

Emerging Concepts in Wildfire Risk Assessment and Management

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Abstract—A quantitative measure of wildfire risk across a landscape—expected net change in value of resources and assets exposed to wildfire—was established nearly a decade ago. Assessments made using that measure have been completed at spatial extents ranging from an individual county to the continental United States. The science of wildfire risk assessment and management continues to build on the basic framework to develop new analysis techniques that address specific fire management problems. This paper reviews central concepts of the basic risk assessment framework and describes several emerging terms and concepts now under development. These new concepts include: 1) describing certain results of stochastic simulation systems as a wildfire event set, 2) defining a biophysical firehed as the land area where fires can originate and eventually reach a designated point, line or area in a designated period of time, 3) defining a fireplain as the land area where fire originating from a designated point, line or polygon (or set thereof) can reach during a designated period of time, 4) an exceedance probability curve, which plots the magnitude of an event (or its effects) against the likelihood that magnitude will be exceeded during a designated period of time, and 5) an analysis of wildfire Risk Associated with an Ignition Location (RAIL analysis), which characterizes the wildfire risk where the risk originates rather than where it occurs.

Keywords: event set, exceedance probability, fireplain, firehed, RAIL analysis

Background

A quantitative measure of wildfire risk across a landscape—expected net change in value of highly valued resources and assets (HVRAs) exposed to wildfire—was established nearly a decade ago (Finney 2005). Continued development of that framework has produced a few general wildfire risk assessment concepts, primarily the conceptualization of wildfire risk as the wildfire risk triangle (Figure 1). Wildfire risk at a given location on the landscape is a function of the likelihood of wildfire burning the location, the fire intensity when it does burn, and the susceptibility of all exposed HVRAs that exist there.

Stochastic simulation of wildfire occurrence, growth, and behavior is the foundation of quantitative wildfire risk assessment. A stochastic simulation incorporates random variation in one or more simulation inputs. For stochastic wildfire simulations, the variable inputs fall into two categories: fire occurrence and weather. These inputs are accommodated in different ways in fire simulation software (Table 1). FlamMap5 (Finney 2006) has a stochastic fire simulation feature that allows simulation of many fires for one weather scenario, often the so-called “problem-fire” scenario. The problem-fire scenario is a weather scenario (wind speed and direction, fuel moistures, and fire spread duration) that leads to damaging short-duration wildfires (Bahro and others 2007; Moghaddas and others 2010). FSim (Finney and others 2011b) also simulates many fires (focusing on fires

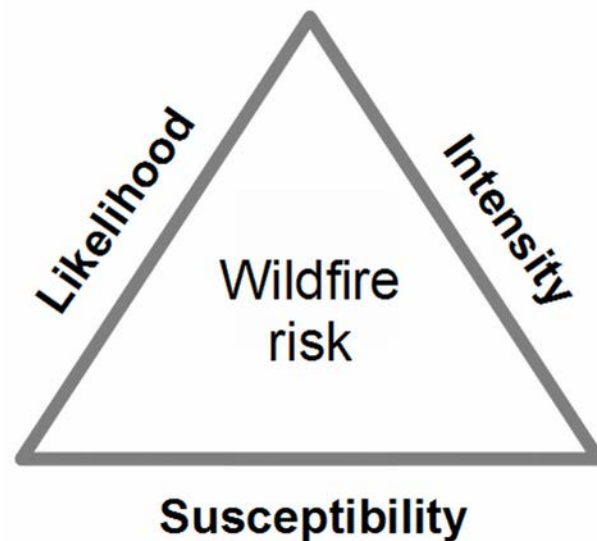


Figure 1—Wildfire risk triangle illustrates the major building blocks of quantitative wildfire risk assessment—the likelihood and intensity of wildfire and the susceptibility of resources and assets exposed to it (from Scott and others 2013).

that escape initial attack and become large), but also simulates many weather scenarios. FSim is a valuable simulation system because its results represent a designated period of time—one complete fire season—and because it attempts to simulate the full range of escaped-fire sizes that can occur on the landscape rather than focus on a problem-fire scenario. FSPRO (Andrews and others 2007; Finney and others 2011a; U.S. Forest Service 2009) is a stochastic simulation system used for incident management planning and decision-making (Calkin and others 2011). FSPRO is used only after a wildfire

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Table 1—Matrix showing the primary fire modeling systems used for simulating one or many fires and one or many weather scenarios. FARSITE is a deterministic simulation system used for one fire and one weather scenario; the others are stochastic, incorporating variability in weather and/or fire occurrence.

	One weather scenario	Many weather scenarios
One fire	FARSITE ^a	FSPPro ^b
Many fires	FlamMap5 ^c	FSim ^d

^a FARSITE is desktop software available at www.firelab.org; its functionality is replicated in the Wildland Fire Decision Support System (WFSS) as “Near-term fire behavior” analysis.

^b FSPPro is currently available only within WFSS.

^c FlamMap5 is desktop software available at www.firelab.org. Some of its functionality is replicated in WFSS; however, the stochastic simulation feature of FlamMap5 described in this paper is not available within WFSS.

^d FSim is custom software developed at the Missoula Fire Sciences Laboratory.

has already ignited, so it does not simulate fire occurrence, only growth for thousands of iterations starting with the same ignition point or perimeter under multiple weather scenarios. The user defines at run-time the duration of the simulation, usually 7 to 21 days. In contrast to these three stochastic simulation systems, the well-known FARSITE fire growth simulator (Finney 1998) is a deterministic simulation system that simulates one fire for one weather scenario, with no accounting for stochastic variability in its inputs.

Stochastic wildfire simulation systems produce raster outputs (a grid of cells or pixels) representing fire likelihood (burn probability) and conditional intensity given that a fire occurs (mean fireline intensity and, with additional calculations, conditional flame length), as well as polygons representing simulated final fire perimeters. Likewise, quantitative wildfire risk assessments can produce both pixel- and polygon-based results. An effects analysis (Scott and others 2013; Thompson and others 2011a, 2011b) is generally accomplished at the pixel-level. Polygon-based results are generally used in an exposure analysis (Scott and others 2012; Thompson and others 2013a).

