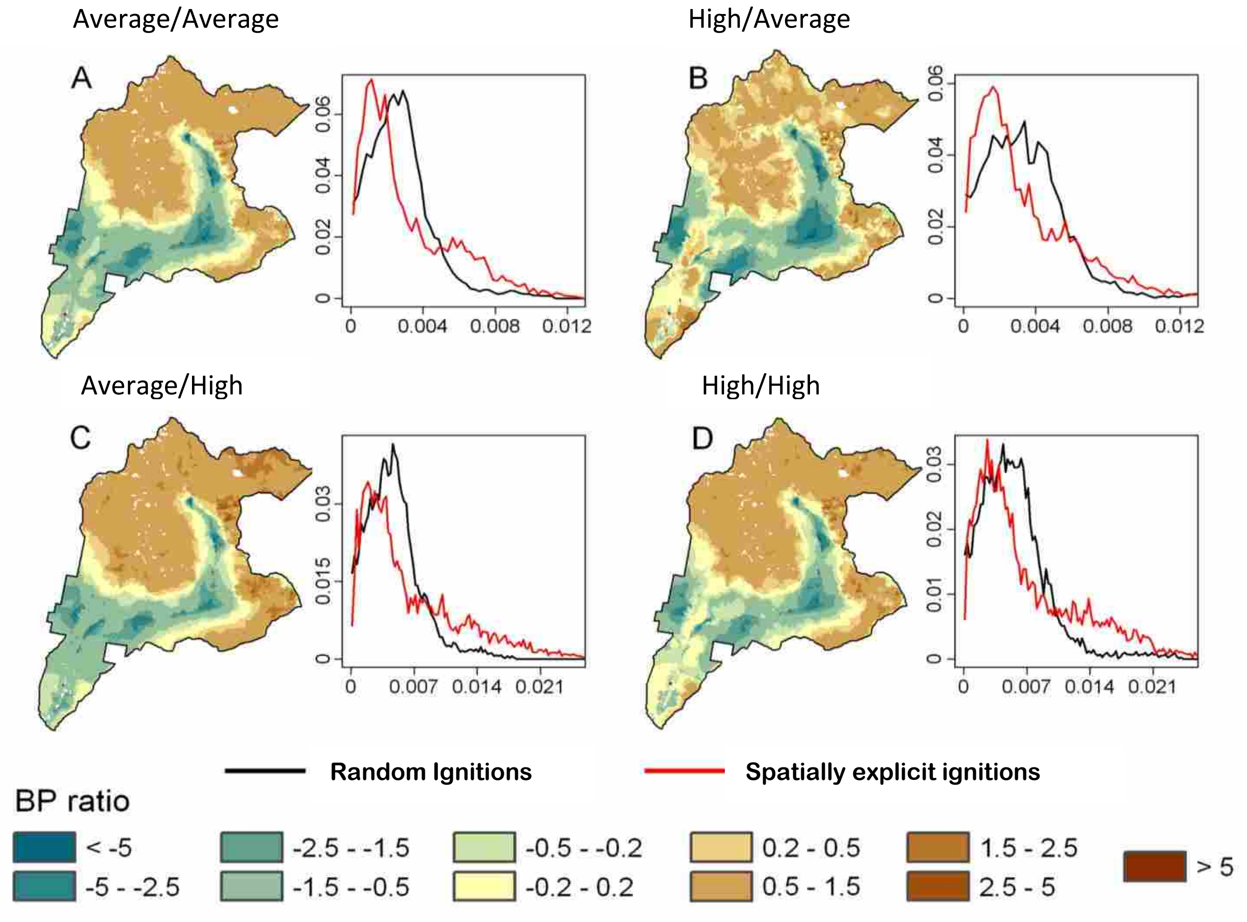


Figure 6. Ratio maps reporting the relative difference in BP between spatially-explicit ignitions and random ignitions.



Notes: Positive values indicate that the BP generated using spatially-explicit ignitions was higher than the BP generated using random ignitions, and negative values indicate that the BP using random ignitions was higher than the BP using spatially-explicit ignitions. Average year spatially-explicit ignitions vs. average year random ignitions (A), extreme year human-caused, and average year lightning, spatially-explicit ignitions vs. extreme year human-caused, and average year lightning random ignitions(B), average year human-caused, and extreme year lightning spatially-explicit ignitions vs. average year human-caused, and extreme year lightning, random ignitions (C), and extreme year spatially-explicit ignitions vs. extreme year random ignitions(D). Corresponding frequency distributions are also shown: Burn Probability is on the x-axis and Frequency is on the y-axis.

