RESEARCH ARTICLE

QUANTIFYING THE THREAT OF UNSUPPRESSED WILDFIRES REACHING THE ADJACENT WILDLAND-URBAN INTERFACE ON THE BRIDGER-TETON NATIONAL FOREST, WYOMING, USA

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ABSTRACT

An important objective for many federal land management agencies is to restore fire to ecosystems that have experienced fire suppression or exclusion over the last century. Managing wildfires for resource objectives (i.e., allowing wildfires to burn in the absence of suppression) is an important tool for restoring such fire-adapted ecosystems. To support management decisions that allow wildfires to burn unsuppressed, land managers need a quantitative assessment of the potential for such wildfires to reach nearby fire-susceptible resources and assets. We established a study area on a portion of the Bridger-Teton National Forest near Jackson, Wyoming, USA, where land managers wish to restore fire by managing wildfires, but are concerned about the threat to residential buildings. We modeled the ignition and unsuppressed growth of wildfires starting in a remote portion of the study area using FSim, a fire occurrence, growth, and suppression simulation model. We then characterized annual area burned and the likelihood that wildfires would reach a nearby wildland-urban interface (WUI) defense zone. Early-season fires burned longer and grew larger than late-season fires, and thus had a higher likelihood of reaching the WUI zone (3 % of May fires compared to 0.1 % of October fires). Because fire managers do not anticipate managing all fire starts for resource objectives, we applied a simple rule set termed "RO rules," indicating the fraction of starts by month to be managed for resource objectives. This reduced the expected number of fires reaching the WUI zone by 70 %, and the expected WUI zone area burned by 61 %. From 1990 to 2009, a mean of 207 ha yr^{-1} had been burned by wildfires starting in the remote portion of the study area. By contrast, we estimated that 14 431 ha yr^{-1} could burn if no fire starts were suppressed, and 4861 ha yr^{-1} after applying the RO rules. Our analysis approach can be extended to determine which parts of the landscape are most likely to produce fires that reach specific targets on the landscape.

INTRODUCTION

The suppression of lightning-caused wildfire ignitions can significantly alter fire regimes, thereby affecting forested ecosystems in the western US (Agee 1993). Fire suppression over many decades, along with other changes such as grazing, logging, and the cessation of Native American burning, has contributed to a reduction in fire frequency and area burned (Heyerdahl *et al.* 2001), leading to increased fuel continuity and load in western forests (Hessburg *et al.* 2005, Naficy *et al.* 2010). In the dry forests of the western United States, for example, fire suppression has led to changes in vegetation structure and composition (Covington and Moore 1994, Keane *et al.* 2002, Scholl and Taylor 2010). Fuel accumulation due to fire suppression is thought to have increased the potential for uncharacteristically large and severe wildfires (Stephens and Moghaddas 2005, Miller *et al*. 2009, Bekker and Taylor 2010). Such wildfires can have negative long-term effects on key ecosystem functions (Certini 2005, Hurteau and Brooks 2011).

Federal agencies explicitly recognized the importance of fire as an ecosystem process when, starting in the early 1970s, federal wildland fire policy stipulated that while all human-caused fires were to be aggressively suppressed, naturally ignited fires (e.g., lightning) could be managed for resource objectives (Stephens and Ruth 2005). Terminology used for such fires has varied considerably over the years: let-burn, prescribed natural fire, wildland fire managed for resource benefit, and fire use. In this paper, we refer to these as resource objective (RO) wildfires. Current policy implementation, however, does not segregate unplanned wildland fires by ignition type. All unplanned ignitions are termed "wildfires," regardless of ignition source, and can be managed using the full range of responses depending on the Land and Resource Management Plan and Fire Management Plan for the area (National Wildfire Coordinating Group 2008). Every wildfire is managed in accordance with the objectives of the wildfire event itself (resource objectives, protection objectives, or both).

The use of RO wildfires is especially important in designated and proposed wilderness areas (Parsons *et al.* 2003), which, according to the Wilderness Act of 1964, are to be protected and managed to preserve (and restore) natural conditions. The suppression of wildfires in wilderness is a human manipulation that can alter natural conditions, and therefore does not support the intent of the Wilderness Act (Miller 2003). Nonetheless, suppression of ignitions, natural or anthropogenic, has been the dominant wildfire management strategy in most wilderness areas. A major reason that fires are suppressed in wilderness is the potential for fires to become large and threaten resources and assets on adjacent nonwilderness lands (Miller and Landres 2004, Black *et al*. 2008). In addition to restoring natural conditions, RO wildfires also have the potential to mitigate fuel hazards at relatively large scales (Miller *et al.* 2000, Parsons *et al.* 2003, Davis *et al.* 2010).

Wildfire has the potential to damage highly valued resources and assets (HVRA; Calkin *et al.* 2010). A wildfire occurring where there exists a fire-susceptible HVRA, such as a wildland-urban interface, is typically managed for

protection objectives. In such places, cost-effectively mitigating wildfire damage to those resources and assets is the primary incident management objective (i.e., wildfire suppression). However, wildfires that have the potential to provide benefits to key resources (e.g., improvement of wildlife habitat, restoration of vegetation structure to the historic or desired condition) may be managed for resource objectives. Some wildfires can be managed for multiple objectives, simultaneously protecting susceptible HVRAs in one sector of the wildfire while accomplishing resource management objectives in another.