Pixel-Based Risk

A pixel-based effects analysis quantifies wildfire risk where the effects occur on the landscape. Although effects can be measured and simulated in any unit of measure, it is typically measured as the net change in value of an HVRA due to burning (also called net value change, or *NVC*). *NVC* can be calculated for an individual HVRA, and also summed across multiple HVRAs of interest. Finney (2005) established the basic actuarial calculation of *NVC*; we modify that calculation here to produce two risk measures instead of one. Conditional net value change (*cNVC*) is the mean *NVC* that would be experienced given that a fire burns the location, incorporating only the intensity and susceptibility sides of the wildfire risk triangle (Figure 1). Expected net value change (*eNVC*) is the expected value of *NVC*, which incorporates all sides of the wildfire risk triangle, including the overall likelihood of burning. *cNVC* is calculated at a given location on the landscape (pixel) as

$$cNVC = \sum_j \sum_i NVC_{ij} * FLP_i$$

where NVC_{ij} refers to the net change in value for HVRA j if burned at fire intensity class i , and FLP_i refers to the conditional probability of fire burning in fire intensity (flame length) class i . Because FLP_i are conditional probabilities, the sum of FLP_i across all intensity classes is 1. Expected *NVC* can then be calculated from *cNVC* as

$$eNVC = cNVC * BP$$

where *BP* is the probability of burning at the location. The units of measure of *BP* depend on the system used—FSim produces annual *BP* values; FSPPro produces *BP* for the next 7 to 21 days, as specified by the user at run-time; and FlamMap5 produces a conditional probability of burning given that a problem fire occurs. *eNVC* is an excellent measure of overall wildfire risk, but first calculating *cNVC* also permits extended analyses that integrate the pixel and polygon results.

Polygon-Based Exposure

All three stochastic simulation systems mentioned above can produce polygons representing the final perimeter of each simulated wildfire. These perimeters allow the characterization of the exposure of an HVRA to wildfire in a way not possible with the pixel-level results. For example, the annual likelihood that wildfire burns any part of a municipal watershed can be calculated by counting the iterations during which wildfire reaches the watershed and dividing by the number of iterations (Scott and others 2012; Thompson and others 2013a). Further, the distribution of conditional watershed area burned—how much of the watershed burns in one year, given that at least some part of it does—offers information about the potential cumulative effects on the watershed that is not possible with the pixel-level analysis alone (Figure 2).

Emerging Concepts

In the following sections we introduce a few emerging concepts in wildfire risk assessment and management. In some cases the concept simply brings a new name to an existing concept.

Event Set

Computer simulation of the economic losses to HVRAs (*NVC*) that can potentially be caused by hazardous natural phenomena is known as natural catastrophe modeling, or “nat cat” modeling (Clark 2002). An event is an instance of the natural phenomenon—a hurricane, an earthquake, or a wildfire, for example. In the context of wildfire, an event can be an individual wildfire or, when using FSim, a whole wildfire season. An event set is a simulated set of events, each with known probability of occurring, along with associated characteristics of each event. A wildfire event set is a set of fire perimeters and associated characteristics for

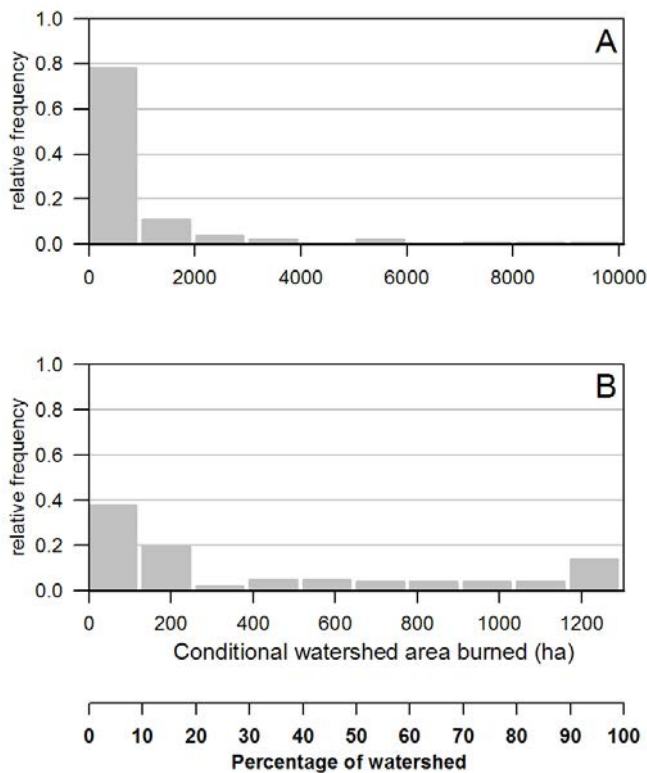


Figure 2—Polygon-based exposure to wildfire of two municipal watersheds on the Beaverhead-Deerlodge National Forest. Watershed A (top) is much larger (10,093 ha) than watershed B (1,330 ha) and therefore is likely to burn only a fraction of the entire watershed during a single fire event. Figure from Scott and others (2012).

each simulated wildfire in the set. The associated characteristics for each wildfire include the date and location of the ignition point, its duration, and its final size. Fire modeling software already exists to generate stochastic wildfire event sets on landscapes ranging from less than 1 million to more than 40 million ha.

The polygon results from a stochastic wildfire simulation system represent an event set (Figure 3). The annual probability of each simulated wildfire is $1/N$ where N is the number of iterations used in the simulation. The spatial nature of a wildfire event means it can be incorporated into analyses that are inherently spatial, such as the exposure analysis described above. The event set provides a basis for estimating the likelihood of a catastrophic event (an event producing effects above some threshold), and is useful for generating an exceedance probability curve (described below).

