Reax Engineering Inc.
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Fire Risk from Overhead Electrical Facilities

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		Prepared by: Chris Lautenberger, PhD, PE	**Reviewed by:**
		Prepared by:	**Reviewed by:**
		Prepared by:	**Reviewed by:**
		Prepared by:	**Reviewed by:**
		Prepared by:	**Reviewed by:**

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1.0 OVERVIEW OF FIRE HAZARD AND RISK

The primary goal of this work is to quantify utility-associated wildland fire hazard / risk in SCE's service territory The terms *fire hazard* and *fire risk* are often used inconsistently and the meaning of these terms in the wildland fire literature is sometimes different from their meanings in other branches of science and engineering. To avoid confusion, and to explicitly identify what this work quantifies, the meanings of *wildland fire hazard* and *wildland fire risk* within the context of this work are explained below.

1.1 Wildland fire hazard

The preferred terminology among land managers is that *fire hazard* should be used to represent the overall flammability of a fuel complex independent of weather conditions. Consistent with that meaning, Hardy [1] proposed the following definition of *fire hazard*:

> Fire hazard: A fuel complex defined by volume, type, condition, arrangement, and location that determines the degree of ease of ignition and resistance to control. Fire hazard expresses the potential fire behavior for a fuel type, regardless of the fuel-type's weather-influenced fuel moisture content.

A timber stand located in an area with weather conditions conducive to high fuel moisture contents, sheltered from the wind, and located 30 miles from the nearest structure represents less of a threat to the built environment and life safety than an identical stand of trees in the wildland urban interface that regularly experiences high winds and low fuel moisture contents. However, since the fuel complexes are identical except for weather related factors, under Hardy's nomenclature [1] they would have the same fire hazard.

Bachman and Allgöwer [2] presented definitions of *hazard* and *wildland fire hazard* that are more appropriate for wildland fire hazard assessment:

> Hazard: A process with undesirable outcomes.
>
> Wildland fire hazard: A wildland fire with undesirable outcomes.

The term *wildland fire hazard* is used here in a manner consistent with the Bachman and Allgöwer definitions [2].

1.2 Wildland fire risk

Hardy [1] also proposed the following definitions of *fire risk*, indicating there is broad agreement on this definition among US and international organizations:

> Fire risk: The chance that a fire might start, as affected by the nature and incidence of causative agents.

This definition is problematic for wildland fire risk assessment, as illustrated by the following thought experiment: Consider a plot of cured grass with fine fuel moisture content of 2%, surrounded on three sides by a fire break and on one side by a busy highway. Under Hardy's *fire risk* definition [1], the fire risk associated with this plot is very high because there is a high probability of ignition. However, the negative consequences of such a fire are minimal, as it would be contained by fire breaks with no impact to the built environment or life safety.

For consistency with the use of the term *risk* in the risk analysis literature, the following definitions of *risk* and *wildland fire risk* proposed by Bachman and Allgöwer [2] are adopted here:

> <u>Risk</u>: The probability of an undesired event and its outcome. An undesired event is a realization of a hazard.
>
> <u>Wildland fire risk</u>: The probability of a wildland fire occurring at a specified location and under specific circumstances, together with its expected outcome as defined by its impacts on the objects it affects.

These definitions are consistent with the conventional definition of *risk*, which is usually taken as the probability of an event occurring multiplied by the potential consequences of that event. Unlike Hardy's definition, a high probability of fire occurrence does not necessarily indicate a high fire risk if values of concern (structures, standing timber, *etc*.) are unaffected [3].

2.0 BACKGROUND: WILDLAND FIRE HAZARD AND RISK QUANTIFICATION INCLUDING UTILITY-ASSOCIATED RISK

With the terms *wildland fire hazard* and *wildland fire risk* now defined, this section presents a general overview of past efforts at quantifying wildland fire hazard/risk (Section 2.1) and a recent study specifically aimed at quantifying wildland fire hazard/risk from powerline fires (Section 2.2).

2.1 General overview

There is no "one size fits all" approach to quantifying wildland fire hazard or risk. Different approaches may be appropriate under different circumstances. Wildland fire hazard/risk assessment using fire behavior modeling has recently seen increased usage due in part to more powerful computational resources, improved fire models, and readily available geospatial input data. For example, ArcFuels [4-5] provides a desktop-based interface between ArcGIS and widely-used fire behavior models such as FARSITE [6] and FLAMMAP [**7**].

Keane *et al.* [8] highlighted the potential for Monte Carlo analysis to be used for wildland fire risk quantification, stating "Andrews (2007) FSPRO approach in which maps of fire intensity distributions are computed from thousands of FARSITE [6] runs is perhaps the most significant step towards fine scale risk mapping." One advantage of such approaches is that fire shadows, islands, and related effects can be captured. For example, with all other factors held constant, an area downwind from an obstacle to fire spread such as a large barren area or water body is less likely to burn than areas upwind from the obstacle to fire spread. Similarly, a patch of highly flammable fuels surrounded by less flammable fuels is less likely to burn [9]. These spatial effects cannot be captured by analyses that consider conditions only at a point, or burn every point as a head fire, but would be captured by analyses that include fire progression. For these reasons, Monte Carlo simulations wherein fire spread is modeled from tens of thousands of separate ignition locations under a range of weather conditions is one of the most promising tools for quantitative wildland fire risk/hazard assessment.