In response to the increasing desire to restore the role of fire in fire-adapted ecosystems through RO wildfire management, some public land managers have shown interest in quantitatively assessing the potential for RO fires to reach fire-susceptible HVRAs such as the wildland-urban interface (WUI). This requires an assessment of where and when ignitions occur, how long a fire might burn, and how far it might spread. Although a wildfire occurring in any location is a candidate for RO management, wildfires selected for RO management generally start in remote portions of the landscape, far from susceptible HVRAs. To aid in long-term planning and communication with the public, managers need basic information regarding the likelihood that initially remote RO wildfires will reach adjacent HVRAs, and the magnitude of impact if they do.

Information regarding wildfire likelihood can be gleaned from Monte-Carlo wildfire simulation models. Such models have been used to quantify burn probability or wildfire threat at a variety of spatial scales, including local projects (Ager *et al.* 2007, Collins *et al.* 2011), regional assessments (Parisien *et al.* 2011, Parks *et al.* 2011), and continental assessments (Calkin *et al.* 2010, Finney *et al.* 2011). Until now, wildfire threat assessments have followed an approach that relies on gridded burn probability results, which are derived by simulating the ignition and spread of a very

large number of wildfires (Miller *et al.* 2008), to quantify expected net value change (Finney 2005, Scott 2006). Historically, these models only generated gridded probabilities of fire likelihood, with little to no information on individual simulated wildfires (Parisien *et al.* 2005, Finney 2006, Miller *et al.* 2008). However, some wildfire simulation models now produce vector format results that identify the final perimeter and associated characteristics of each simulated wildfire. This information allows an approach to assessing burn probability and wildfire threat that incorporates the ignition location and date, as well as the area of an HVRA burned by each individual fire.

In this paper we present a case study on the Bridger-Teton National Forest (BTNF) near Jackson, Wyoming, USA. The study landscape comprises a mix of land uses including WUI, managed forests (land managed for multiple uses, including timber production), designated wilderness, and wilderness study area (land under study for designation as wilderness). As in many areas of the western United States, these land uses are geographically arranged such that the wilderness and wilderness study area portion of the landscape, where land managers wish to use wildfire to accomplish resource objectives, is separated from the WUI by a buffer of general forest (Figure 1). Local fire management staff was interested in information regarding the likelihood that a wildfire managed for resource objectives would reach the WUI (M. Johnston, USDA Forest Service, personal communication). We used a Monte-Carlo wildfire simulation model to estimate 1) the annual likelihood that an RO wildfire originating in a designated remote area of the landscape (termed the RO start zone) will reach a designated portion of the WUI, and 2) the expected annual WUI-area burned. We used the new vector-based approach of the FSim model (Finney *et al.* 2011) to conduct the assessment described in this paper. The methodology presented here can be applied to a wide range of wildfire threat assessments and serves as a ba-
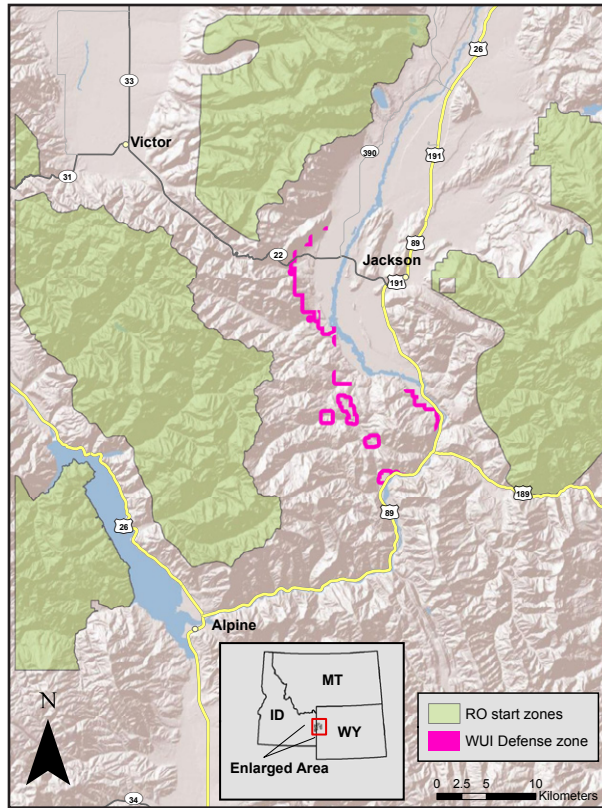
Figure 1. Study area map showing the wildland-urban interface (WUI) defense zone and start zone for the simulation of unsuppressed wildfires managed for resource objectives (RO start zone).

sis for evaluating the effectiveness of alternative fuel treatment scenarios in reducing the likelihood of wildfire reaching fire-susceptible resources and assets.

METHODS

Study Area

The 4000 km² study area (Figure 1) includes the town of Jackson, Wyoming, and consists of both private and federally managed land (parts of Grand Teton National Park, the National Elk Refuge, and the Caribou-Targhee and Bridger-Teton national forests), including a portion of the Jedediah Smith Wilderness and the Palisades wilderness study area. A wide range of vegetation types occurs within the study area. The valley bottoms, at roughly

2000 m elevation, are covered by grasslands and grass mixed with sagebrush (*Artemisia tridentata* Nutt.). The highest peaks in the study area exceed 3600 m; the terrain above 3000 m typically does not support wildfire spread due to the prevalence of rock and persistent snow. The slopes between the valley bottoms and the peaks are covered by coniferous forests, montane meadows, and stands dominated by quaking aspen (*Populous tremuloides* Michx.).