Fireshed Analysis

A watershed is the land area from which surface water drains to a specified point, line or area. Likewise, we define a fireshed biophysically as the land area within which a wildfire can start and eventually spread, during a designated period of time, to a specified point, line or area of concern (Thompson and others 2013a). Examples of points of concern include individual structures, communication and other administrative sites, historic cabins and small-extent wildlife habitat features like active nesting sites.

Examples of linear features of concern include electric transmission lines, scenic highway corridors and wildlife travel corridors. Examples of areas of concern include human communities (towns), large-extents of wildlife habitat, high-value vegetation communities, and municipal watersheds. The “designated period of time” for determining the size and location of a biophysical fireshed depends in part on the stochastic simulation system used. FSim inherently represents a whole fire season; FlamMap5 represents one or a few burning periods (specified at run-time). The fireshed concept helps focus attention on the portions of the landscape where an ignition is most likely to reach a susceptible HVRA. For operational wildfire incident planning, the fireshed concept can inform evacuation planning and the development of management action points.

The term fireshed has previously been used to describe a fire management planning area based on relatively uniform characteristics: fire regime, condition class, fire history, and potential wildfire hazard and risk (Ager and others 2006; Bahro and Barber 2004; Collins and others 2010). That definition of a fireshed—relative uniformity of important characteristics—is more analogous to a forest stand than a watershed.

A biophysical fireshed can be generated deterministically or stochastically. Stochastically, a wildfire event set forms the basis for identifying a biophysical fireshed. In a GIS, all simulated perimeters that reach the designated point, line or area of concern are selected. The X- and Y-coordinate values from the attribute table are then used to plot the start locations of these wildfires. Finally, the fireshed can be delineated by tracing a line around the outermost ignition locations (for example, a concave or convex hull), with perhaps an additional buffer. For example, Thompson and others (2013) used this approach to delineate the whole-season fireshed for the habitat of a butterfly species listed federally as threatened, Pawnee Montane Skipper (*Hesperia leonardus montana*), on the Pike and San Isabel National Forests, Colorado, USA (Figure 4).

This approach works with FSim and FlamMap5 perimeters, both of which place ignitions randomly across the landscape. The fireshed concept does not work with FSPro because it uses a fixed ignition location. Under uniform weather conditions, the minimum-travel time algorithm used to simulate fire growth (Finney 2002) can be modified to deterministically simulate a fireshed. For example, the WildfireAnalyst software (www.technosylva.com) includes a feature called Evacuation Mode that deterministically generates the fireshed for a specified point or line for a given duration of spread under uniform weather conditions.

Fireplain Analysis

A floodplain is the land area inundated by water during a flood of a specified magnitude. We define a fireplain as the land area where wildfire can spread to from one or more points or lines of ignition during a designated period of time. As with the fireshed concept, the designated period of time is determined by the system being used and

FIRE_NUMBE	ERC_STARTD	ERC_PERCEN	NUM_BURNDA	START_DAY	Xcoord	Ycoord	SizeHa	Thd_yr	Fire-level NVC
0	100	99	79	172	356419.073165	3931681.51135	82330	100001	-176502
1	100	99	79	172	158064.404416	4281627.97771	66791	100001	0
2	97	99	71	180	232776.588329	4157935.67847	51920	100001	-353795
3	97	99	71	180	243386.580591	4162046.21413	51300	100001	-337523
4	92	98	66	181	205262.808455	4172825.39691	52263	100001	-231691
5	85	93	40	204	331357.762945	3946304.08671	17542	100001	-3186
6	85	93	50	204	331319.631472	3983601.27514	20787	100001	-22757
7	85	93	50	204	300666.182291	4098183.8414	25789	100001	-61822
8	92	98	33	221	232444.06319	4175763.28906	17127	100001	-17843
9	94	99	28	226	165885.758963	4291153.01009	3965	100001	0
10	94	99	28	226	346553.195548	3900806.99899	4511	100001	0
11	81	88	16	157	195443.382527	4210690.96989	694	100002	-5976
12	81	88	82	157	332774.847411	3949952.32079	38073	100002	-34015
13	78	85	26	163	224869.44338	4130369.36488	889	100002	0
14	78	85	76	163	333158.036222	3959847.1354	33219	100002	-33722
15	78	85	76	163	235840.455374	4153553.86258	69276	100002	-509844
16	85	93	57	210	342478.988306	3986628.65023	46521	100002	-15918
17	85	93	57	210	163820.735036	4285169.48526	30008	100002	0
18	85	93	48	210	196543.568662	4256128.01666	30401	100002	-777904
19	84	92	37	230	345580.148457	3870172.91121	16942	100002	0
20	83	90	10	250	188099.450566	4184843.47214	55	100002	0
21	75	81	27	154	195471.508841	4219237.30643	4664	100003	-54918
22	75	81	53	154	339541.153085	3991812.06666	4880	100003	-6610
23	74	80	46	196	353261.605897	3912064.12364	2417	100003	0
24	86	93	24	220	193605.686865	4186215.8799	182	100003	0
25	81	88	53	201	233442.735082	4124527.82039	6166	100005	0
26	75	81	48	206	201951.346215	4199109.28587	9691	100005	-51477
27	75	81	48	206	342033.509168	3888895.52876	5766	100005	0
28	74	80	42	185	220722.344571	4210468.22335	2288	100007	-2986
29	86	93	24	227	339716.208571	3961571.75741	594	100007	-45
30	76	83	19	238	237222.197098	4116887.43884	95	100007	0
31	80	87	10	251	348217.892826	3921770.98964	68	100007	-33

Figure 3—Tabular representation of a wildfire event set produced by FSim. Pictured here is the attribute table associated with a set of polygons representing the final perimeters of 529,458 wildfires occurring during 20,000 iterations on a landscape encompassing 9.7 million ha.

by run-time settings. The term fireplains is a neologism that puts a name to the form of analysis that started with FSPro, which indicates the fireplains for the period of time designated by the analyst at run-time, usually one to several weeks, from the current wildfire perimeter. In FSPro, the fireplains is visualized as a *BP* “footprint”, which becomes larger for longer durations (Figure 5). An incident fireplains as produced by FSPro is useful in its own right for strategic planning of the incident, and also forms the basis for an incident-level risk assessment (Calkin and others 2011).