Carmel *et al*. [10] conducted Monte Carlo simulations of fire spread using hundreds of FARSITE [6] runs to assess fire risk in a 300 km^2 area near Mt. Carmel in Northwestern Israel. Weather inputs were developed from three nearby weather stations during a single year (2004). Standard fuel models were adapted for local conditions. Noting that most fires in this area are anthropogenic, 80% of ignition locations were randomly placed in a buffer zone near roads and hiking trails, with the remaining 20% of ignition locations placed randomly across the landscape. 500 FARSITE [6] simulations were conducted and used to generate a heat map that identified hot spots and cold spots corresponding to the number of times that a particular location was burned by the simulated fires, which can be thought of as being analogous to fire frequency. The Carmel *et al*. study was published in 2009 [10]; tragically, in December 2010, a 2180 hectare fire burned through the Mt. Carmel area, causing 45 deaths. This provided an unfortunate but unique opportunity for the authors to assess their pre-fire risk map [10] in a post-fire study [11]. In the later study [11], the authors concluded that most of the areas burned in the 2010 fire corresponded to high risk levels in the pre-fire risk map.

Ager, Finney, and McMahan [12] indicate that the actuarial definition of wildfire risk is "the expected net value change calculated as the product of (1) probability of a fire at a specific intensity and location, and (2) the resulting change in financial or ecological value." Based on that definition, they developed a modeling framework that can be used to calculate the net value change for fire events of various severity. Their modeling process involved three separate steps: 1) Applying the Forest Vegetation Simulator/Parallel Processing Extension to simulate the effect of various landscape fuels treatments; 2) Using FLAMMAP to calculate elliptical fire spread dimensions, and 3) Applying RANDIG to simulate propagation of randomly ignited fires. One of the emphases of this work was the effectiveness of fuels management type and area. Three different prescriptions were simulated for six different treatment areas and four hypothetical loss functions. Flame length was used as a metric so that fire occurrence was considered a net positive event for low-intensity fire, but a net negative event for high intensity fire. Fire spread duration was established using a Monte Carlo approach to investigate the differences in net value change attributed to the different loss functions, fuels treatment types, and treatment areas.

2.2 Australian work to quantify powerline fire risk

On 7 February 2009, hot dry winds led to ignition and rapid of several powerline-ignited fires in the Australian state of Victoria, ultimately resulting in over 150 fatalities and the loss of thousands of structures. Motivated by these tragic fires, the Powerline Bushfire Safety Program (part of the Victoria State Government Department of Economic Development, Jobs, Transport, and Resources) commissioned a project to identify powerline fire ignition points likely to result in high fire loss consequence with a goal of targeting investment at areas of highest bushfire risk as a priority [13].

A fire spread simulator known as PHOENIX RapidFire [14-18] was used to simulate fire spread from multiple ignition points under specific weather conditions. Key inputs and assumptions of that study are summarized below:

- 27,860 separate ignition points within 1 km of powerlines were established across Victoria on a 2 km grid
- Weather conditions were based on the 1983 Ash Wednesday fires (a similar pattern to Black Saturday as mentioned above)
- Negligible suppression response, *i.e.* fire development not affected by firefighting activities
- Grass curing and moisture was assumed to be worst-case conditions based on driest years in the past decade
- Fuel climax conditions (recently burned fuels modeled as if they had not recently burned)
- Time of ignition corresponded to the peak Forest Fire Danger Index (FFDI) of the day

In the Australian work, probability of ignition was assumed to be uniform across Victoria, meaning all areas were assumed to be equally likely to experience powerline-related ignitions. The primary output from this work was an estimate of the number of homes burned by a powerline-ignited fire starting at a particular location. Figure 1 shows the primary output of this analysis. Each of the 27,860 ignition points is colored according to the number of home losses predicted for a fire starting at that particular location. Red and purple dots correspond to locations where a fire ignition (under the specific set of modeled conditions) would result in more than 2,000 destroyed homes.

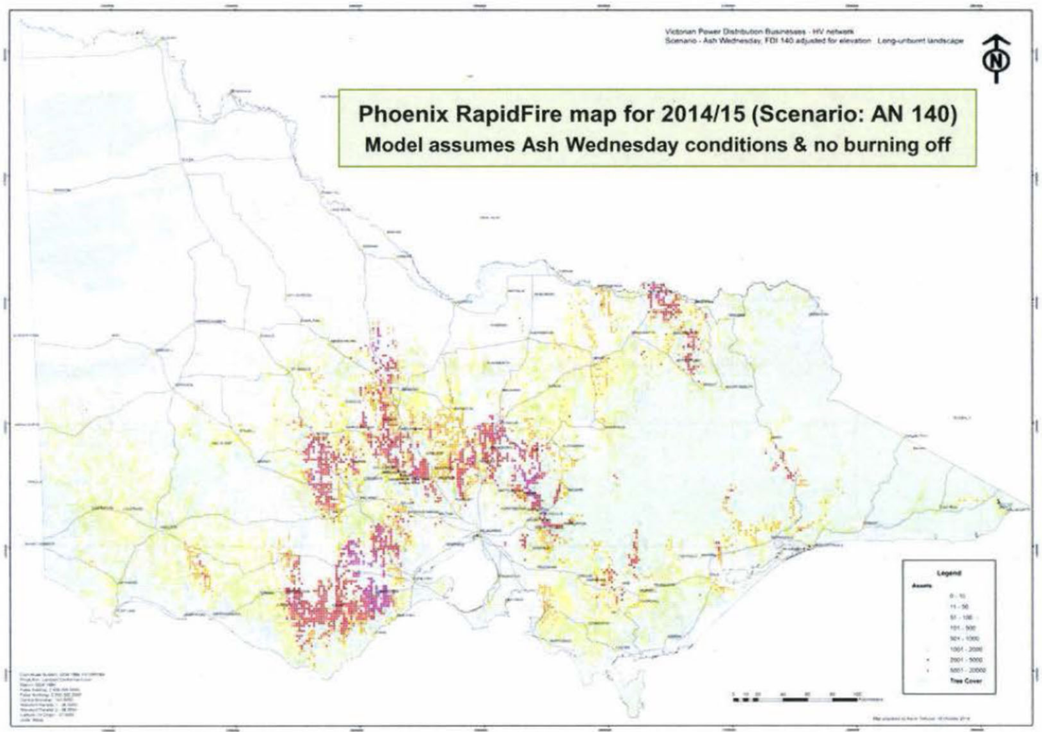


Figure 1. Phoenix RapidFire map of estimated home losses across Victoria for powerline fires ignited under Ash Wednesday weather conditions [13].