A WUI defense zone was established within the study area to identify areas in which wildfire is unwanted due to its potential impact on adjacent residential structures. The WUI defense zone consists of 2500 ha of federally managed land within 400 m of private residential land. The WUI defense zone is located on the west side of the Jackson Hole valley (Figure 1). The Bridger-Teton National Forest (BTNF) fire management staff established an RO start zone to identify where ignitions may be considered for RO management. This 1400 km² zone is separated from the WUI defense zone by roughly 3 km to 10 km (Figure 1). The RO start zone occurs primarily on the adjoining Caribou-Targhee National Forest and Grand Teton National Park.

RO rules. Bridger-Teton National Forest staff anticipates that only a fraction of wildfires originating in the RO start zone will be managed for resource rather than protection objectives. Under RO rules, a large proportion of ignitions originating in the RO start zone would be suppressed. The fraction of fires selected for RO management (F_{RO}) is expected to increase as the fire season progresses (Table 1). In total, an estimated 43 % of ignitions would be managed for RO. These rules stipulate that very few early season fires fall under RO management and will be suppressed, but that many late-season fires will be managed for resource objectives (Table 1). The RO rules will be applied to analysis of the baseline simulation results (see *Perimeter Analysis* section), which assumes that no ignitions are suppressed.

Table 1. Historic mean annual number of wildfire ignitions (1990 to 2009) in the resource-objectives wildfire start zone (N_H), designated fraction of wildfire ignitions to be managed for resource objectives (F_{RO}), and expected annual number of wildfires managed for resource objectives (N_{RO}) by month of fire start. N_{RO} is the product of N_H and F_{RO}.

	N_H (fires yr^{-1})	F_{RO} (%)	N_{RO} (fires yr^{-1})
May	0.2	0	0.0
Jun	0.7	10	0.1
Jul	2.4	25	0.6
Aug	4.3	45	1.9
Sep	1.9	60	1.1
Oct	0.8	80	0.6
Nov	0.0	80	0.0
Dec	0.0	80	0.0
Total	10.2	43	4.4

Fire modeling landscape. A fire modeling landscape is a set of geospatial data layers characterizing vegetation, fuel, and topography. In FSim (Finney *et al*. 2011) and related fire modeling systems, the fire modeling landscape is a raster format "landscape file" consisting of data layers that represent surface fuel (fire behavior fuel model), canopy fuel (canopy base height and canopy bulk density), forest vegetation (forest canopy cover and forest canopy height) and terrain characteristics (slope steepness, aspect, and elevation).

The fire modeling landscape data layers representative of *circa* 2001 were obtained from the LANDFIRE project (Rollins 2009). The layers included the standard surface and canopy fuel characteristics included in a FARSITE (Fire Area Simulator; Finney 1998) landscape file: surface fire behavior fuel model, canopy base height, canopy bulk density, forest canopy cover, and forest stand height. These layers were updated to reflect wildfires occurring from 2001 through 2008, and critiqued and edited (Stratton 2006, 2009) by local fuel and fire management staff with guidance from members of the LANDFIRE program and the Fire Modeling Institute, Missoula

Fire Sciences Laboratory, USDA Forest Service. The critique and update process, which produced a fire modeling landscape representative of 2009, was identical to that used by the LANDFIRE program itself, but was carried out for this fire modeling landscape rather than for an entire mapping zone.

Surface fuel was characterized by assignment of a fire behavior fuel model (Scott and Burgan 2005). Ten fuel models were mapped within the fire modeling landscape. Approximately one-third of the project area was characterized as a timber-grass fuelbed (TU1), with pockets of heavy timber-shrub (TU5) or moderate timber litter (TL4) found on the cooler and wetter north-facing aspects. The majority of the nonforested fuelbeds within the project area were characterized as light grass (GR1) or moderate grass-shrub (GS2). Grass-shrub fuelbeds can exhibit high rates of spread and flame lengths under dry fuel conditions. Fuel models GR2, GS1, TL1, TL3, and TL5 occurred in small amounts. Roughly ten percent of the landscape was nonburnable due to bare ground, open water, agricultural practices, urban areas, or persistent snow or ice.

Model Background

We used FSim (Finney *et al*. 2011) to simulate the ignition and unsuppressed growth of wildfires starting in the designated RO fire start zone. FSim is a comprehensive, Monte Carlo-style fire occurrence, growth, and suppression simulation system that pairs a fire growth model (Finney 1998, 2002) and a model of ignition probability with simulated weather streams in order to simulate fire ignition and growth for tens of thousands of fire seasons. The results of these simulations are used to estimate annual burn probability (BP) and mean fireline intensity (MFI) in raster format. Burn probability is the annual probability of burning, and is estimated by dividing the number of simulated fires that burned each pixel by the total number of seasons. Mean fireline inten-

sity is the arithmetic mean fireline intensity of the simulated wildfires that occurred at each pixel. FSim also produces a vector format geospatial layer consisting of the final perimeter of each simulated wildfire; start date, start location, duration, and final size are also saved to a file.

Simulation of daily values of Energy Release Component (ERC) of the National Fire Danger Rating System is the foundation of FSim's operation. The ERC is calculated from historical weather data (Cohen and Deeming 1985). The simulated ERC is used in two ways: first, to determine the probability of a fire start for each day, and second, to determine which of three fuel moisture scenarios to use for the day. The three scenarios correspond to ERC classes with breaks at the eightieth, ninetieth, and ninety-seventh percentile ERC values. The ERC is simulated for each day of each simulated fire season based on the historic seasonal trend in mean and standard deviation of ERC using temporal autocorrelation (Finney *et al*. 2010). Fire growth occurs only on days for which the simulated ERC exceeds the eightieth percentile.

In addition to the fire modeling landscape and the fuel moisture conditions, simulated fire growth for each day of each fire is a function of wind speed and direction. Wind characteristics for each day are determined by a random draw from the historic monthly joint frequency distribution of wind speed and direction. This draw is independent of ERC, and each day's draw is independent of the others.

