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A polygon-based modeling approach to assess exposure of resources and assets to wildfire

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A polygon-based modeling approach to assess exposure of resources and assets to wildfire

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Abstract Spatially explicit burn probability modeling is increasingly applied to assess wildfire risk and inform mitigation strategy development. Burn probabilities are typically expressed on a per-pixel basis, calculated as the number of times a pixel burns divided by the number of simulation iterations. Spatial intersection of highly valued resources and assets (HVRAs) with pixel-based burn probability estimates enables quantification of HVRA exposure to wildfire in terms of expected area burned. However, statistical expectations can mask variability in HVRA area burned across all simulated fires. We present an alternative, polygon-based formulation for deriving estimates of HVRA area burned. This effort enhances investigations into spatial patterns of fire occurrence and behavior by overlaying simulated fire perimeters with mapped HVRA polygons to estimate conditional distributions of HVRA area burned. This information can be especially useful for assessing risks where cumulative effects and the spatial pattern and extent of area burned influence HVRA response to fire. We illustrate our modeling approach and demonstrate application across real-world landscapes for two case studies: first, a comparative analysis of exposure and area burned across ten municipal watersheds on the Beaverhead-Deerlodge National Forest in Montana, USA, and second, fireshed delineation and exposure analysis of a geographically isolated and limited area of critical wildlife habitat on the Pike and San Isabel National Forests in Colorado, USA. We highlight how this information can be used to inform prioritization and mitigation decisions and can be used complementarily with more traditional pixel-based burn probability and fire intensity metrics in an expanded exposure analysis framework.

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1 Introduction

Spatially explicit burn probability (BP) modeling is increasingly applied to assess wildfire risk to highly valued resources and assets (HVRAs) and to inform development of mitigation strategies (Miller and Ager 2012; Parisien et al. 2012; Calkin et al. 2011; Thompson et al. 2011, 2012; Bar Massada et al. 2009; Carmel et al. 2009; Miller et al. 2008). Such BP modeling is accomplished with a Monte Carlo style wildfire simulation system that simulates the occurrence and growth of wildfires for thousands of iterations, each representing a complete fire season, across landscapes consisting of up to several million pixels (Scott et al. 2012a; Finney et al. 2011). BP is calculated for each pixel on a landscape as the number of iterations that result in that pixel burning divided by the total number of iterations (Finney et al. 2011). In a given iteration, a pixel is assumed to either burn completely or not at all, so pixel-level BP is equivalent to BP at a point on the landscape. Some BP modeling systems, including FSim (Finney et al. 2011) and FlamMap v5 (Finney 2006), also generate information about the characteristic fire intensity at each pixel. These results characterize the central tendency of fire intensity at each pixel, given the variability in the fire environment, including relative spread direction. Flame length and fireline intensity are two typical measures of fire intensity used to characterize wildfire hazard (Ager et al. 2012a).

A foundational component of wildfire risk assessment is exposure analysis, which characterizes wildfire likelihood and intensity in the locations where HVRAs occur (Ager et al. 2012a; Salis et al. 2012; Thompson and Calkin 2011). Exposure of an HVRA to wildfire can be quantified as the joint distributions of BP and fire intensity, as well as the expected annual area burned (Scott et al. 2012a). Expected annual HVRA area burned is calculated as

$$MBP_{HVRA} \times A_p \times N_{HVRA}$$

where MBP_{HVRA} is the mean BP of the pixels representing the HVRA, A_p is the land area represented by a single pixel, and N_{HVRA} is the number of HVRA pixels. However, an exposure analysis that relies exclusively on pixel-level BP potentially masks important variability in the spatial pattern and extent of wildfire–HVRA interactions, because the spatial extent of each simulated wildfire is not captured in the simple tallies that generate the pixel-level results.

In this paper, we present an alternative polygon-based formulation for deriving estimates of HVRA BP (i.e., polygon-level BP) and area burned. This effort enhances investigations into spatial patterns of fire occurrence and behavior by overlaying simulated fire perimeters with mapped HVRA polygons to estimate the conditional distribution of HVRA area burned. Conditional HVRA area burned is calculated on a per-iteration rather than a per-pixel basis and thus provides an estimate of how much of the HVRA could burn in a given fire season. This information is useful for assessing wildfire exposure and risk where spatial cumulative effects and the spatial pattern and extent of area burned influence HVRA response to fire. Rhoades et al. (2011), for instance, found that post-fire changes to streamwater chemistry and turbidity after the Hayman Fire were closely related to the proportional extent of basin that burned.

This alternative modeling approach can address questions such as, “What is the probability that over 75 % of the HVRA area burns in a single fire event or a single fire season?” Thus, the ability to derive polygon-level probability distributions for area burned enables improved spatial characterization of HVRA exposure to wildfire, identification of at-risk HVRAs, and, ultimately, informed and efficient strategic planning. Information regarding fire intensity for each simulated perimeter is not produced by the fire modeling system due primarily to current limitations of data storage capacity. The polygon-based approach therefore complements but does not replace the pixel-based approach.

To begin, we describe the polygon-based approach and review the important differences between it and the pixel-based approach. We then illustrate the polygon-based modeling approach for two case studies that relate to different HVRAs on National Forests in the western United States. We propose an expanded framework for wildfire exposure analysis that couples pixel-based and polygon-based approaches in a complementary fashion. Lastly, we discuss the strengths and limitations of the polygon-based approach and recommend possible future applications for comprehensive wildfire risk assessment and mitigation.

1.1 A polygon-based approach to estimating HVRA BP

The polygon-based approach requires geospatial data representing the perimeters of all simulated wildfires and a polygon representing each HVRA. Note that there could be multiple polygons that each represent the same HVRA category, for instance low density rural communities, watersheds, old growth stands, and core habitat areas. The first steps are to identify and tally the simulated wildfire perimeters that overlap the HVRA and then to calculate the area of overlap between each perimeter and the HVRA. HVRA BP is the count of simulation iterations that overlap the HVRA divided by the total number of iterations. This value represents the annual probability that a wildfire will reach any portion of the HVRA. The mean conditional HVRA area burned is the sum of overlap of all simulated fires divided by the number of fires that overlap the HVRA. This represents the average amount of HVRA that burns, given that any of it does burn. The unconditional expected annual HVRA area burned is calculated as the product of HVRA BP and mean conditional HVRA area burned, representing the average annual amount of HVRA area expected to burn.