In its default application, FSim simulates fire starts across the entire landscape. By manipulating the ignition density grid input, it can be also used to simulate fire occurrence and growth from any portion of the landscape (Thompson and others 2013b). When used in this way, FSim produces season-long fireplains for ignitions arising from a designated area of the landscape. For example, FSim was used in the southern Sierra Nevada range, California, USA, to simulate the occurrence and unsuppressed growth of lightning ignitions originating within the portions of the landscape where mechanical fuel treatment is not permitted—Wilderness areas, inventoried roadless areas, wild

and scenic river corridors, and so on. The resulting burn probability map indicates the fireplains for such wildfires (Figure 6).

A third form of fireplains analysis is used in a new type of risk assessment called a RAIL analysis (described below), which characterizes the wildfire risk associated with a specific ignition location, rather than where the effects occur on the landscape. This last form is currently implemented in custom stochastic fire modeling software that systematically simulates fire growth, under variable weather, for all ignition locations of concern (Ramirez, personal communication). With this type of fireplains analysis, fire growth from all potential ignition points is simulated with the same set of weather scenarios so that variation in results is due to the fire growth potential related to fuel and topography (Figure 7). The period of fire growth for this form of fireplains analysis can vary from very short (hours) to an entire fire season, depending on the application. In concept, this type of fireplains analysis is like doing an FSPro simulation for all ignition locations of concern, even though a wildfire has not yet ignited.

Figure 4—Delineated fireshed for the Pawnee montane skipper habitat on the Pike and San Isabel National Forests, Colorado, USA, 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. From Thompson and others (2013).

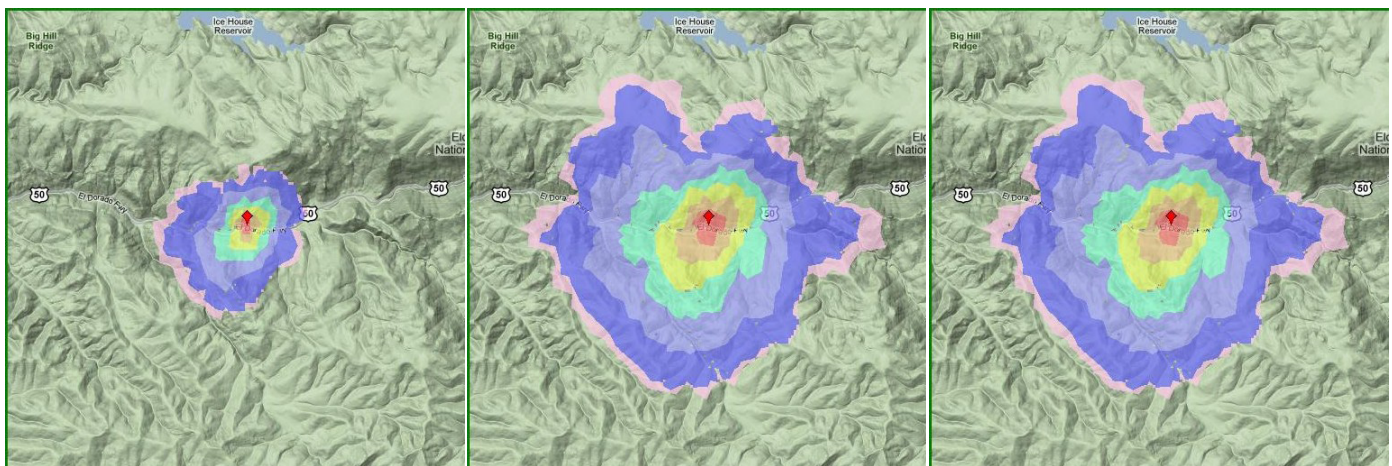
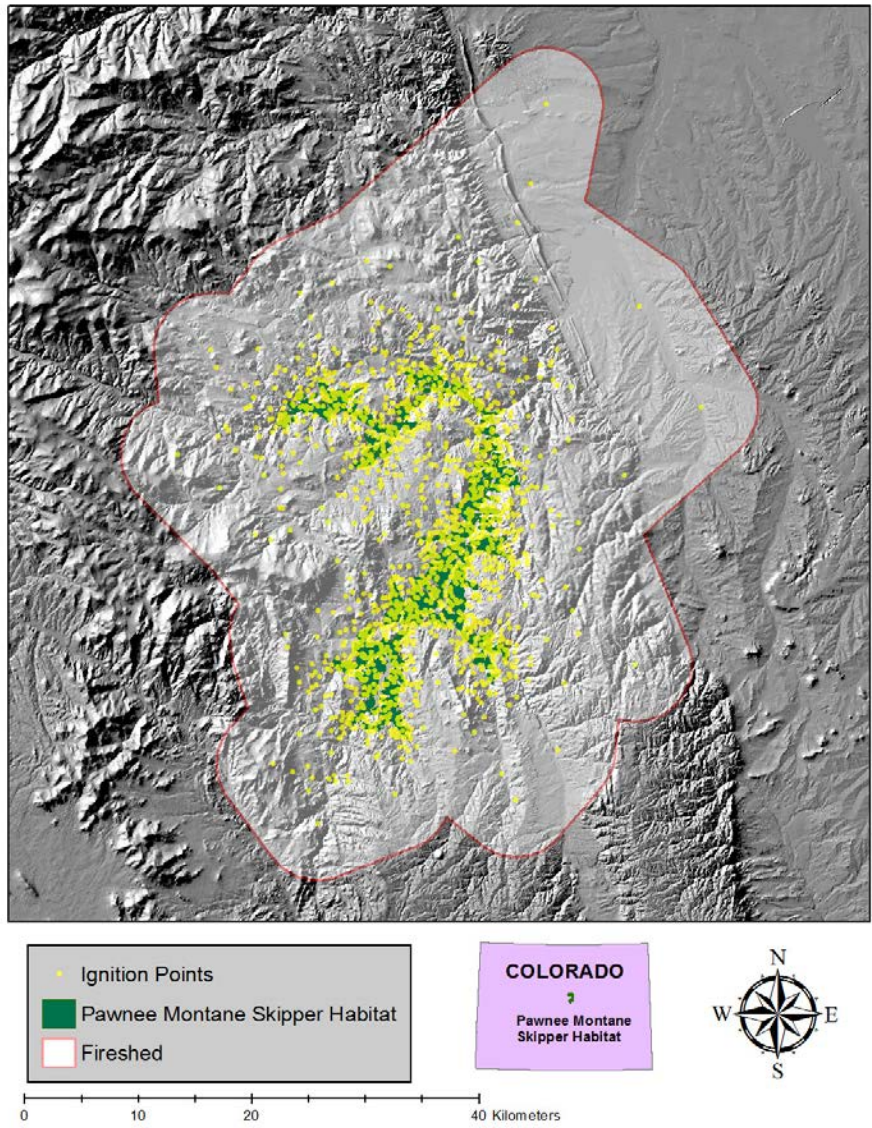