2.3 CPUC Fire Map 1

Development of CPUC fire risk maps in California proceeded in two phases. The first phase, termed "Fire Map 1," commenced in early 2014 and concluded in early 2016. Fire Map 1 depicted the physical and environmental conditions associated with an elevated risk of power-line fires. The second phase ("Fire Map 2") commenced in mid-2016 and concluded in early 2018. Fire Map 2 designated utility fire-hazard zones with elevated risk of power-line fires occurring and spreading rapidly so that the fire-prevention measures/regulations could be effectively deployed.

The California Public Utilities Commission directed an Independent Expert Team (IET), led by CALFIRE, to develop a statewide map that identifies "the fundamental physical and environmental features that lead to an elevated likelihood of overhead utility facilities initiating fires that are then likely to lead to large and damaging wildfires" [19]. Fire Map 1 development is described in a report issued by the IET on February 16, 2016 [19].

In Fire Map 1, a 10-year climatology was developed using the Weather Research and Forecasting (WRF) model [20-21] to provide gridded statewide hourly wind/weather fields. After filtering based on Fosberg Fire Weather Index (FFWI), these climatological inputs were distilled to a small subset that was used to drive a statewide Monte Carlo fire spread analysis involving over 100 million randomly distributed ignition points. Fire progression was simulated for a duration of one hour using GridFire [22], an open source raster-based fire spread model that is similar to HFire [23]. The Monte Carlo analysis was mirrored by Reax Engineering in its capacity as subject matter experts for several stakeholders using ELMFIRE [24-25] (Eulerian Level Set Model for Fire Spread).

The final Fire Map 1 product was termed the "Utility Threat Index" (UTI). It is a combination of an "ignition index" (which considers wind speed and fuel moisture content) and a "spread index" (which describes fire spread rate and intensity using fire "volume", *i.e.* burned area multiplied by average flame length from each ignition point). Fire Map 1 did not address assets at risk such as structure density or proximity to communities or populated places; it was only intended to quantify potential for ignition and spread of wildland fires independent of their potential impacts to communities.

2.4 CPUC Fire Map 2

CPUC Fire Map 2 was developed by a Peer Development Panel (PDP) in accordance with the workplan prescribed in CPUC Decision 17-01-009 [26] issued on January 19, 2017. Fire Map 2 is a 3-tiered map with each tier defined as follows:

1. Tier 1 is all area in the state of California that is not in Tier 2 or Tier 3.
2. Tier 2 is elevated risk (including likelihood and potential impacts of occurrence) from wildfires associated with overhead utility powerlines or overhead utility powerlines also supporting communication facilities, including impacts to people or improved property.
3. Tier 3 is extreme risk (including likelihood and potential impacts of occurrence) from wildfires associated with overhead utility powerlines or overhead utility powerlines also supporting communication facilities, including impacts to people or improved property.

In late 2016, a preliminary map known as "Shape A" was developed by the PDP co-leads (Pacific Gas & Electric, Reax Engineering, and San Diego Gas & Electric) according to a "recipe" prescribed in the Fire Map 2 work plan. Per the work plan, Shape A was a hybrid of Fire Map 1, fire history, an earlier map known as the FRAP Fire Threat Map, and designated communities at risk. Due to the coarse nature of the Shape A recipe, it encompassed essentially all areas of California capable of supporting propagating wildland fires (including nonburnable "islands" such as waterbodies, urban/developed areas, and barren landscape). Due to the "broad brush stroke" used to create Shape A, the PDP co-leads removed obviously nonburnable areas from Shape A to create and "initial Shape B" which was ultimately approved by the IRT and filed with the CPUC on March 20, 2017. The initial Shape B was considered as a starting point for the Tier 2 footprint.

After the initial Shape B / Tier 2 was created, utilities designated one or more Territory Leads (TLs) to classify areas of their service territory as either Tier 1, Tier 2, or Tier 3 upon consideration of the Tier definitions presented above and examination of a multitude of factors such as local knowledge, fire history, Fire Map 1 scores, and potential impacts to communities. TLs made recommendations to the PDP (which consisted of representatives from utilities, communication infrastructure providers, industry experts, fire officials, and interested stakeholders). The PDP then reviewed each TL proposal and subsequently made recommendations to an Independent Review

Team (IRT), led by CALFIRE, which provided PDP oversight and ultimately approved or rejected each TL/PDP proposal. The final 3-tiered CPUC fire threat map was developed through this iterative process.

Between March and November 2017, more than 1,300 changes to the Initial Shape B were proposed, analyzed, and adjudicated by TLs, the PDP, and the IRT. Three types of map changes were used:

1. Classify an area as Tier 1 that was classified as Tier 2 in the initial Shape B
2. Classify an area as Tier 2 that was classified as Tier 1 in the initial Shape B
3. Classify an area as Tier 3

As described earlier, each proposed map change was reviewed first by the PDP and then by the IRT. This was accomplished using through this process a public-facing web-portal developed specifically for this mapping project. In some cases, these proposed changes went through several iterations with IRT rejections followed by resubmissions with boundary adjustments or new supporting data. This iterative process of expert input and review further refined designated map tiers.