This polygon-based calculation of expected annual HVRA area burned is consistent with the pixel-based calculation described above; the result will differ only if the geospatial polygon and pixel characterizations of the simulated wildfires or HVRAs differ. Thus, the advantage of the polygon-based approach is not the calculation of expected annual HVRA area burned, but that the *distribution* of conditional HVRA area burned—not just the mean—can be characterized. Further, any characteristics associated with each simulated wildfire—start location and date, for example—can be related to the amount of HVRA area burned by that fire. Knowing the start location of fires that reach the HVRA, as well as the locations of those that do not, allows an intricate analysis of the factors affecting the likelihood that wildfire will reach an HVRA and the amount of HVRA area burned if it does (Scott et al. 2012b).

1.2 Polygon-based modeling and fireshed delineation

As part of the interdisciplinary fireshed assessment process for designing and scheduling fuel management projects, the term fireshed has been used to describe a planning area delineated based on fire regime, condition class, fire history, potential wildland fire behavior, and fire hazard and risk (Collins et al. 2010; Ager et al. 2006a; Bahro and Barber 2004). The notion is that firesheds are conceptually analogous to watersheds where they demarcate areas of similar wildfire threat, within which a similar management strategy could influence wildfire outcomes (Bahro et al. 2007). However, unlike watersheds, firesheds may vary widely in size and shape depending on how fuel types, local topography, and weather influence potential fire behavior; fireshed boundaries are also influenced by the values they contain (e.g., human infrastructure, wildlife habitat) and by fire management opportunities—will fire managers be allowed to manage the fire for resource benefit or must they conduct full suppression activities throughout the fire incident (Bahro et al. 2007). Firesheds are in a sense more similar to forest stands as relatively homogenous fire management planning units, whereas watersheds are more defined by spatial relationships and connectivity. Additionally, fireshed boundaries are defined at a coarse scale and are not fixed; the boundaries will change over time as fuel conditions and the characteristics of the fire threat change in response to management and natural changes in the landscape (Finney and Cohen 2003).

Fireshed delineation begins with the identification of a “problem” fire—a historic or hypothetical wildfire with potential for great impact on human and natural resources, based on fuel, terrain, and historical weather patterns (Bahro et al. 2007). Firesheds, although typically small in a relative landscape context, tend to cover fairly extensive areas encompassing several times the size of the problem fire and are sufficiently large as to assess the effectiveness of fuel treatments at changing the outcome of a large wildfire event (Ager et al. 2006a, b). However, there is no accepted quantitative method how to systematically demarcate firesheds.

Saah et al. (2010) recently devised a new quantitative approach to determining firesheds by integrating data on land cover, weather, topography, and fire probability into a semi-automated statistical process that establishes the firesheds within a study area. Their method considers five main factors: the fire behavior triangle of fuels, weather, and topography; barriers to fire spread (both natural and anthropogenic); potential fire behavior (under a “near-worst case” weather scenario); fire occurrence probability patterns; and fire history. However, the delineation process is largely statistical in nature, relies on subwatershed boundaries to delineate “fire basins,” and does not explicitly consider the spatial growth of multiple fires across the landscape.

Simulated fire perimeters produced by a Monte Carlo wildfire simulator facilitate a more precise definition and delineation of a fireshed. The use of perimeters also sharpens the conceptual analogy to a watershed. Whereas a watershed is the area of land where the water that falls on it drains to a designated point, we define a fireshed as the land area where a fire can occur (ignite) and eventually spread to a defined point, line, or polygon. Thus, this definition explicitly considers fire growth as a function of topography, fuels, and other conditions that can influence spread, rather than using those factors as a proxy. This is an HVRA-based definition of a fireshed. The size and shape of the HVRA under consideration as well as broader landscape characteristics and weather patterns will influence the size and shape of the fireshed.

The interpretation of the fireshed will depend on the simulation system used to delineate it. When simulating entire fire seasons, as we do here, the fireshed is the area where fires can ignite and eventually reach the target HVRA during the course of an entire season. When using models that simulate shorter duration “problem fire” scenarios, the fireshed is the area a wildfire can occur, whether as an ignition or after spreading there from another start location, and reach the HVRA during a problem fire event of a given duration.

2 Methods

2.1 Wildfire simulation

The modeling approach we present with these two case studies relies on the FSim large fire simulation system (Finney et al. 2011), but any Monte Carlo style wildfire simulation model that produces final fire perimeters as a polygon feature could be used. Monte Carlo modeling systems simulate stochastic (random) processes over many thousands of iterations and then integrate those iterations into a coherent result. An FSim iteration spans one complete fire season. For that reason, the terms "fire season" and "year" are often used synonymously with iteration. Simulations with FSim typically use 10–50 thousand iterations (Finney et al. 2011).

FSim consists of three fire simulation modules: fire occurrence, fire growth (Finney 2002), and fire containment (Finney et al. 2009). These modules are built on the foundation of a fourth module of weather generation (Finney et al. 2011). The weather generation module simulates daily values of the energy release component (ERC) of the National Fire Danger Rating System (Cohen and Deeming 1985) using time series analysis. The occurrence module simulates the daily likelihood that a fire will escape initial attack and become a large fire. Ignition locations are probabilistically generated according to an ignition density grid built off of historical ignition location patterns. This likelihood is calculated as a function of ERC-G for each day of a simulation. The fire growth module simulates the daily growth of a newly ignited or ongoing fire, through both spotting and flame front spread, as a function of fuel, weather, and topography as described in a fire modeling landscape file (LCP). Flame front spread is simulated for surface fires (Rothermel 1972) and passive and active crown fires (Scott and Reinhardt 2001; Van Wagner 1993; Rothermel 1991; Van Wagner 1977). The containment module simulates the likelihood that, on any given day of a simulation, the simulated fire will be contained and therefore no longer grows on subsequent days.