Figure 5—Hypothetical fireplains as simulated with FSPro for 7 days (left), 14 days (center) and 21 days (right). These fireplain simulations are useful for managing individual wildfire incidents and allocating resources among simultaneous incidents.

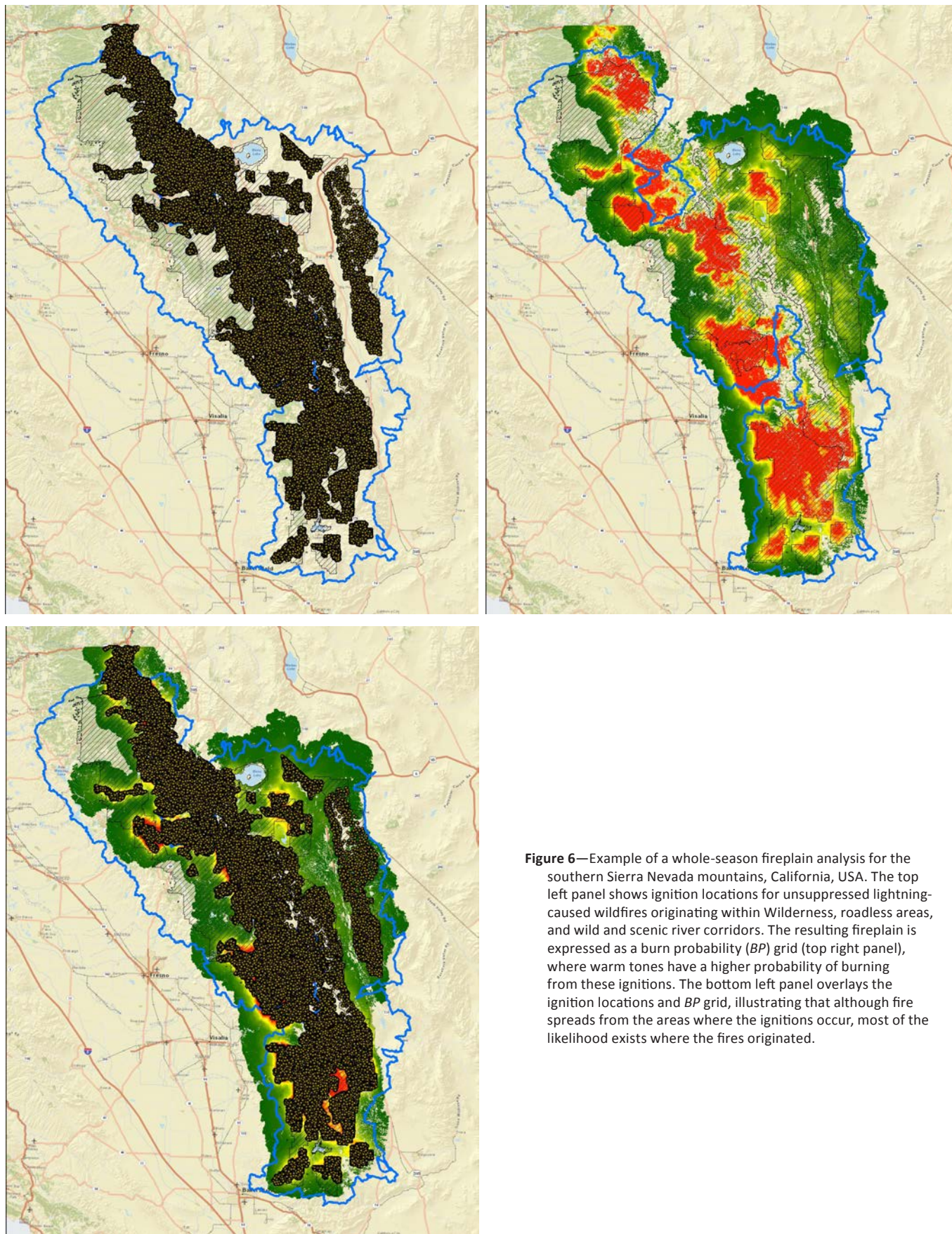


Figure 6—Example of a whole-season fireplain analysis for the southern Sierra Nevada mountains, California, USA. The top left panel shows ignition locations for unsuppressed lightning-caused wildfires originating within Wilderness, roadless areas, and wild and scenic river corridors. The resulting fireplain is expressed as a burn probability (BP) grid (top right panel), where warm tones have a higher probability of burning from these ignitions. The bottom left panel overlays the ignition locations and BP grid, illustrating that although fire spreads from the areas where the ignitions occur, most of the likelihood exists where the fires originated.