Since the Tier definitions included "impacts to people or improved property" but the Utility Threat Index from Fire Map 1 was agnostic as to the locations of structures and communities, during the Map 2 development process it became necessary to combine structure density with Fire Map 1 to inform classification as Tier 1, Tier 2, or Tier 3. In summer of 2017, the PDP co-leads developed "draft Tier 3 guidance" that combined the Utility Threat Index from Fire Map 1 with structure density from the US census. The Independent Review Team modified this approach slightly and developed an Integrated Utility Threat Index (iUTI) that combined Fire Map 1's Utility Threat Index with structure density from a California-specific layer known as "WUIDEN4".

Although the iUTI was originally developed to prioritize areas for designation as Tier 3, it eventually became apparent that the iUTI could also inform Tier 2 designations. Late in the Fire Map 2 development process, deliberations between the PDP and IRT regarding areas proposed for removal from Tier 2 were guided by iUTI scores. This suggested that the arduous process of developing Shape A, removing nonburnable areas to create an initial Shape B, and then manually proposing and reviewing over 1,300 map changes could have been automated and expedited using iUTI or similar data products.

CPUC Fire Map 2 was finalized by the PDP in November/December 2017, and ultimately approved by the CPUC in early 2018.

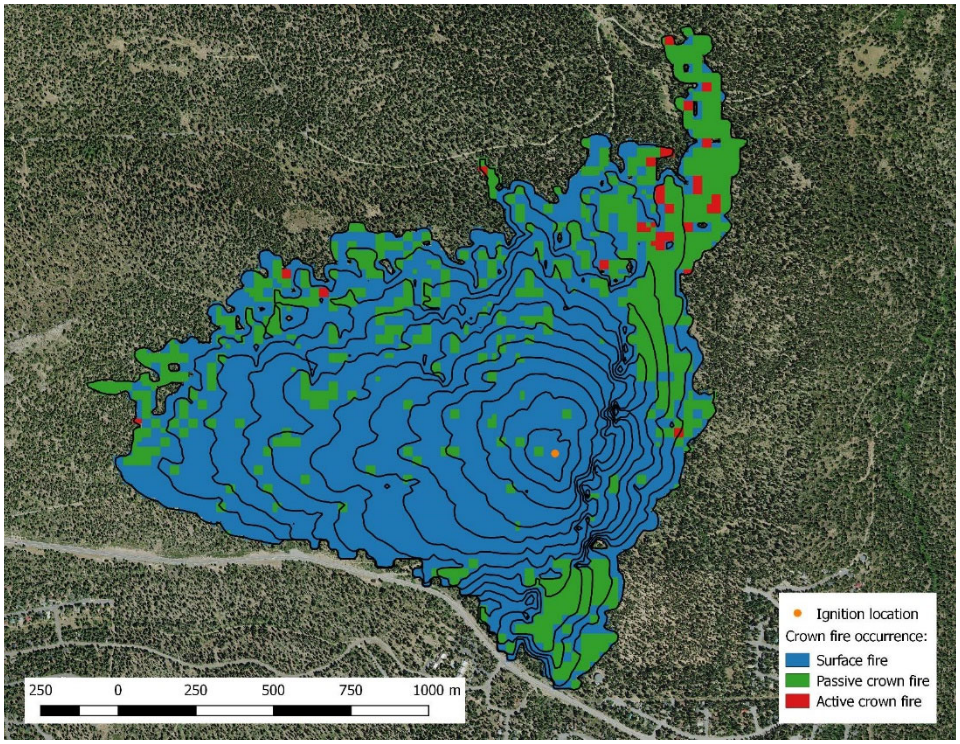
3.0 Fire Ignition and Spread Modeling Methodology

As described in Section 2.1, Monte Carlo analysis has shown great promise for quantifying wildland fire hazard and risk. Furthermore, this same basic approach has already been successfully applied in Victoria, Australia to quantify fire risk associated with overhead electrical utility ignited fires (Section 2.2). The current section describes the Monte Carlo analysis that is used here to quantify wildland fire hazard / risk across SCE's service territory. The methodology applied here is based on that described by Lautenberger [27].

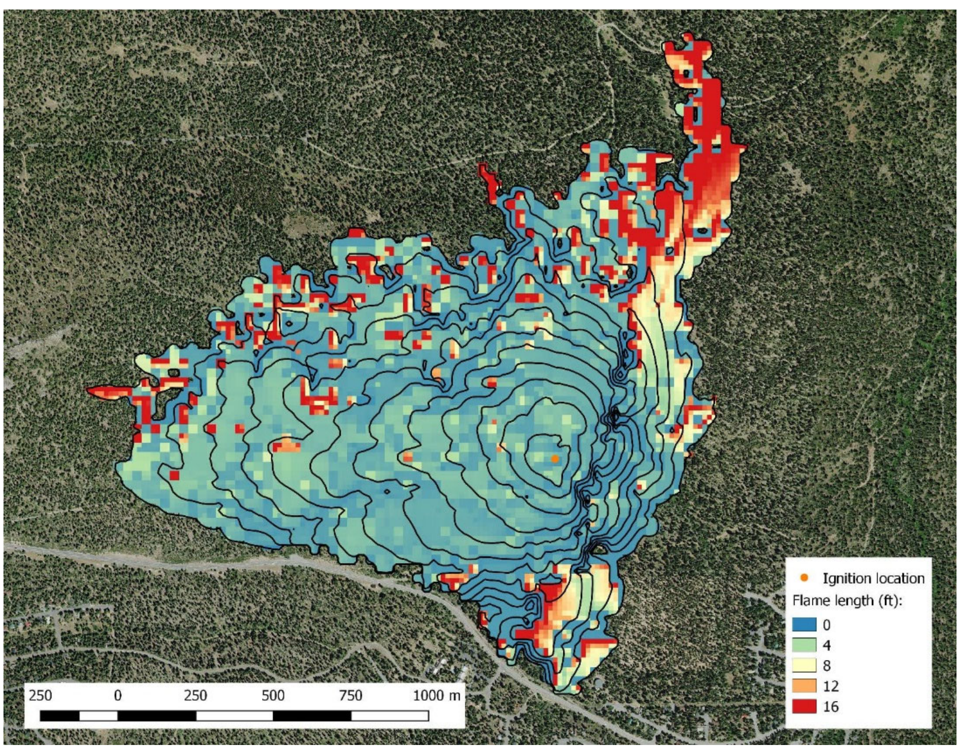
3.1 Monte Carlo fire spread model: ELMFIRE