An FSim run captures variability surrounding input variables and provides probabilistic information on the range of potential realizations of a fire season. Application of FSim requires careful critique of terrain, fuel, and vegetation characteristics, historical weather data, and information on historical fire occurrence (Scott et al. 2012a, b; Thompson et al. 2012). FSim produces pixel-based estimates of BP and mean fireline intensity in raster (gridded) data format, as well as polygon-based information in ESRI shapefile format, consisting of each simulated wildfire perimeter and its associated characteristics, including the start day, start location, number of active burn days, and the final fire size. Although the initial purpose of FSim was to support continental-scale assessment of wildfire hazard, it was implemented in discrete geographic units (Fire Planning Units) roughly ranging in size from 1 to 30 million ha (Finney et al. 2011). The results were mosaiced together in a GIS. The appropriate scale for an individual FSim run is therefore not continental, but the smaller extent, similar to an individual forest or park unit.

2.2 HVRA exposure

To calculate HVRA exposure, we overlaid the simulated fire perimeters on each HVRA boundary to identify (1) the number of fire perimeters that burned into any portion of the HVRA (also noting the number of unique simulation iterations represented) and (2) the area of HVRA burned by each of those fires and iterations. From those results, we calculated the polygon-level BP (HVRA BP), the distribution of HVRA area burned, and the mean conditional HVRA area burned. Mean conditional HVRA area burned is the mean area of intersection between the simulated fire perimeters and the HVRA, counting only those perimeters that did intersect the HVRA. For an HVRA consisting of multiple discrete polygons (e.g., several individual watersheds within a municipal watersheds HVRA), the analysis is performed independently for each discrete polygon, not for all polygons at once.

2.3 Case study 1: municipal watershed exposure and area burned

Following an assessment of wildfire threat to multiple HVRAs on the Beaverhead-Deerlodge National Forest, Montana, USA (Scott and Helmbrecht 2010), Scott et al. (2012a) assessed the exposure to wildfire of ten municipal watersheds located within the 6.1 million ha landscape. Land ownership in the study area consists of National Forest System land surrounded by land under private and other federal ownerships. Explicit identification of municipal watersheds by name or location can be a sensitive issue due to the potentially serious consequences of disruption. Therefore, exact names and locations of municipal watersheds across the landscapes are not provided; we instead refer to the watersheds by code letter (A through J). For use in the analysis, however, we were provided with a polygon-based geospatial dataset indicating the location of each watershed in the study area.

The fire modeling landscape file (LCP) required by FSim was generated for the rectangular, 6.1 million ha landscape, based on LANDFIRE v1.0.2 (www.LANDFIRE.gov), using a critique and update workshop process during which local fuel and fire behavior specialists provided input (Scott and Helmbrecht 2010), producing fuel, vegetation and topography layers current as of 2009. All layers were produced in the best-fit UTM zone projection (NAD83 UTM Zone 12 N). The native 30 m resolution of the critiqued and updated LANDFIRE data layers was then resampled to 90 m before generating the required LCP.

No single RAWS station within the landscape contained sufficient data to rely upon solely, so FSim inputs were generated for a composite of five RAWS stations: ENNIS, FRENCH CREEK, GALENA, PBURG, and WISE RIVER. Weather data from these stations begin from 1999 to 2003 and end, for the purpose of this assessment, in 2009. Monthly distributions of wind speed and direction data, for a combination of 10-min average and gusts, were compiled for the assumed burning period 10 am through 8 pm.

Historic fire occurrence data for the period 1990–2009 were acquired and critiqued, then clipped to the landscape boundary. These occurrence data were used with the composite RAWS data to generate the required coefficients for a logistic regression equation that determines the probability of a large-fire day. The occurrence data were also used to generate the distribution of the number of large fires per large-fire day. A coarse-scale spatial ignition probability grid generated for use by FSim across the United States (Finney et al. 2011) was used. That grid indicates the relative density of large fire (>121 ha) start locations for a coarse cell size (20 km) and using a large search radius (75 km).

We used FSim to simulate 40,000 fire season iterations, at a calculation resolution of 90 m. The simulations were set to start at the beginning of the historic fire season (July 1) and had a maximum fire size limit of 202,000 ha. The FSim suppression module was enabled, and the Scott and Reinhardt (2001) crown fire calculation method was used. The rate of spread for fuel models GR1, GS1, and GS2 (Scott and Burgan 2005) was adjusted by a factor of 0.5; the spread rates for all other fuel models were not adjusted. From geospatial overlay results, we calculated the watershed-level BP, the distribution of conditional HVRA area burned (that is, given that some part of the watershed burned), and the mean conditional HVRA area burned.

2.4 Case study 2: fireshed delineation and wildfire exposure for critical wildlife habitat

The Pawnee montane skipper (*Hesperia leonardus montana*) is a butterfly listed as a federally threatened species. Though no critical habitat is officially designated, the skipper's habitat is restricted to approximately 9,000 ha along the South Platte River in Colorado, including land within the Pike and San Isabel National Forests. Though low severity fire can be beneficial due to removal of understory and creation of small forest openings, there is concern over the extent of recently burned habitat and the skipper's limited distribution (Kotliar et al. 2003). Thus, the exposure of Pawnee montane skipper habitat to broad scale burning during large fire events is important to characterize, as is understanding the landscape extent to which fire management may help protect or restore skipper habitat.

To support a quantitative wildfire risk assessment on the Pike and San Isabel National Forests, we assessed wildfire likelihood and intensity using FSim for a rectangular 7.4 million ha study area that includes the National Forest boundaries and a 25 km buffer around them. We obtained fuel, vegetation and topography layers from the LANDFIRE project (version 1.1) at the native pixel size of 30 m in the best-fit UTM zone projection (NAD83 UTM Zone 13 N). We resampled these layers to a 90-m pixel size and generated an LCP, but made no other adjustments to the layers. We used data from the CHEESMAN RAWS (1987–2010) to generate monthly wind speed and direction distributions after converting the 10-min average wind speed to the probable maximum 1-min average wind speed (Crosby and Chandler 1966).

We used historical fire occurrence data for the landscape area (1992–2010) to generate the required logistic regression coefficients for predicting large-fire occurrence probability and to determine the historic distribution of the number of large fires per large-fire day. We used a coarse spatial ignition probability grid constructed with the same method as that described above for the Beaverhead-Deerlodge National Forest.