FSim includes an optional suppression module based on a containment probability model (Finney *et al*. 2009). Because the suppression module is not used in this study and FSim does not employ a specific fire- or season-ending threshold, simulated wildfires were permitted to grow until the end of the fire season. Therefore, our simulations assumed that an unsuppressed wildfire would spread on any day for which the simulated ERC was above the eightieth percentile, regardless of how many no-spread days occurred previously. The simulations spanned a single calendar year, meaning that all fires ended on December 31, regardless of ERC.

Simulation Inputs

Fire weather. We supplied FSim with weather data for the period of 1990 to 2010 from the Raspberry Remote Automated Weather Station (RAWS). These data were used to estimate daily ERC values. We chose the Raspberry RAWS because its location was more representative of the project area than the Grant Teton RAWS, even though it is farther from the project area. Wind direction at the Grand Teton RAWS is influenced by its proximity to the Teton Range, which runs SSW to NNE, just west of the Grand Teton RAWS. The Raspberry RAWS is located in an area of continuous low mountains and therefore captures a wider variety of wind directions that better represent the fire modeling landscape as a whole.

By default, FSim populates the fuel moisture content values from the percentile values calculated in FireFamily Plus (Bradshaw and McCormick 2000) and applies those values to the entire landscape and to all surface fuel models; it does not allow fuel moisture conditioning (adjustment of fine dead fuel moisture content based on aspect, elevation, vegetation cover, and recent weather). On landscapes with significant variability in elevation and canopy cover, using a single value for dead fuel moisture across the whole landscape would tend to underestimate dead fuel moisture at higher elevations and under a forest canopy. Even though fuel moisture conditioning is not available within FSim, we were able to semi-condition dead fuel moistures because FSim can optionally use fuel moisture values specified for each fuel model separately. We conditioned dead fuel in FlamMap (Finney 2006) so that the landscape mean 1 hr timelag moisture content was approximately equal to

the percentile value calculated in FireFamily-Plus, and then calculated the mean moisture content where each fuel model occurs on the landscape. Using this procedure, fuel models typically found at higher elevations and under a forest canopy (e.g., TU5) were assigned higher dead fuel moisture content values than unsheltered fuel models found at lower elevations (e.g., GR2 and GS2).

Fire occurrence. FSim requires a summary of historic fire occurrence information for the fire modeling landscape. We gathered fire occurrence data (start location and date, cause, and final size) for all jurisdictions in the analysis area during the period of 1990 to 2009, critiqued the data to identify and remove duplicate and erroneous values, and then selected only wildfires originating within the RO start zone. We used FireFamilyPlus software to estimate the probability of fire occurrence as a function of ERC. Because multiple fires can start on the same day, we also provided a table to FSim that indicated the historic distribution of the number of fires per fire day. FSim uses these historic fire occurrence parameters to simulate the ignition of wildfires as a function of simulated ERC. Finally, we summarized the historic mean annual number of ignitions in the RO start zone (N_H) by month (Table 1), which allowed us to calculate the expected annual number of wildfires managed for resource objectives (N_{RO}) by multiplying N_H by F_{RO}.

Ignition density. Ignition locations are not uniformly distributed across our study area and have been shown to contribute to burn probability patterns (Parks *et al.* 2012). Therefore, we created a probability density grid representing the spatial pattern of ignitions. This ignition grid was used by FSim to determine where ignitions were placed for each simulated fire. We used a statistical modeling approach (i.e., logistic regression) very similar to that of Syphard *et al.* (2008) to create an ignition grid for which spatial environmental predictor lay-

ers were used to model the probability of ignition occurrence. Because lightning-caused and anthropogenic ignitions have different spatial patterns, we created two models representative of each; those ignitions with an "unknown" cause were included with the anthropogenic model. We created this ignition density grid for a much larger area than the study area (Figure 2) so that it could be used in a subsequent interagency wildfire risk assessment for the Bridger-Teton National Forest and Grand Teton National Park.
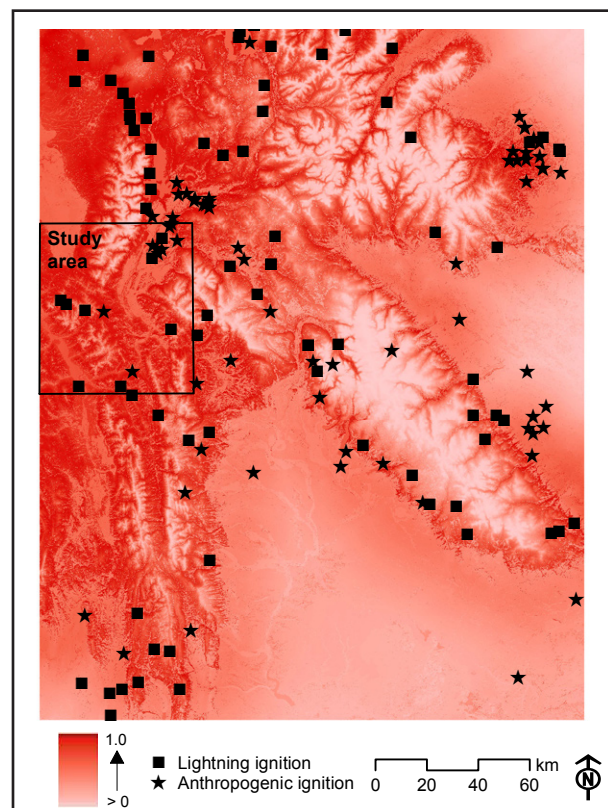

Figure 2. Ignition density grid values across the landscape for which it was created, with locations of lightning and anthropogenic wildfires ≥40 ha indicated. The study area for the present analysis is indicated as the rectangular area west of map center.