The open source software ELMFIRE [24-25] (Eulerian Level Set Model for Fire Spread) is used here to quantify wildland fire hazard via Monte Carlo analysis. ELMFIRE's computational engine is similar to other two-dimensional fire simulators such as FARSITE [6] or PHOENIX RapidFire [14-18] in that it calculates surface fire spread rate using the Rothermel surface spread model [28, 29], assumes that each point along the fire front behaves as an independent elliptical wavelet [30] with length to breadth ratio determined semi-empirically [6, 31], and simulates transition from surface to crown fire using the Van Wagner criterion [32] (with passive/active crown fire spread rates calculated from Cruz *et al*. [33]). ELMFIRE tracks the fire front using a narrow band level set method [34], a numerical technique for tracking curved surfaces on a regular grid. Parallelization is achieved using Message Passing Interface (MPI).

To demonstrate how ELMFIRE simulates fire spread, Figure 2 shows 24-hours of fire progression from an individual ignition site. The black contour lines in Figure 2 a represent fire front position at 2-hour intervals. Figure 2 a also shows which parts of the burned area experienced surface fire (blue), passive crown fire (green), or active crown fire (red). Figure 2b similarly shows fire perimeter contours and flame length variation within the fire perimeter. Flame length is highest in areas that burn as heading fires or those that experience crown fire, and lowest in areas that burn as a flanking or backing fire or as a surface fire. In this example, fire area after 24 hours of spread is approximately 560 acres.



(b)



(a)

Figure 2. Sample ELMFIRE fire spread simulation for individual fire ignition. (a) Fire type (surface fire, passive crown fire, or active crown fire). (b) Flame length.

3.2 Fuel and topography inputs

Fuel and topography layers were obtained from the LANDFIRE 2014 (LANDFIRE 1.4.0) database [35-36] at a resolution of 30 m. Topography layers include elevation, slope, and aspect. Fuel layers include surface fuel model (in the Scott and Burgan 40 system [37]), canopy height, canopy cover, canopy base height, and canopy bulk density. The surface fuel layer was modified to correct known mapping errors in LANDFIRE using the methodology of Sapsis *et al*. [19].

3.3 Wind and weather inputs

The general approach to developing wind and weather inputs involves using the North American Regional Reanalysis (NARR) dataset [38] in conjunction with a fire weather filter to identify days of historical fire weather significance. The Weather Research and Forecasting (WRF) model is then used to generate wind and weather fields only for those days identified as being significant from a fire weather perspective.

The NARR dataset is maintained by the National Centers for Environmental Prediction, the National Weather Service, and the National Oceanic and Atmospheric Administration. It is a gridded meteorological dataset that provides a "snapshot" of the atmosphere every 3 hours at approximately 32 km resolution. Being a reanalysis, NARR is a hybrid of weather modeling and meteorological observations (surface observations of temperature, relative humidity, wind speed/direction, and precipitation, weather balloon observations of wind speed/direction and atmospheric, sea surface temperatures from buoys, satellite imagery for cloud cover and precipitable water*, etc.*). Essentially, a weather model similar to WRF assimilates/ingests several thousand weather observations over a 3 hour period and then uses that information to create a 3D representation of the atmosphere every 3 hours. This includes not only surface (meaning near ground level) quantities but also upper atmosphere quantities as well. The NARR dataset is available from 1979 (when modern satellites first became available) to current day (with a lag of a few weeks).

Although NARR's 32 km resolution is too coarse to be useful for fire spread modeling purposes, it can be used to identify historical fire weather days to be recreated at higher resolution using WRF. The basic idea is to determine dates for each 32 km by 32 km NARR pixel in SCE's service territory where the most severe fire weather conditions have occurred between 1999 and 2018. The primary advantage of identifying historical fire weather events using reanalysis data, instead of surface (weather station) observations, is that the NARR dataset is both spatially and temporally uniform whereas point observations are not.

The first step to identify historical fire weather days is selection of a single criterion that can be used to identify the most severe fire weather conditions in the NARR dataset. While there are many possibilities, a modification to the Fosberg Fire Weather Index (FFWI) [39] was selected. FFWI combines temperature, relative humidity, and wind speed into a single index ranging from 0 to 100, with 100 corresponding to a wind speed of 30 mph and fine fuel moisture content of 0%. The FFWI formula is presented as Equation 1:

$$\text{FFWI} = \eta\sqrt{(1+U^2)} \tag{1}$$

where U is the 20-ft wind speed in miles per hour and η is a function of equilibrium moisture content, M_{eq}:

$$\eta = 1 - 2\left(\frac{M_{eq}}{30}\right) + 1.5\left(\frac{M_{eq}}{30}\right)^2 - 0.5\left(\frac{M_{eq}}{30}\right)^3 \tag{2}$$

In Equation 2, M_{eq} is calculated as [40, 41]:

$$M_{eq} = \begin{cases} 0.03 + 0.28 \times \text{RH} - 0.00058 \times \text{RH} \times \text{T} & \text{for RH} < 10\% \\ 2.23 + 0.16 \times \text{RH} - 0.0148 \times \text{T} & \text{for } 10 \le \text{RH} < 50\% \\ 21.1 - 0.4944 \times \text{RH} + 0.00557 \times \text{RH}^2 - 0.00035 \times \text{RH} \times \text{T} & \text{for RH} \ge 50\% \end{cases} \tag{3}$$

where RH is relative humidity in percent and T is temperature in °F.