We then used FSim to simulate 20,000 fire season iterations at a calculation resolution of 90 m. The simulations were set to start at the beginning of the historic fire season (April 1) and had a maximum fire size limit of 162,000 ha. As with the first case study, the FSim suppression module was enabled, and the Scott and Reinhardt (2001) crown fire calculation method was used. The rate of spread for fuel models GR2 and GS2 was adjusted by a factor of 0.4; GS1 by 0.5; and GR1, GR3, GR4, and SH1 by 0.7. We did not adjust the spread rates for any other fuel models.

We plotted the start locations of the simulated wildfires that reached the skipper habitat and then used those results to identify the general fireshed for the skipper habitat. No simulated wildfires that reached the habitat started more than 25 km away. We then focused a second simulation that restricted fire starts to the 600,000 ha area within 30 km of the habitat—an area slightly larger than the maximum suggested by the initial forest-wide simulation—in order to generate more observations of fires with potential to reach the habitat without unnecessary simulation of fires with no chance to reach the habitat. This focused simulation was accomplished by setting the spatial ignition probability values to zero in the portion of the landscape outside the 30 km focused study area. Within the focused study area, the spatial ignition probability was assumed to be identical to the forest-wide value, meaning that simulated fires in the focused simulation would start with the same spatial ignition probability as in the forest-wide simulation. Because of the coarse resolution of the ignition probability grid, ignition probability is relatively uniform within the focused simulation area. In order to keep the annual number of wildfires within this focused study area consistent with the forest-wide simulation, we adjusted an input into

FSim[1] to account for the difference in fire occurrence between the focused and the forest-wide study areas. The focused study area comprises 8.2 % of the forest-wide landscape area, but it accounts for 10.1 % of the spatial ignition probability, which is calculated by dividing the sum of spatial ignition probability values within the focused study area by the sum across the forest-wide study area. The focused FSim simulation was conducted for 60,000 iterations, producing the same results that a whole landscape simulation of 60,000 iterations would produce, but several days of computing time are avoided.

From geospatial overlay results, we calculated the habitat-level BP, the distribution of HVRA area burned, and the mean conditional HVRA area burned. We also plotted the start locations of fires reaching the habitat and determined the shortest distance from the start location to the habitat by distance class. We used the start locations to compile a detailed summary of the likelihood of fire reaching the habitat by distance and to delineate the fireshed for the habitat. The fireshed was delineated by buffering an arbitrary 5 km around the concave hull surrounding the ignition locations that resulted in habitat burning.

3 Results

3.1 Case study 1: municipal watershed exposure and area burned

Exposure levels vary considerably across the ten municipal watersheds assessed (Table 1). Watershed F is the one most likely to experience a wildfire, with an annual HVRA BP of 0.003325 (Table 1; column c). This watershed is the most likely to burn in part because it is large and has the greatest burnable area (Table 1; column b), so the simulated fire perimeters are more likely to intersect it. Burnable watershed area is the total area of the watershed less the area mapped to a non-burnable land cover type (open water, bare ground, etc.). Watershed F has a relatively low mean conditional HVRA area burned relative to its size (column e), meaning that, when it does burn, an average of just 13.8 % of the watershed burns in one fire season. Watershed E has the greatest mean conditional HVRA area burned, at 1,234 ha (Table 1; column d). Watershed D ranks highest (41.9 %) in mean conditional HVRA area burned expressed as a fraction of the burnable watershed (Table 1; column e), followed closely by watersheds E (40.9 %), G (40.5 %), C (38.1 %), and I (34.8 %). For other watersheds, the mean conditional HVRA area burned tends to be much lower, especially for watershed A (4.7 %). The expected value of annual HVRA area burned (Table 1; column f), obtained by multiplying HVRA BP (Table 1; column c) by mean conditional HVRA area burned (Table 1; column d), is highest in watershed F. This result is consistent with the pixel-based results reported in Table 2 (column e) in Scott et al. (2012a).

Column g in Table 1 presents the expected annual percent of HVRA area burned within each municipal watershed, obtained by multiplying the watershed-level burn probability (HVRA BP; column c) by the mean conditional percentage of the HVRA area burned (column e). This approach normalizes area burned by total watershed size and accounts for variability in burn probability across watershed polygons. Watershed D ranks highest (0.13 %) in expected annual percent area burned, followed by watersheds E and I (0.09 %) and watershed G (0.08 %).

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[1] Specifically, we adjusted the AcreFract parameter, which allows users to modify the spatial ignition density on the basis of total ignitions and the area of the analysis area. Adjusting the AcreFract to reflect this ratio allows an annualized interpretation of the results.

Table 1 Summary of polygon-based wildfire hazard characteristics within each of the ten municipal watersheds on the Beaverhead-Deerlodge National Forest

(a) Watershed	(b) Burnable watershed (HVRA) area	(c) HVRA burn probability	Mean conditional HVRA area burned		(f) Expected annual HVRA area burned	(g) Expected annual % HVRA area burned
	Ha	Fraction	(d) ha	(e) % of total watershed	ha/year	%/year
A	10,093	0.003175	505	4.7	1.60	0.01
B	3,115	0.001700	284	9.0	0.48	0.02
C	521	0.001050	337	38.1	0.35	0.04
D	722	0.003125	330	41.9	1.03	0.13
E	2,494	0.002175	1,234	40.9	2.68	0.09
F	5,930	0.003325	888	13.8	2.95	0.05
G	1,580	0.001975	645	40.5	1.27	0.08
H	1,264	0.001225	264	20.4	0.32	0.02
I	1,303	0.002500	630	34.8	1.58	0.09
J	1,330	0.000750	231	12.2	0.17	0.01

Expected annual HVRA area burned (column f) is the product of HVRA burn probability (column c) and the mean conditional HVRA area burned (column d). Expected annual HVRA % area burned (column g) is the product of burn probability (column c) and the mean conditional % area burned (column e). Expected HVRA annual area burned as a fraction of the burnable watershed area is therefore equivalent to the mean pixel-based burn probability shown in Table 2 (column b) of Scott et al. (2012a)

Figure 1 presents the conditional watershed area burned by two scales, absolute (ha) and percentage of burnable watershed area. The relative frequency distributions of conditional HVRA area burned reveal some interesting patterns. Watersheds A, B, F, H, and J are all heavily left-tailed, with less than 10 % of the burnable area of those watersheds burning 60–80 % of the time, and very little or no chance of burning more than 70 % of the watershed at one time. This result is influenced by the relatively large size of these watersheds. The smaller watersheds (C and D, for example) have a greater likelihood of burning completely in a single fire. Those and other watersheds (E, G, and I) exhibit a U-shaped distribution, indicating that they are most likely to burn very little or completely, but rarely was a moderate fraction burned. These results suggest substantial spatial variability in the potential for large fire spread across the landscape and among the watersheds analyzed.