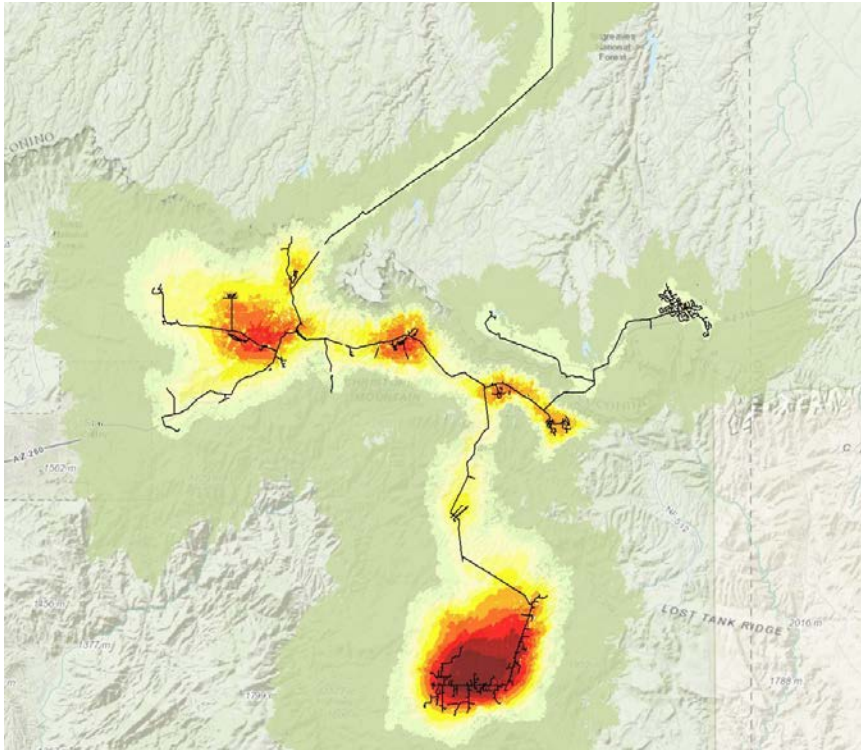


Figure 7—A short-duration fireplain for a single burning-period for an electric power distribution network where each segment of the network is treated as a potential ignition location with equal likelihood of igniting a wildfire.

Exceedance Probability

Spatially resolved risk assessment results (*cNVC*) and fire effects models (for example, fire-caused sedimentation or debris-flow probability and volume) can be used to augment the information available for each record in the event set. For example, a model of fire-caused sediment production, like WEPP (Elliot 2004), can be used to assign total estimated sediment production to each simulated wildfire. This augmented event set can then be used to produce an exceedance probability (EP) curve that relates the magnitude of a fire effect (sediment production, fire size, suppression cost, etc.) to the likelihood of exceeding that magnitude. As with other concepts presented in this paper, the time period for that likelihood varies from a few hours to a whole fire season depending on the simulation system used as well as user-defined settings.

The *EP* for event *k* in the set is calculated as

$$EP_k = \frac{\text{rank}(M_k)}{N + 1}$$

where EP_k is the exceedance probability for event *k* and $\text{rank}(M_k)$ is the rank (largest first) of the magnitude of event *k* (M_k) among all *N* events or simulations. For example, let's say that a 7-day, FSPRO simulation produced 1,008 simulated wildfires with a minimum final size of 2,015 ha and a maximum of 20,477 ha (we're using fire size as a measure of magnitude in this example). The rank of the minimum-size fire is 1,008, so the probability of exceeding that size is 1,008/1,009, or 99.9 percent. The rank of the largest fire is 1, so its *EP* is 1/1,009, or 0.099 percent. An *EP* curve is a plot of M_k on the X-axis against EP_k on the Y-axis for all events in the set (Figure 8). For the dataset described above, there is a 1 percent chance ($EP = 0.01$) of exceeding 17,848 ha after

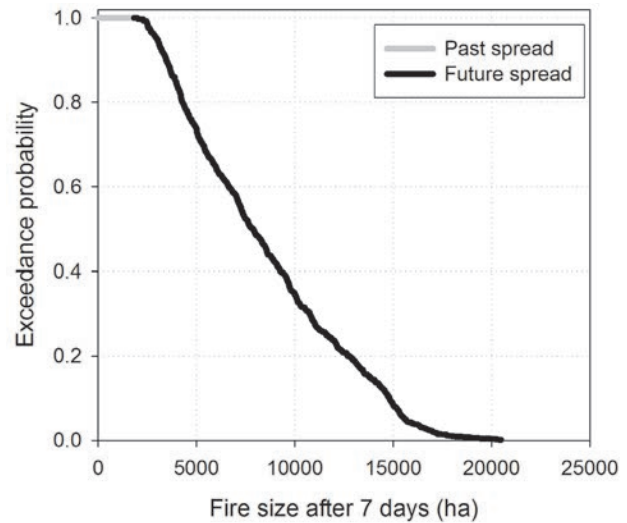


Figure 8—Exceedance probability curve for fire size after 7 days of fire growth based on FSPRO simulation of 1,008 7-day periods of unsuppressed fire growth. Fire size at the beginning of the simulation was 4,500 ha.

7 days of growth. Note that $1-EP$ is the percentile rank, so 17,848 ha is equivalent to the 99th percentile size.