FFWI is very sensitive to wind speed, and less sensitive to relative humidity and temperature. For example, FFWI is 80 for a wind speed of 50 mph and an equilibrium moisture content of 10%, but only 73 for a wind speed of 25 mph and an equilibrium moisture content of 2%. Ignition and growth of a wildland fire to threatening scales may be more likely under the latter conditions, but spread rates for an *already established* wildland fire could be higher under the former conditions.

It was found during the CPUC Fire Map 1 development process that using a Fosberg Fire Weather Index (FFWI) could result in "off season" (generally, during the winter, *i.e.* after significant rains) days being falsely identified as fire weather days. To avoid these problems, a Modified Fosberg Fire Weather Index (MFFWI) is used in this work to identify wind events that occur simultaneously with low relative humidities and high temperatures. MFFWI is defined as follows:

$$\text{MFFWI} = \text{FFWI} \times \frac{P_{ign}}{100} \tag{4}$$

where P_{ign} is Schroeder's ember ignition probability [42] as given in Table 1 as a function of fuel temperature and fine fuel moisture content. The data were originally published [42] with temperatures in degrees Fahrenheit and this convention is retained here. It is seen that the ember ignition probability is strongly sensitive to moisture content, and less sensitive to temperature.

Table 1. Ignition probability by woody embers/firebrands as tabulated by Schroeder [42].

Fuel	*Fine Fuel Moisture Content (%)*														
Temp (F)	*1.5*	*2.0*	*2.5*	*3.0*	*4.0*	*5.0*	*6.0*	*7-8*	*9-10*	*11-12*	*13-16*	*17-20*	*21-25*	*26-30*	*>30*
30-39	87	80	74	69	59	51	43	34	25	17	10	4	1	0	0
40-49	89	83	77	71	61	53	45	36	26	18	11	5	1	0	0
50-59	92	85	79	73	63	54	47	37	27	20	11	5	2	0	0
60-69	94	88	81	76	65	56	49	39	29	21	12	6	2	0	0
70-79	97	90	84	78	68	59	51	41	30	22	13	6	2	0	0
80-89	100	93	87	81	70	61	53	42	31	23	14	7	2	1	0
90-99	100	96	90	84	73	63	55	44	33	24	15	7	3	1	0
100-109	100	99	93	86	75	66	57	46	35	26	16	8	3	1	0
110-119	100	100	96	89	78	68	59	48	36	27	17	9	3	1	0
120-129	100	100	99	93	81	71	62	51	38	29	18	9	4	1	0
130-139	100	100	100	96	84	74	65	53	40	30	20	10	4	1	0
140-149	100	100	100	99	87	77	67	55	42	32	21	11	5	2	0
150-159	100	100	100	100	90	80	70	58	45	34	22	12	5	2	0

First, 10 m wind components, 2 m temperature, and 2 m relative humidity are extracted from the NARR dataset and converted to GeoTiff files at 3 hour intervals from 1999 to 2018 (20 years). 10 m wind components were used to calculate 20 ft wind speed, in mph, and wind azimuth, in degrees. FFWI and MFFWI were then calculated at 3 hour intervals using the formulas presented above. Because rapidly spreading fires often cause significant damage in the first ~6 hours of a burn period, MFFWI values were averaged over a 6-hour period.

Next, the 6-hr average files were processed to determine the maximum 6-hr average MFFWI that occurred in a particular calendar day. Finally, for each 32 km by 32 km pixel in the NARR dataset, the ~7,000 (20 yr × 365 days/yr) daily maximum MFFWI values were sorted from high to low, with the date carried along and sorted analogously. These were then written to two (MFFWI and date) stacked GeoTiff rasters such that the first band in the MFFWI file contains the highest MFFWI value over 20 years, and the date file contains the date corresponding to the highest MFFWI. The second band contains the second highest MFFWI and date corresponding to that MFFWI, and so on.

With historical fire weather dates now identified, a 20-year (1999-2018) fire weather climatology was developed using the Weather Research and Forecasting (WRF) model to recreate historical days of fire weather significance across SCE's service territory. Approximately 900 days were included in this climatology, but for fire modeling purposes this data set was distilled to the most severe 40 days for a given location within SCE's service territory. High-resolution (2 km) hourly gridded fields of relative humidity, temperature, dead fuel moisture, and wind speed/direction were extracted from this analysis and provided as input to a Monte Carlo-based fire modeling analysis.

3.4 Stochastic selection of ignition locations and wind/weather conditions

SCE provided Reax was GIS data depicting the locations of overhead transmission and distribution lines. Figure 3, as an example, shows GIS data depicting the location of SCE overhead facilities. A 100 m buffer was applied to these facilities data to create an "ignition mask" where random ignitions are distributed within in areas defined by the ignition mask layer. In the Monte Carlo fire spread modeling analysis, 30% of the pixels within this buffer are ignited. As an example, Figure 4 shows ignition locations distributed randomly within a 100 m buffer surrounding SCE overhead facilities. Each 30 m pixel is colored according to risk calculated for that ignition location / time of ignition combination.