3.2 Case study 2: fireshed delineation and wildfire exposure for critical wildlife habitat

Over the course of 60,000 iterations, a total of 34,404 simulated wildfires occurred within the habitat and the 30 km area surrounding the habitat. Of those fires, 1,829 intersected the habitat, occurring in 1,716 iterations; that is, two fires intersected the habitat on 103 iterations and on one iteration three separate fires reached the habitat. The result is an estimated annual habitat-level burn probability (HVRA BP) of 0.0286. Regardless of the number of fires per iteration reaching the habitat, most of the iterations resulted in only a small fraction of the habitat burning (Fig. 2).

The mean conditional HVRA area burned was 328 ha, but the median was just 53 ha and the maximum was 9,719 ha, meaning that 96 % of the habitat burned in one simulation

Table 2 Polygon-based exposure of skipper habitat to wildfire by distance of fire start location to the habitat

Distance from ignition point to habitat (km)	Distance zone area (ha)	Simulated fires			Habitat area burned (ha)			Mean simulated fire duration	Mean simulated fire size
		Total number	Number reaching the habitat	Fraction (%)	Mean conditional	Maximum	Expected annual		
Habitat itself	25,045	609	609	100.0	259	9,719	2.6	5.8	1,227
0–1	58,581	1,372	803	58.5	308	6,668	4.1	7.4	2,036
1–2	40,895	1,016	175	17.2	371	6,165	1.1	11.8	4,284
2–3	38,398	960	88	9.2	396	3,062	0.6	15.0	6,867
3–4	35,991	928	47	5.1	427	3,242	0.3	17.8	9,670
4–5	33,577	839	34	4.1	339	2,582	0.2	20.2	15,491
5–6	68,905	1,705	35	2.1	435	4,136	0.3	23.3	26,964
7–10	112,398	2,783	20	0.7	553	2,365	0.2	29.7	43,387
10–15	214,102	5,142	6	0.1	103	205	0.0	29.7	39,501
15–20	248,895	5,560	3	0.1	58	148	0.0	25.0	87,317
20–25	287,163	6,380	1	0.0	6	6	0.0	32.0	69,442
25–30	325,194	7,110	0	0.0	–	–	–	–	–
Grand total	1,489,143	34,404	1,821	5.3	309	9,719	9.4	8.8	3,898

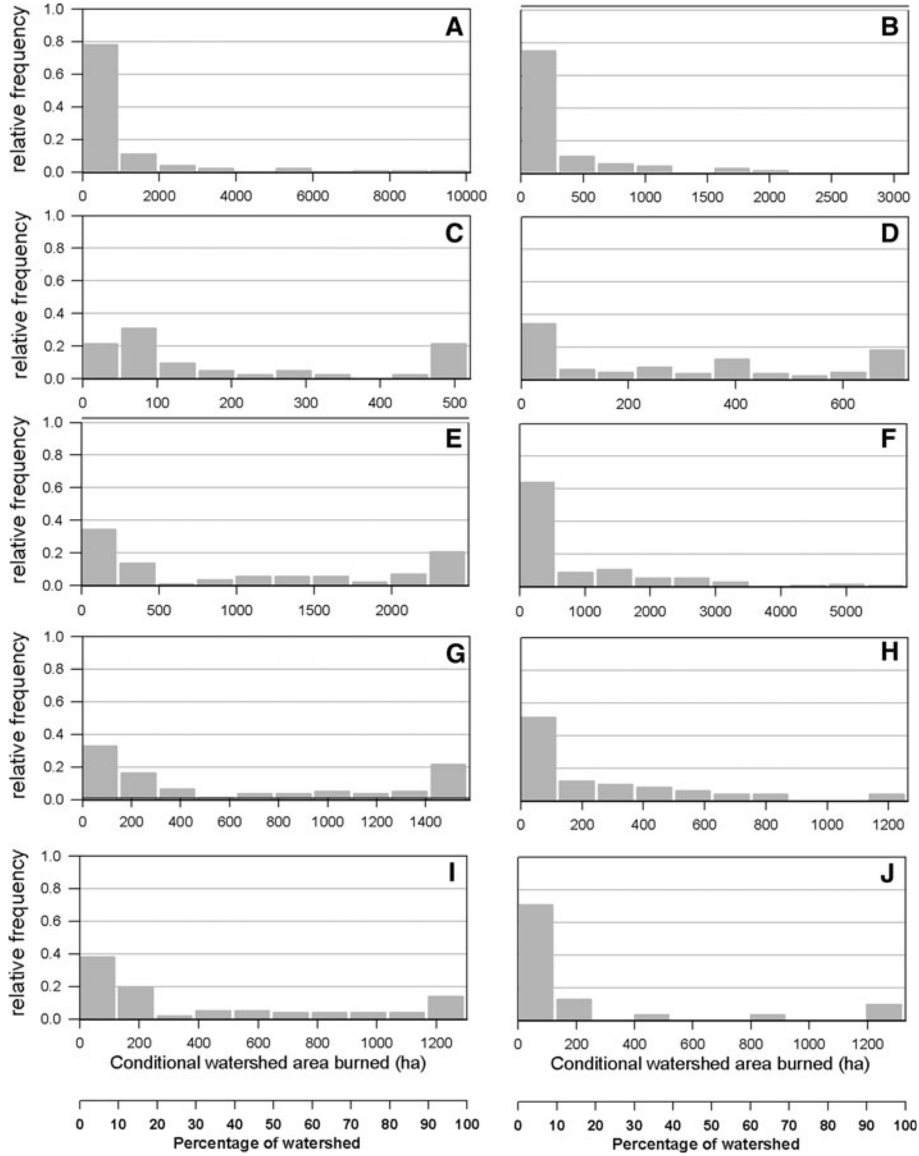

Fig. 1 Conditional watershed area burned (absolute area and as a percentage of burnable watershed area) for municipal watersheds A through J. *Each bar* represents 10 % of the burnable watershed area (see additional X-axis shown for bottom panels). An additional X-axis indicates the absolute watershed area burned. Burnable watershed area is the total area of the watershed less the area mapped to a non-burnable land cover type (open water, bare ground, etc.)

iteration. The expected annual HVRA area burned is 9.4 ha/year, less than 0.1 % of the habitat. Figure 3 displays four of the simulated fires that burned the greatest amount of habitat, with the extent of habitat area burned ranging from 41.3 to 89.8 %. Thus, although quite rare across simulation results, under the right conditions, most or the entire habitat could be burned by wildfire during a single season.