By integrating the pixel-level fire effects and polygon representation of fire perimeters to augment an event set attribute table, an *EP* chart that displays the likelihood of exceeding a range of effects thresholds can be plotted. For example, in an unpublished analysis associated with the Mokelumne Watershed Avoided Cost Analysis study (Buckley and others 2014), the total fire-caused sediment load associated with each simulated wildfire event, generated with FSim, was added to each wildfire that

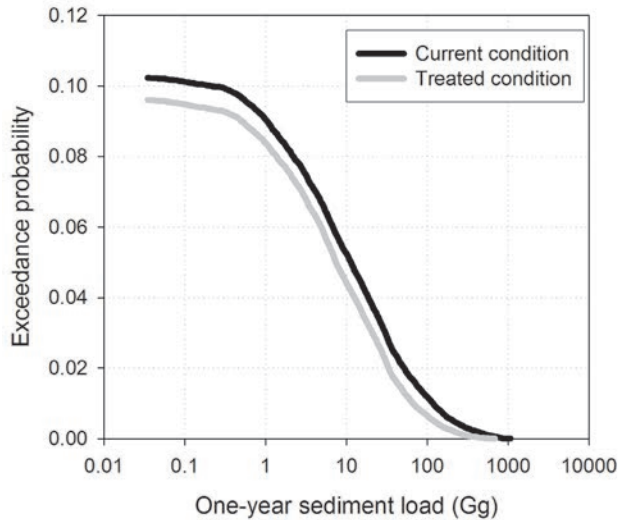


Figure 9—Exceedance probability curves (semi-log scale) for fire-caused sediment load into a small reservoir in the upper Mokelumne River basin in the Sierra Nevada mountain range, California, USA. Curves are shown for the current landscape condition (black line) and a hypothetically treated landscape (gray line). Two effects of the hypothetical fuel treatment can be visualized from this chart—the change in sediment production for a given likelihood is represented by the horizontal distance between the curves at any probability; the change in likelihood for a given sediment load is the vertical distance at any sediment load

reached the watershed of a small reservoir in the upper Mokelumne River basin in the Sierra Nevada mountain range, California, USA. The analysis was conducted on a representation of the current fuelscape and a hypothetical representation of a fuelscape after being managed with a variety of mechanical and prescribed-fire treatments. In this example of a polygon-based exposure analysis using FSim, there was only a 10.2 percent chance in any year that a wildfire would burn any part of the watershed; the hypothetical fuel treatment reduced this to 9.6 percent (Figure 9). For the current landscape condition there is a 1 percent chance ($EP = 0.01$) of causing 117 Gg sediment in any year; that was reduced to 67 Gg for the hypothetically treated landscape (Figure 9).

RAIL Analysis

Through a variety of techniques, it is possible to estimate the wildfire risk (measured as expected net value change) associated with a particular ignition location. This analysis takes into account the ignition potential at the location, fire growth potential surrounding the ignition location and HVRA vulnerability in that area (Figure 10). An analysis of the risk associated with an ignition location (RAIL analysis) identifies locations where ignitions tend to have high consequences due to spread potential and HVRA vulnerability. Such an analysis is useful for suggesting where prevention and pre-suppression activities may have the greatest benefit, and assisting in pre-wildfire strategic response planning. Two potential RAIL analysis techniques include: 1) a dedicated ignition-focused simulation, and 2) geospatial analysis of an augmented wildfire event set.



Figure 10—RAIL analysis triangle. The wildfire risk associated with an ignition location is a function of the likelihood of ignition at the location and the fire growth potential and the vulnerability of resources and assets in the area surrounding the location.

A dedicated ignition-focused stochastic simulation is one for which weather varies stochastically but ignition locations are deterministic (limited to the ignition locations of concern). Fire duration can vary from a few hours to a whole season, depending on the simulation system used. For example, the wildfire risk associated with overhead electricity distribution equipment, which are possible wildfire ignition sources, can be assessed by stochastically simulating fire growth and effects from each potential source (Ramirez, personal communication). In the absence of information about the likelihood of ignition for each point, the result is a map of conditional net value change resulting from an ignition at each point (Figure 11).

A wildfire event set that has been augmented to include spatially cumulative *NVC* for each event can be used in a landscape-wide RAIL analysis. This is typically a coarse-resolution analysis due to the dispersed nature of the ignition points available for most simulations. For example, *cNVC* was estimated for each 90-m pixel across the southern Sierra Nevada mountains. The total *cNVC* for each wildfire was estimated by summing the *cNVC* values for all pixels within each simulated fire perimeter. That sum was then associated with each fire's ignition location. The ignition locations (points) were converted to a 2 km raster using ESRI's Point to Raster tool; each 2 km cell was assigned the mean *cNVC* of all ignition points falling within the cell. This raster was then smoothed with two low-pass filters to mitigate graininess. The resulting grid (Figure 12) indicates the mean effect of wildfires—whether positive or negative—originating from different parts of the landscape. This information may prove useful in planning the response to wildfires before one occurs.