For each random ignition location, the weather stream is also selected randomly from the 40 most severe fire weather days (based on FFWI) for that ignition location. Six hours of weather data, corresponding to approximately one burn period, are extracted from the fire weather stream and provided as input to the fire spread simulation.

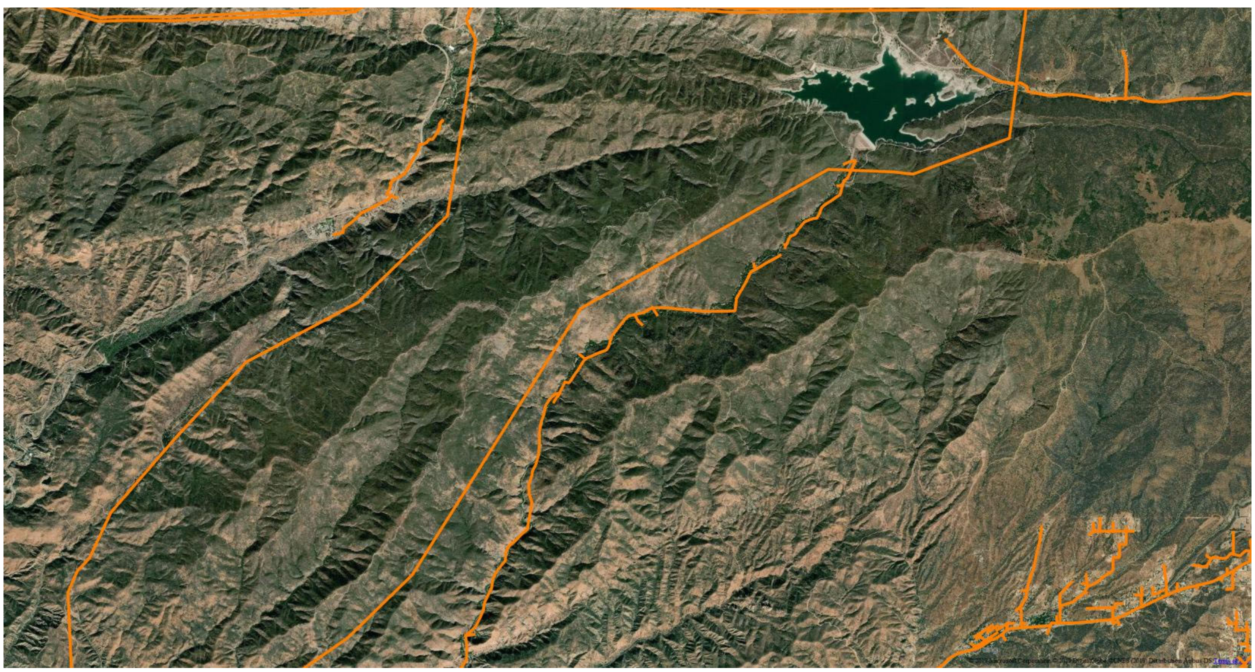


Figure 3. Example showing SCE overhead facilities.