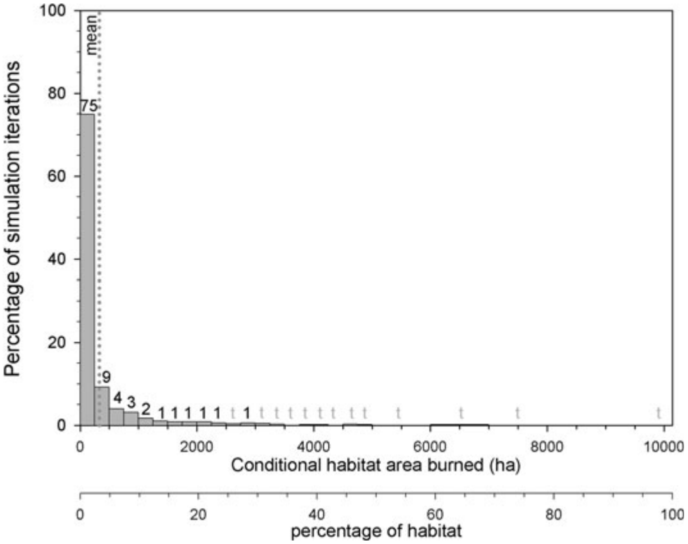

Fig. 2 Conditional distribution of Pawnee montane skipper habitat area burned. Results present the relative frequency of how much of the habitat area (absolute and as a percentage) is burned per iteration. *Bar* labels indicate the percentage of simulation iterations in each class; *t* = less than 0.5 %)

A summary of simulated wildfire characteristics by distance from the ignition location to the habitat reveals some interesting relationships (Table 2). The total number of fires that reach the habitat is a function, in part, of the area within a distance zone, but the fraction of total ignitions that reach the habitat exhibits the expected pattern of decreasing fraction with increasing distance. Nearly, sixty percent of fires starting within 1 km of (but not within) the habitat reached it, but less than 0.1 % of fires starting at least 10 km away did, and no fires starting more than 25 km away reached the habitat. Among fires that started within the habitat, a mean of 259 ha of habitat was eventually burned. This mean conditional HVRA area burned increased to roughly 405 ha for fires starting between 2 and 10 km away and then declined rapidly for more distant fires. By contrast, the largest maximum habitat area burned tended to occur in fires starting near the habitat. Ultimately, fires starting in and within 1 km of the habitat accounted for 72 % of the expected annual HVRA area burned. Fires that start some distance from the habitat must become large in order to reach the habitat. Fires that reach the habitat from within 1 km averaged 7.4 days in duration and around 2,000 ha in final size, whereas the fires starting 7–10 km away averaged nearly 30 days duration and more than 40,000 ha in final size.

Figure 4 presents an illustration of how a fireshed could be mapped for the Pawnee montane skipper habitat. The identified fireshed boundary encompasses more than 250,000 ha of land area. The highest concentrations of ignitions that reach the habitat are oriented in roughly the same shape as the habitat itself. The figure along with the information from the table illustrates how the HVRA-based method of delineating firesheds is based on fire growth potential and the spatial connectivity of HVRAs and simulated fire spread pathways.

4 Discussion and conclusion

Results of the two case studies presented herein provide useful information to facilitate risk-based mitigation of wildfire threats to human and ecological values. Comparative