Table 1. Large fires on federal government land in the United States 1980-2009.

| Fire size & years | All federal fires | Rocky Mountain states* | Montana |
|---|---|---|---|
| ≥300ac (≈120ha) | | | |
| 2000-2009 | 9,033 | 4242 | 662 |
| 1980-1999 | 11,605 | 5673 | 563 |
| 1980-2009 | 20,638 | 9,915 | 1,225 |
| ≥10,000ac (≈4,050ha) | | | |
| 2000-2009 | 1,211 | 528 | 97 |
| 1980-1999 | 1,087 | 439 | 46 |
| 1980-2009 | 2,299 | 967 | 143 |
| ≥100,000ac (≈40,490ha) | | | |
| 2000-2009 | 159 | 33 | 5 |
| 1980-1999 | 83 | 25 | 4 |
| 1980-2009 | 242 | 58 | 9 |

Note: *****Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming

Table 2. All recorded fire starts in the study area 2000-2010.

| Year | Human-caused fires | | | Lighting-caused fires | | | Total fires | | |
|---|---|---|---|---|---|---|---|---|---|
| | Number | Escaped fires* | Percent escaped | Number | Escaped fires | Percent escaped | Number | Number escaped | Percent escaped |
| 2000 | 32 | 1 | 3.1 | 23 | 0 | 0.0 | 55 | 1 | 1.8 |
| 2001 | 15 | 0 | 0.0 | 6 | 0 | 0.0 | 21 | 0 | 0.0 |
| 2002 | 22 | 0 | 0.0 | 7 | 0 | 0.0 | 29 | 0 | 0.0 |
| 2003 | 39 | 0 | 0.0 | 40 | 5 | 12.5 | 79 | 5 | 6.3 |
| 2004 | 23 | 0 | 0.0 | 10 | 0 | 0.0 | 33 | 0 | 0.0 |
| 2005 | 32 | 0 | 0.0 | 3 | 0 | 0.0 | 35 | 0 | 0.0 |
| 2006 | 42 | 1 | 2.4 | 14 | 0 | 0.0 | 46 | 1 | 2.1 |
| 2007 | 36 | 0 | 0.0 | 5 | 0 | 0.0 | 41 | 0 | 0.0 |
| 2008 | 30 | 1 | 3.3 | 4 | 0 | 0.0 | 34 | 1 | 2.9 |
| 2009 | 30 | 0 | 0.0 | 1 | 0 | 0.0 | 31 | 0 | 0.0 |
| 2010 | 6 | 0 | 0.0 | 0 | 0 | 0.0 | 6 | 0 | 0.0 |
| **Total** | **307** | **3** | **1.0** | **113** | **5** | **4.4** | **420** | **8** | **1.9** |

Note:*Escaped fires burned at least 50 ha.

Table 3**.** Ignition zones for the study area.

| Zone | Area of zone (ha) | Number of fires 2000-10 | Fires/ha | Fires/ha/year |
|---|---|---|---|---|
| Gold Creek | 15033 | 28 | 0.0019 | 0.0002 |
| West Riverside | 724 | 33 | 0.0456 | 0.0041 |
| East Missoula | 891 | 14 | 0.0157 | 0.0014 |
| Rattlesnake | 2463 | 27 | 0.0110 | 0.0010 |
| Pattee Canyon | 507 | 23 | 0.0454 | 0.0041 |
| Mount Sentinel | 1270 | 44 | 0.0346 | 0.0031 |
| I90 East | 147 | 13 | 0.0884 | 0.0080 |
| I90 West | 163 | 4 | 0.0245 | 0.0022 |
| Broadway to I90 | 1319 | 53 | 0.0402 | 0.0037 |
| Grant Creek | 1425 | 9 | 0.0063 | 0.0006 |
| West Zone | 2148 | 13 | 0.0060 | 0.0005 |
| BIA Zone | 9067 | 22 | 0.0024 | 0.0002 |
| Firestone Flats | 319 | 22 | 0.0690 | 0.0063 |

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