Because large-fire (≥100 ha) and small-fire start locations have different spatial patterns, and because large fires account for 92 % of the historic area burned on this landscape, we used observed locations of large fires that occurred

between 1990 and 2009 to build the models; there were 85 lightning and 71 anthropogenic ignitions. Because the logistic regression modeling technique requires "absence" data in addition to ignition "presence" data, we randomly selected 500 pixels to serve as pseudo absences; Barbet-Massin *et al.* (2012) suggest random sampling of pseudo absences when using regression modeling approaches. We chose 500 pseudo absences so that the resulting ratio of ignition presences to pseudo absences (~1:6.5) would be similar to that of Syphard *et al.* (2008) (1:5.5). We could have used more pseudo absences; however, subsequent analyses showed that increasing the number did not improve model fit as measured by the area under the curve (AUC) statistic. The ignition presence and absence locations were equally weighted and serve as the dependent variable in the logistic regression models. We evaluated a number of environmental predictor layers (Table 2) as independent variables for each model.

At each ignition and pseudo absence location, we extracted the values for each predictor layer using a geographic information system (GIS). We used a generalized linear model (family = binomial) to conduct logistic regression in the R statistical program (R Development Core Team 2007). We evaluated both the linear and quadratic polynomial form of each predictor variable (excluding vegetation) to evaluate possible nonlinear responses. Final models were selected through forward and backward stepwise regression, which is an automated model selection procedure based on Akaike information criterion (AIC); this was conducted with the "step.gam" function (using the default settings) in the "gam" package in R (Hastie 2011). The overall area under the curve statistic (AUC) (Mason and Graham 2002; NCAR-Research Application Program 2012), a measure of the probability that the logistic regression model correctly classifies randomly selected samples as ignition presence or absence, was 0.72 for the lightning model and 0.74 for the anthropogenic model; these AUC values are in line with those of another study using a similar approach to model ignition probability (Syphard *et al.* 2008) and indicate that the models perform better than random assignment of presence and pseudo absence. We also tested for the presence of spatial patterns in the model by generating variograms of model residuals (not shown); these variograms show that there was no spatial autocorrelation in the residuals of the lightning model and that there was mild autocorrelation at relatively fine scales (<2500 m) in the anthropogenic model, which is likely because anthropogenic

Table 2. Geospatial data layers used to generate the ignition density grid.

Predictor layer	Layer description	Source
Vegetation type	Biophysical setting (BpS) type (aggregated to nonfuel, conifer-conifer/hardwood, hardwood, grassland, shrubland, and riparian)	LANDFIRE (Rollins 2009)
Elevation	Meters above sea level	USGS
Potential solar radiation	A proxy for aspect	Derived from elevation grid in ArcMap (ESRI Inc. 2008)
Topographic position index	Index that identifies valleys and ridges	(Weiss 2001)
Distance to trails*	Meters to nearest trail	Bridger-Teton National Forest
Distance to roads*	Meters to nearest road	Bridger-Teton National Forest

* These variables were not included in the lightning model.

ignitions are oftentimes clustered (e.g., near campgrounds). The lack of strong autocorrelation in model residuals indicates that this is not an overwhelming issue in model fitting.

The resulting equations produced by each model were then applied to the spatial predictor layers using the "raster" package (Hijmans and van Etten 2011) in R, which in turn created spatial ignition density grids representing the lightning and anthropogenic models. Each grid was then rescaled between zero and one. We then created a composite ignition density grid by taking the weighted average of the lightning and anthropogenic grids; lightning ignitions had more weight because there were more lightning versus anthropogenic ignitions. Finally, we rescaled the final composite ignition density grid between zero and one (Figure 2). The resulting ignition density values were relative in that a value of 0.6 has twice the ignition density as a value of 0.3.

Perimeter Analysis

We used the vector format results to identify which simulated fires reached the WUI defense zone and then computed the mean final fire size (S) and duration (D) by month of fire start (i) separately for all simulated fires and for those that reached the WUI. The expected annual area burned (A) was calculated as

$$A = \sum (\bar{S}_i N_{H_i}) \qquad (1)$$

where i refers to the months May through December. This is not an estimate of presettlement area burned, but rather an estimate of hypothetical area burned on the contemporary landscape if wildfires occurred at the recent historic rate and under recent historic weather and were left unsuppressed. Replacing N_H with N_{RO} in equation 1 results in the expected annual area burned after applying the RO rules (A_{RO}). This replacement applies to equations 2 through 4, as well.

Next, we calculated the defense zone area burned (A_{WUI}) by each fire. The fraction of fires that reach the WUI defense zone (F_{WUI}) was calculated by dividing the number reaching the defense zone by the total number of simulated fires. The expected annual number of fires reaching the WUI defense zone (N_{WUI}) was calculated as

$$N_{WUI} = \sum F_{WUI_i} * N_{H_i} \qquad (2)$$

and the mean conditional WUI area burned (A'_{WUI}) was computed as

$$A'_{WUI} = \sum A'_{WUI_i} * N_{H_i} \qquad (3)$$

Mean conditional WUI area burned is the mean WUI area burned by the simulated fires that actually reached the WUI defense zone. Simulated fires that did not reach the WUI are not included as zero area burned in the calculation. Finally, the expected annual WUI area burned (A_{WUI}) was calculated as

$$A_{WUI} = \sum A'_{WUI_i} * N_{WUI_i} \qquad (4)$$

We combined monthly FSim results and historic monthly occurrence as described in this section to correct an apparent shortcoming in the simulation results discovered during initial simulations. In our simulations, there were too many early- and late-season fires (relative to historic occurrence), and too few occurring mid season. Seasonal timing of starts matters when simulating the likelihood of a fire reaching the WUI defense zone because early-season fires tend to burn longer and therefore become larger than mid- and late-season fires.