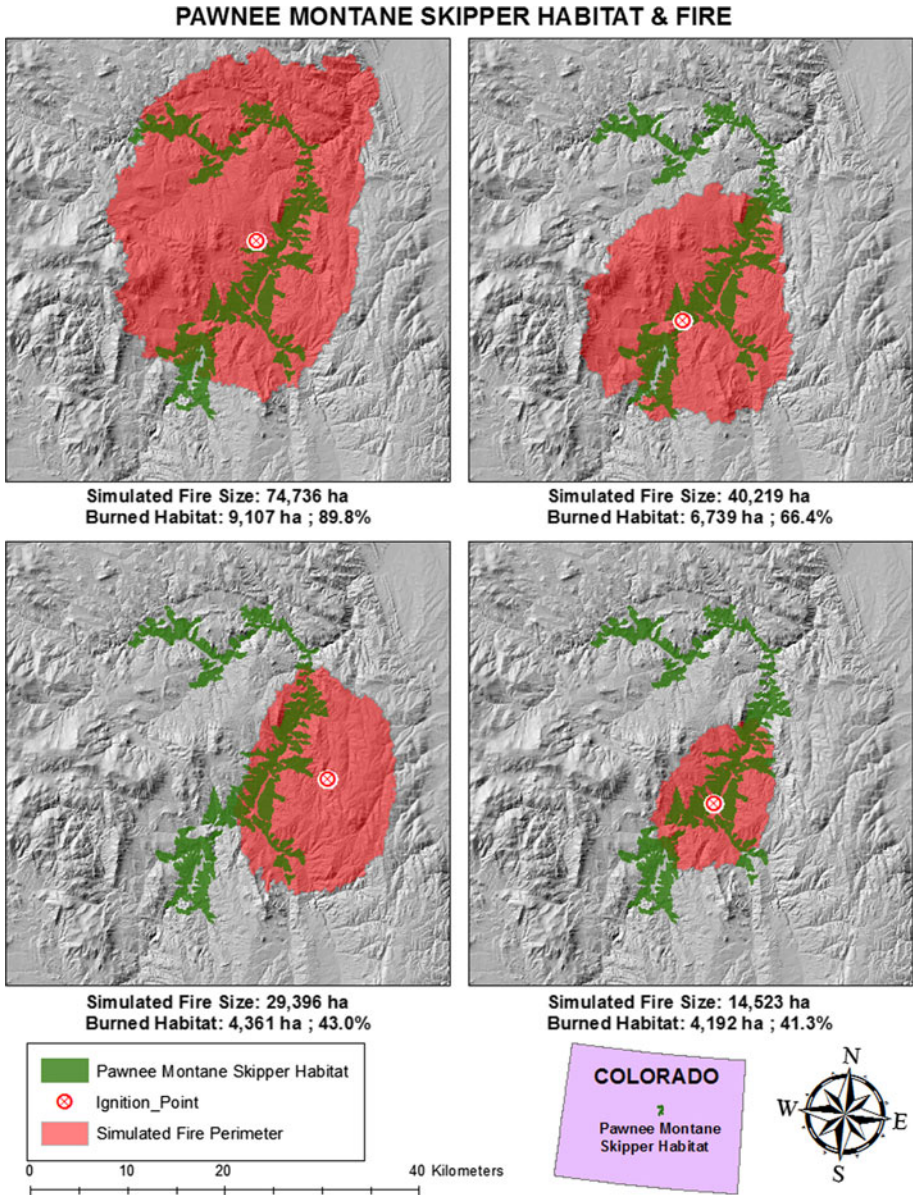

Fig. 3 Ignition locations, fire perimeters, and fire sizes for four of the fires that burned the greatest amount of Pawnee montane skipper habitat

analysis of municipal watershed exposure highlighted substantial spatial variation in the pattern and likelihood of burning, which could, for instance, help differentiate priorities for hazardous fuel reduction treatments. The reason for this spatial variability likely stems from at least two sources: relative differences in historical ignition density across the large landscape, as well as differences in mean large fire size. These factors in turn are influenced by spatial variation in broader environmental factors such as ignitions, fuels,

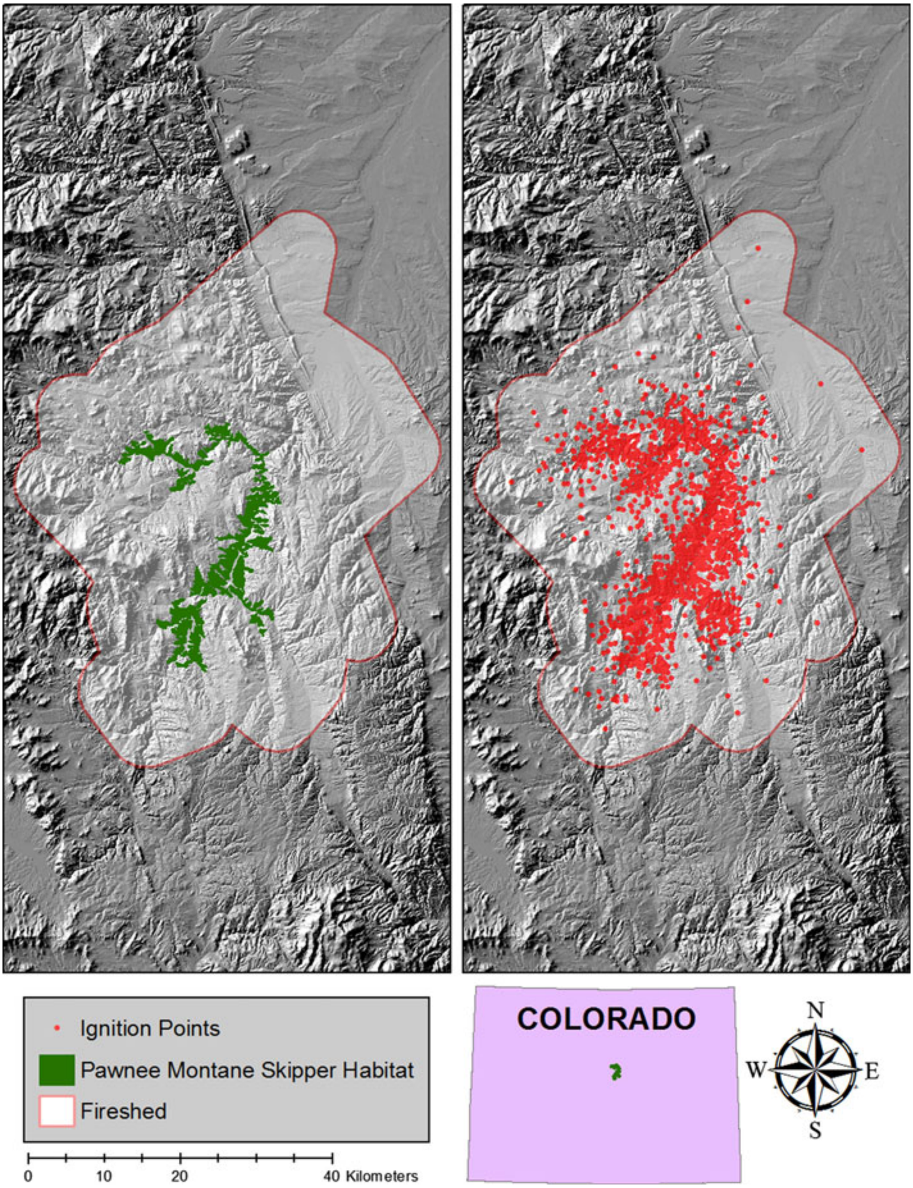

Fig. 4 Delineated fireshed for the Pawnee montane skipper habitat, including ignition locations for all simulated wildfires that reached habitat polygons. The delineated fireshed is a five km buffer around the concave hull of ignition locations of simulated wildfires that reached any part of the habitat

topography, and weather, and ongoing work is helping to quantify and better understand their relative influence on simulated burn patterns (Parks et al. 2012; Bar Massada et al. 2011; Parisien et al. 2011). In a similar vein, the novel approach to fireshed delineation not only explicitly captures fire spread potential across landscapes, but also allows for an in-depth analysis of landscape factors and the characteristics of fires reaching HVRA