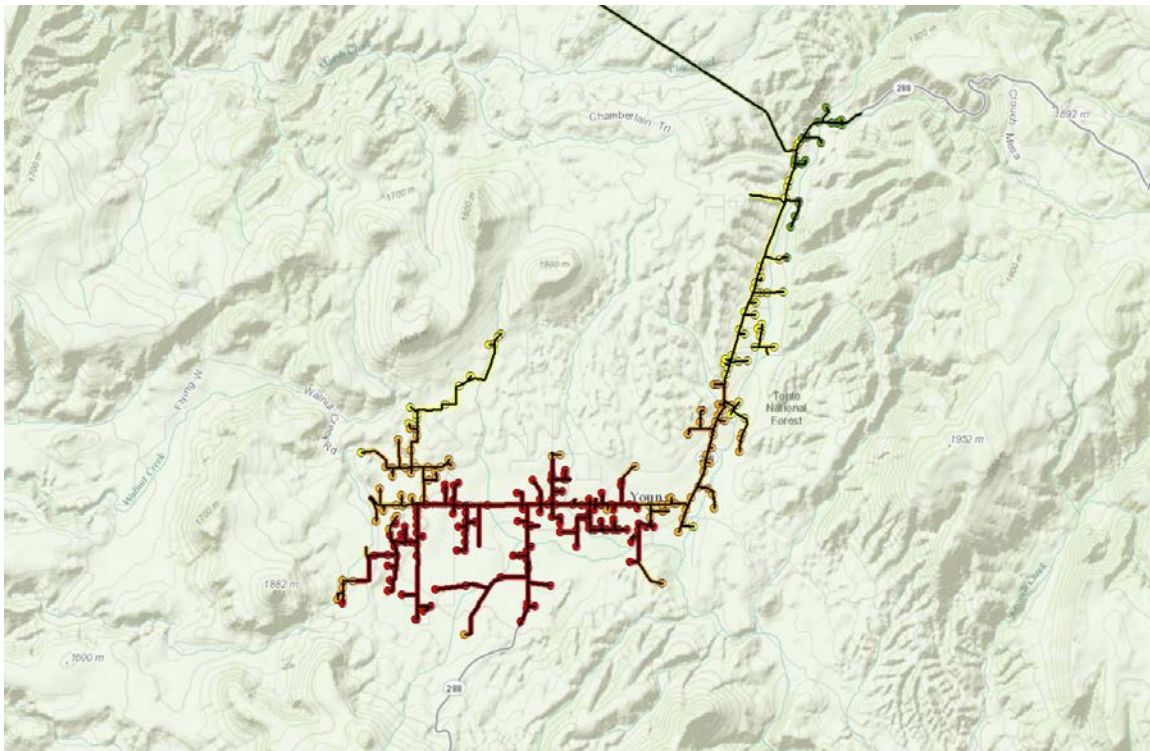


Figure 11—RAIL analysis for an electricity distribution network. The relative conditional risk (given that a fire start occurs somewhere on the network) associated with each potential ignition location on the network.

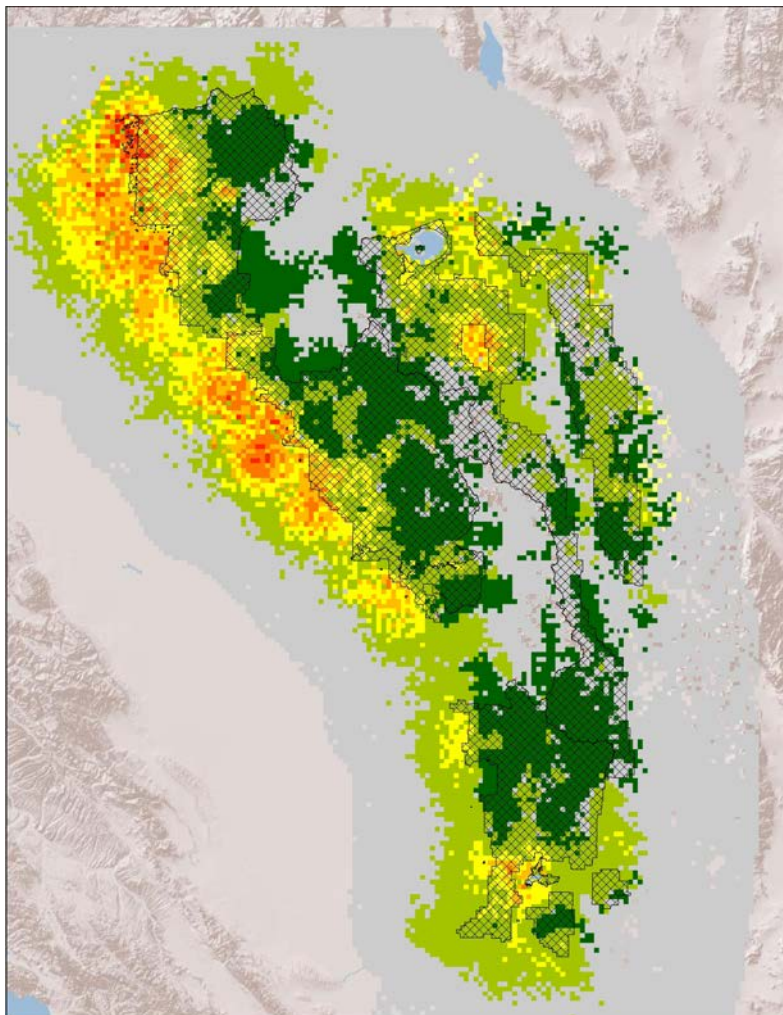


Figure 12—Landscape-wide RAIL analysis for the southern Sierra Nevada. The total *cNVC* for each wildfire was estimated by summing the *cNVC* values for all pixels within each simulated fire perimeter. That sum was then associated with each fire's ignition location. The ignition locations (points) were converted to a 2 km raster using ESRI's Point to Raster tool; each 2 km cell was assigned the mean *cNVC* of all ignition point falling within the cell. This raster was then smoothed with two low-pass filters to mitigate graininess. The resulting map indicates the regions of the landscape where fire ignitions tend to cause adverse effects (warm tones) and where they tend to result in net beneficial effects (greens).

Conclusion

The quantitative wildfire risk framework first promulgated by Finney (2005) has proven itself useful for addressing a variety of fire management problems at a variety of spatial scales (Miller and Ager 2012). The concepts presented here build on that basic framework by bringing into the field of wildfire risk assessment and management some terms and concepts used in other fields, either directly or with some adaptation to fit within the special characteristics of wildfire occurrence and behavior. The concepts presented here will require further refinement before being brought into standard use, but nonetheless represent another step forward.

Acknowledgments

The examples used in this paper were drawn from a variety of published and unpublished projects conducted with our colleagues; we are grateful for their contributions: Phil Bowden, Region 5 of U.S. Forest Service; David Buckley, Timmons Group; Julie Gilbertson-Day, Rocky Mountain Research Station; Don Helmbrecht, TEAMS Enterprise; Erin Noonan-Wright, Wildland Fire Management RD&A Program; Joaquin Ramirez, Technosylva, Inc.; and the entire team on the Mokelumne Watershed Avoided Cost Analysis project. We also thank Erin Noonan-Wright and Greg Dillon, Missoula Fire Sciences Lab, for their reviews of this manuscript.

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