RESULTS

The simulation produced 32 757 wildfire ignitions in the RO start zone over 10 000 sim-

ulated fire seasons. Mean duration (*D*) and final fire size (*S*) varied throughout the season; early-season fires burned longer and grew larger than late-season fires (Table 3). Mean final fire size increased exponentially with duration (Figure 3). Most fires burned for just a

Table 3. Mean duration (*D,* days) and size (*S,* ha) of all simulated wildfires, fraction of simulated fires that reach the wildland-urban interface (WUI) defense zone (F_{WUI}), and duration (D_{WUI}) and size (S_{WUI}) of simulated wildfires that reach the WUI defense zone by month of fire start.

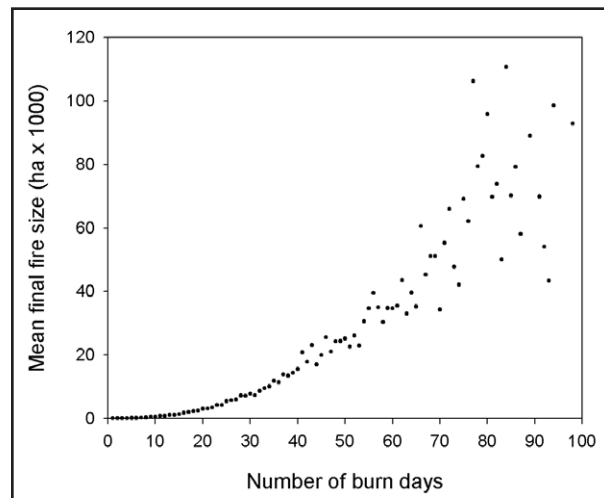|	*D* (days)	*S* (ha)	F_{WUI} (%)	D_{WUI} (days)	S_{WUI} (ha)
May	12.6	3951	3.0	55.9	50372
Jun	12.4	3171	2.1	53.6	43088
Jul	10.4	1974	1.3	49.4	34718
Aug	9.0	1288	0.7	45.1	28895
Sep	7.2	582	0.2	32.6	14489
Oct	6.6	490	0.1	41.5	23732
Nov	4.7	158	0.1	39.0	25932
Dec	3.0	34	0.0	n/a	n/a

Figure 3. Mean final size of simulated unsuppressed wildfires in relation to fire duration. Without suppression, simulated wildfires grow on any day for which the simulated Energy Release Component index of the National Fire Danger Rating System is above the eightieth percentile value.

short time. The modal duration was three days, and 87 % of all fires burned less than 20 days (Figure 4).

Assuming all fire starts grow without suppression, the expected annual area burned is 14431 ha yr⁻¹, largely (71 %) from fires starting during July and August (Table 4). The ap-
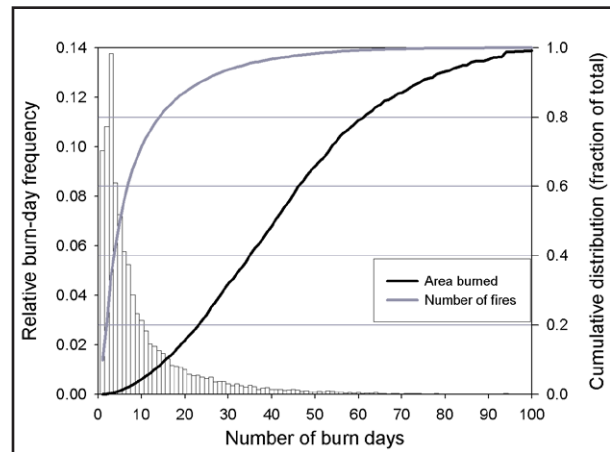

Figure 4. Relative frequency distribution of fire duration (gray bars) and cumulative distribution of number of fires (gray line) and area burned (black line) of all simulated unsuppressed wildfires on the study area using the FSim fire occurrence and

Table 4. Expected annual area burned (ha yr⁻¹) for all simulated unsuppressed wildfires originating in the RO start zone (*A*) and with application of RO rules (A_{RO}) by month of fire start.

	All fires		RO fires	
	A (ha yr⁻¹)	Percent of total	A_{RO} (ha yr⁻¹)	Percent of total
May	593	4	0	0
Jun	2062	14	206	4
Jul	4738	33	1185	24
Aug	5450	38	2493	51
Sep	1105	8	663	14
Oct	392	3	313	6
Nov	0	0	0	0
Dec	0	0	0	0
Total	14431	100	4861	100

plication of RO rules reduced the expected annual acres burned by two-thirds to 4861 ha yr^{-1}, with 76% occurring in fires starting in July and August (Table 4). By contrast, observed fires originating in the RO start zone from 1990 to 2009, which were managed primarily for protection objectives (i.e., full suppression of all starts), burned an average of just 207 ha yr^{-1}, illustrating the magnitude of the effect of fire suppression (including preparedness and initial attack) on annual area burned.