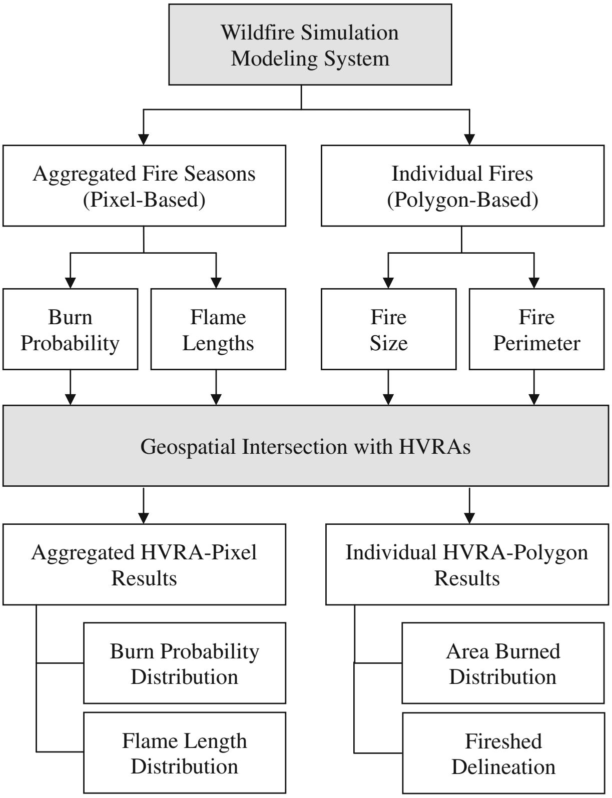

Fig. 5 Framework and workflow for expanded wildfire exposure analysis process. The key analytical steps are highlighted in *gray*. Pixel-based and polygon-based wildfire potential metrics are intersected with HVRA polygons to provide multiple, complementary characterizations of HVRA exposure to wildfire

polygons. Capturing the variability surrounding expectations of HVRA area burned can help land managers to better identify contributing factors (HVRA BP, conditional distribution for HVRA area burned) and design management responses accordingly.

Derivation of HVRA area burned distributions (unconditional and conditional) provides a new approach to wildfire exposure analysis and could provide complementary information when assessing potential fire consequences. Specifically, the polygon and HVRA BP modeling approach provides a better characterization of burn extent and variability within HVRAs, which may be useful for considering cumulative effects and potentially nonlinear ecosystem responses. Notably, what the polygon approach does not provide, at least as currently implemented in the fire modeling systems we used, is information relating to fire intensity. To comprehensively assess risk, information on fire intensity is critical (Miller and Ager 2012; Finney 2005), and therefore, pixel-based metrics are still necessary. FSim outputs include probability distributions of fireline intensity and flame length that capture variability in fire behavior and are useful for estimating likely fire effects (Thompson et al. 2011), and thus the modeling system can provide outputs necessary for both types of analysis.

Figure 5 proposes an expanded exposure analysis framework that includes both pixel-based and polygon-based modeling approaches. Both approaches rely on the same fire modeling system, but differ in the use of raster versus vector outputs. Jointly, the wildfire potential metrics (burn probability, fireline intensity, fire size, and HVRA area burned distributions) provide multiple characterizations of HVRA exposure to wildfire. The improved representation of variability in HVRA exposure in turn can lead to improved characterizations of wildfire risk (Thompson and Calkin 2011; Hanewinkel et al. 2011). Similarly, the improved representation and systematic approach to fireshed delineation could help better inform strategic fire management efforts.

The potential scope of application is quite broad, with watersheds and habitat just two examples where the spatial pattern and extent of HVRA area burned might be important to characterize. Analyzing wildfire-watershed risks across other landscapes could prove particularly informative. The feasibility of application is also quite broad, requiring access to HVRA geospatial data and requisite geospatial analysis skills for overlaying HVRA locations with fire simulation outputs. A user base of fire modeling specialists is probably the more limiting factor currently.

A clear direction for future work is to integrate polygon-based exposure analysis with fire effects analysis for more comprehensive risk assessment considering the likely consequences of fire (e.g., Thompson et al. 2011). Adjustment factors to HVRA fire response functions (see Thompson et al. 2012) could be applied on the basis of conditional area burned distributions. Alternatively, response functions could be defined on the basis of contiguous HVRA polygons rather than on a per-pixel basis.

Another direction for future work is expanded analysis of fireshed features. What are the characteristics of fires that pose a threat to HVRAs and could this information lead to mitigation strategies? This information has potential use for pre-fire planning and development of fire management plans, as well as for strategic fuels treatment and preparedness planning. Delineating firesheds also clearly lends itself to analysis of source–sink relationships and identifying sources of fire for a given HVRA (Ager et al. 2012b).

FSim is a fire modeling system with limitations, uncertainties, and potential errors. Careful calibration and validation efforts, however, have illustrated strong confidence in modeling results for a variety of applications (Scott et al. 2012a; Thompson et al. 2012; Finney et al. 2011). Of particular concern here is the fact that so far FSim validation exercises have related to fire size distributions and burn probabilities and not directly to the shape of fire perimeters. The effect of suppression effort on large fire containment is a key source of uncertainty in this respect (Finney et al. 2009). A more recent version of FSim has a perimeter clipping algorithm to approximate suppression operations and large fire containment, which could produce different results for fire perimeter overlays (M. Finney, Rocky Mountain Research Station, personal communication, January 2012), and which could provide a basis for additional experimentation. Further, the sufficiency and availability of spatial data on historical fire perimeters across landscapes may preclude using perimeters as a validation option for some time to come. Thus, current and future efforts should evaluate model outputs in this light and should strive for inclusion of local knowledge and expertise in the evaluation process. These limitations point to a boarder need for science delivery to the field to understand how to use the fire modeling systems such as FSim; to understand their respective strengths, limitations, and uncertainties; and understand how to use such tools appropriately to help answer meaningful questions.

In summary, we have demonstrated a novel approach for analyzing exposure of HVRAs to wildfire. The technique is complementary to existing exposure analysis methods and can provide key additional information on the spatial pattern and extent of area burned. Future work will seek to refine modeling approaches, incorporate these approaches into expanded risk assessment frameworks, and apply these approaches to a variety of fire-prone landscapes.

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