Fires reaching the WUI defense zone arrived from all directions and tended to start near the WUI defense zone (Figure 5). Early-season fires were several times more likely to reach the WUI defense zone than mid- or late-season fires (Table 3). For example, 3.0% of fires starting in May eventually reached the WUI defense zone, whereas just 0.7% of August fires and 0.1% of October fires did so. Wildfires that reached the WUI defense zone were larger and longer in duration than average. For example, wildfires that reached the WUI after starting in May burned an average of 55.9 days and grew to an average of 50372 ha, which was more than four times the duration of all May fires, and more than 12 times their size (Table 3).

Despite the higher propensity for an early-season fire to reach the WUI, the relatively low historic occurrence rate of early-season fires means that they did not account for a large fraction of fires that eventually reached the WUI (Table 5). Without RO rules, fires starting in May and June accounted for 22% of all fires that reached the WUI. The application of RO rules significantly reduced the impact of May and June fires; just 6% of fires that reached the WUI originated in those months.
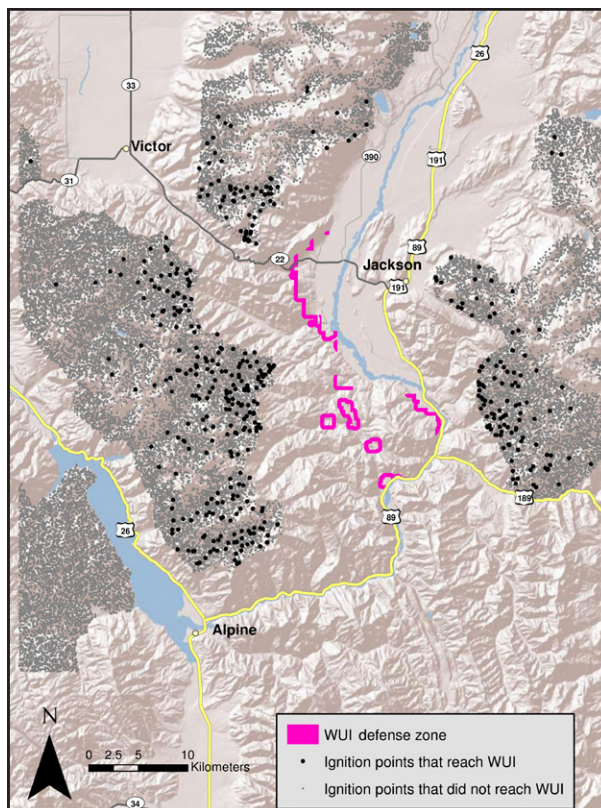

Figure 5. Ignition locations of simulated unsuppressed wildfires that reached the wildland-urban interface (WUI) defense zones (black dots) and those that did not (small gray dots). Simulated wildfires were not allowed to start outside of the resource-objectives wildfire start zone.

Table 5. Expected annual number of wildfires that reach the wildland-urban interface (WUI) defense zone (N_{WUI}), conditional WUI defense zone area burned per fire (A'_{WUI}, ha fire^{-1}), and expected annual WUI-area burned (A_{WUI}; ha yr^{-1}) for all fires and with application of RO rules by month of fire start. A'_{WUI} is assumed to be the same for RO fires as it is for all fires.

	All fires			**RO fires**	
	N_{WUI} (fires yr^{-1})	A'_{WUI} (ha fire^{-1})	A_{WUI} (ha yr^{-1})	N_{WUI} (fires yr^{-1})	A_{WUI} (ha yr^{-1})
May	0.004	550	2.4	0.000	0.0
Jun	0.014	488	6.8	0.001	0.7
Jul	0.032	362	11.5	0.008	2.9
Aug	0.030	289	8.7	0.014	3.9
Sep	0.003	90	0.3	0.002	0.2
Oct	0.000	168	0.1	0.000	0.1
Nov	0.000	279	0.0	0.000	0.0
Dec	0.000	0	0.0	0.000	0.0
Total	0.084	465	29.9	0.025	11.8

The RO rules alone reduced the annual number of fires expected to reach the WUI by 70 %. Ignoring their low occurrence rate, early-season fires burned a larger mean WUI defense zone area than late-season fires (Table 5). The expected annual WUI area burned peaked in July without applying RO rules. With those rules, the peak shifted to August and fell considerably. Overall, the RO rules reduced the expected annual acres burned within the WUI by 61 %, from 29.9 ha yr^{-1} to 11.8 ha yr^{-1} (corresponding to a reduction from 1.2 % yr^{-1} to 0.5 % yr^{-1} of the 2500 ha WUI defense zone).

DISCUSSION

Assuming that lightning and anthropogenic wildfires occur at the recent historic rate, relatively few wildfires originating in the RO start zone and left unsuppressed appeared capable of reaching the WUI defense zone—even without the RO rules. The few simulated wildfires that managed to traverse the distance were long-duration, large, and tended to start close to the WUI defense zone. Early-season wildfires, which tended to burn for a longer duration and become larger, were more likely than late-season wildfires to reach the WUI. These results confirmed local staff's expectation that they would favor protection objectives for early-season wildfires, but resource objectives for late-season wildfires. Although the fraction of fires that reached the WUI defense zone (F_{WUI}) declined as the season progressed, it did not decline to zero. Conversely, although the fraction of fires that reached the WUI defense zone was several times greater for early-season fires than mid- and late-season fires, even early-season fires had a low likelihood of reaching the WUI. Careful selection of early-season ignitions for resource-objective management (based on location and weather) coupled with limited fire suppression actions to minimize spread toward the WUI, could be a viable strategy for mitigating the threat of RO fires reaching the WUI defense zone on this landscape.

Several factors explain the relatively small expected annual WUI defense zone area burned (11.8 ha yr^{-1}). First, this analysis focused on the 2500 ha federally managed WUI defense zone, a relatively small buffer (400 m) on one side of the linear boundary between public and private land in the WUI, rather than on the much larger area of the privately owned WUI. For example, a wildfire that is 1000 m wide where it crosses the public-private boundary will burn just 40 ha of WUI defense zone (1000 m × 400 m), whereas several times that amount of private-land WUI could be burned beyond this buffer zone. Second, expected annual WUI defense zone area burned incorporates the likelihood that wildfires will reach any part of the WUI defense zone, which is relatively low (8.4 % of all fire starts; 2.5 % considering the RO rules). The conditional mean WUI defense zone area burned (of the fires that do reach the defense zone) is 465 ha, which corresponds to roughly 11.6 km of public-private boundary burned.

Applying the simple RO rules reduced the expected annual number of RO fires that reach the WUI defense zone by 70 % (compared to managing all ignitions for RO). This is consistent with the finding of Cary *et al.* (2009) that ignition management and weather affected fire likelihood more than simulated fuel treatments. This is a conservative estimate of the effect of RO rules because 1) our analysis assumed random selection of RO wildfires, and 2) our analysis assumed that there is no suppression at any time during a wildfire, even if it clearly threatens to reach the WUI. In practice, the selection of wildfires for RO management is not random, but informed by a variety of factors known to fire managers at the time of a wildfire start, including the spread potential at the location of the start, and the past and forecast weather. The unsuppressed wildfires that reached the WUI in our simulations would likely receive aggressive suppression actions on the portions threatening to reach the WUI, and would thus be less likely to reach the WUI than estimated here.

In the case of unsuppressed wildfires that must traverse some distance between a start zone and a threatened resource or asset, these results suggest that it is primarily the largest of possible fires that traverse the distance and that those large fires tend to be long-duration events. Despite this tendency, comparatively small, short-duration fires are still capable of reaching across the gap between the RO start zone and WUI defense zone, especially if starting in the portion of the RO start zone closest to the WUI defense zone. On 22 July 2001, the Green Knoll Fire started along the eastern edge of the RO start zone, directly west of the WUI defense zone. In just a few days the fire spread 9 km to the northeast and grew to 1533 ha, burning 182 ha of the WUI defense zone, despite being managed for protection objectives. This example of a relatively small fire reaching the WUI from the start zone does not necessarily contradict our results, but it does point out the geospatial variability in threat within the RO start zone.

This analysis does not reflect the possible future threat-reduction benefits of allowing RO managed fires to occur (Miller and Davis 2009). That is, an RO managed fire this year may limit the size or severity of wildfires occurring in future years (Collins *et al.* 2009). Such an analysis would require adding a temporal component to the simulation modeling, as suggested by Davis *et al.* (2010).

The cumulative distributions of the number of simulated fires and area burned (Figure 4) contrasts with the results of studies relying on short-duration problem-fire scenarios (e.g., Collins *et al.* 2011, Ager *et al.* 2010, Gercke and Stewart 2006, Moghaddas *et al.* 2010). The problem-fire approach identifies a weather scenario associated with significant historic spread events, and then simulates fire growth for that relatively short duration (typically one to three burning periods). Indeed, 34 % of wildfires in our simulations burned for three days or less, even without simulation of fire suppression. However, those short-duration fires accounted for just 0.4 % of the area burned. The contribution of large fires to BP is proportional to area burned, not number of fires, so accounting for their occurrence is critical for unbiased estimation of BP. More importantly, considering large, long-duration fires has implications for fuel management. The BP has been shown to be quite sensitive to a variety of fuel management scenarios when assessed using problem-fire simulations (Ager *et al.* 2010, Collins *et al.* 2011). We hypothesize that the effect of fuel management on BP could be smaller than what has been found for short-duration problem fire simulations. Large, long-duration wildfires simply have ample time to go around or through fuel treatment areas. Our simulations did not include a suppression effect on fire size, but if they had, there would have been fewer large, long-duration fires.

MODEL APPLICATIONS

The methods used in this study could be applied by researchers and fuel management planners to quantify wildfire threat to a variety of HVRAs (e.g., energy infrastructure and wildlife habitat) and to compare the effects of alternative fuel management strategies on wildfire threat as others have done with different fire simulation models (Ager *et al.* 2010, Collins *et al.* 2011). Although we assessed the special case of remote, unsuppressed wildfires reaching a WUI, our general analytical framework could be applied to simulation of any geographic arrangement of fire start and HVRAs, with or without suppression. Further analysis is possible with the fire simulation system we used. For example, rather than designate *a priori* the RO start zone, it may be possible to geospatially calculate the fraction of fires that reach the WUI (by month), giving fire managers information regarding portions of the landscape likely to produce fires reaching HVRAs (Ager *et al.* 2012).

Applying this method on other landscapes requires four types of inputs. First, a geospatial representation of surface and canopy fuel

characteristics, topography, and forest vegetation is needed in the form of a FARSITE landscape file. In the US, these datasets are available from the LANDFIRE project. Second, a 20- to 30-year history of fire occurrence for the fuelscape (principally including the date and final size of wildfires that escape initial attack) is required. Information on smaller fires contained during initial attack, while critical for preparedness planning, is unimportant for simulating BP because small fires contribute so little to overall BP. Third, a weather summary for the period of historic fire occurrence, including daily precipitation, temperature, relative humidity, and hourly wind speed and direction during the fire season, is necessary. Finally, information regarding the location of fire-susceptible HVRAs permits calculation of the likelihood that wildfire will reach those locations, and its potential magnitude of impact. Until recently, a significant investment in computing hardware was required to run FSim. However, advances in computing power now allow FSim to be run on an inexpensive, consumer-grade personal computer.

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