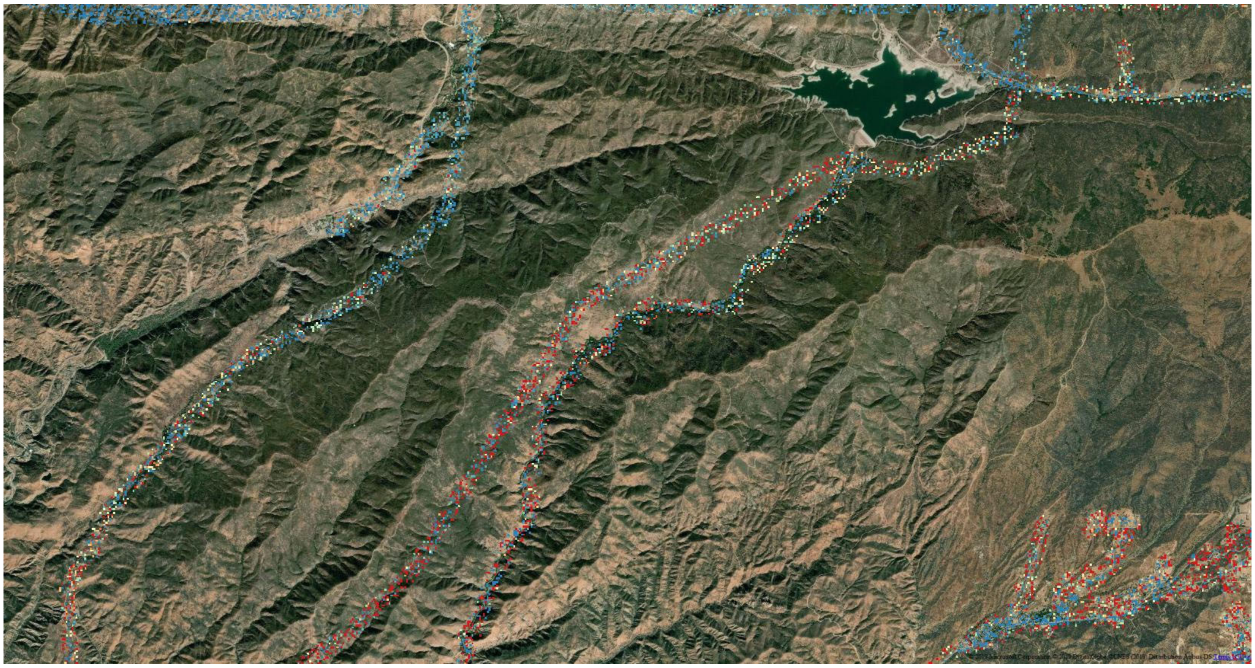


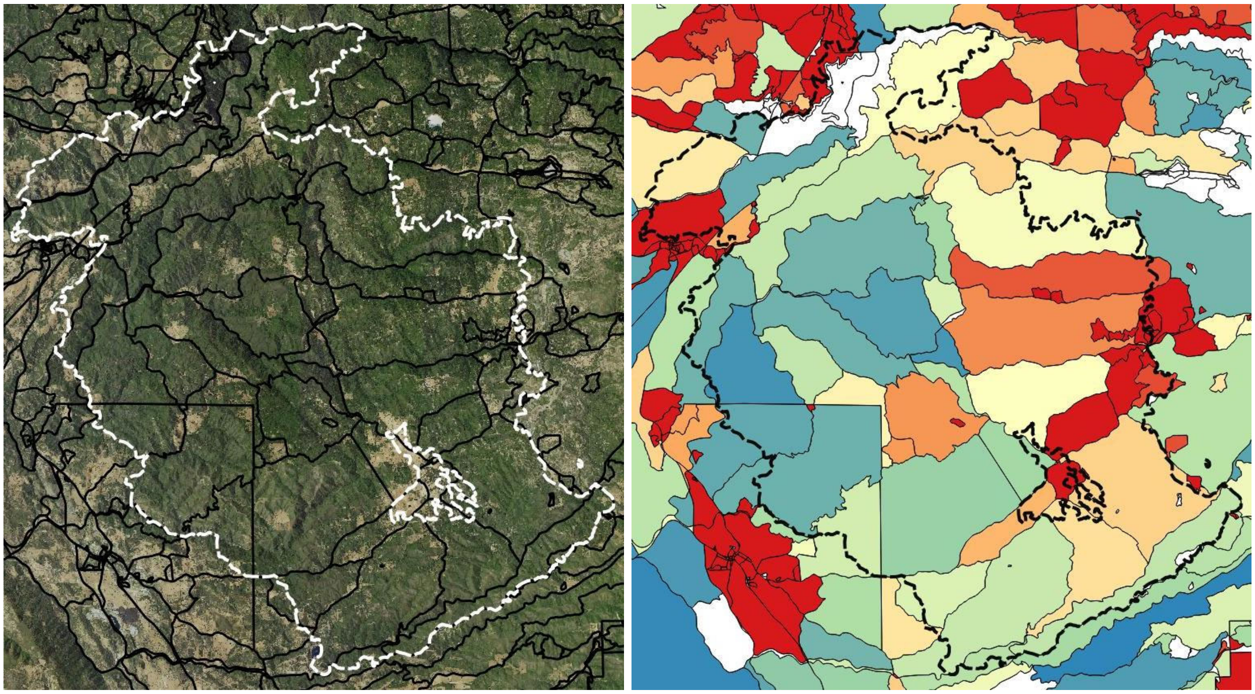
Figure 4. Example showing ignition locations distributed randomly within a 100 m buffer surrounding SCE overhead facilities.

3.5 Quantification of fire consequence

Miller and Ager [3] emphasize that within the context of wildland fire, both positive and negative outcomes can be realized from a given fire. A low-intensity fire occurring within the historic range of variability may provide a net benefit to the burned areas. While this may be true for some fires, it is usually not true for fires burning under extreme fire weather conditions (high wind, low humidity) in areas adapted to low intensity high frequency fire. It is also not likely true for fires burning through intermix or interface areas with structures. Fire consequences may include impacts to structures and people, natural resources, critical infrastructure, and other assets at risk. In this work, at the direction of SCE, only negative impacts to structures is addressed.

The first step in modeling fire impacts to structures and communities is to develop a dataset that identifies the location of structures. 2010 US Census data for California were obtained in GIS (shapefile) format [43 - 44]. Population density (people/mi^2) and housing density (structures/mi^2) were then calculated for each of the 710,145 census blocks in California by dividing the population or housing count for each census block by its area. The result was then burned to a raster having the same projection and resolution (30 m) as the underlying fuels inputs.

An example of this structure density calculation (outside of SCE's service territory) is shown graphically in Figure 5. The dashed line is the outline of the 2015 Butte Fire. In Figure 5a, census blocks (black lines) are overlaid on orthoimagery. Figure 5b shows housing density calculated for each census block. The values range from close to 0 (blue) to greater than 30 structures/mi^2 (red). White polygons in Figure 5b have zero housing density.



(a) (b)

Figure 5. Butte Fire footprint (dash line). (a) Census blocks (solid lines) on orthoimagery. (b) Housing density (structures per square mile) colored from 0 (blue) to 32 (red).

For each simulated fire, the total number of impacted structures is estimated by integrating area burned with housing density for each pixel within the fire perimeter at the end of a 6-hour simulation. While this method cannot determine whether specific structures would be impacted by a particular fire, it captures average losses at the census block level. For example, if a fire burns 1 sq mi of an area having a housing density of 20 structures per square mile, the total number of impacted structures reported by ELMFIRE would be 20. Actual impacted structures would depend on the location of those structures in the census block relative to fire location.

Affected structures (*i.e.*, those within the fire perimeter) does not necessarily correspond to damaged or destroyed structures. Post-fire inspection of neighborhoods that have experienced wildland urban interface fires often reveals that many structures within the fire perimeter survive. Structure survivability is a complex function of defensible space, construction techniques, suppression efforts, etc. While others have attempted to model structure losses based on factors such as flame length or ember density, such methods have not been validated and may introduce a false sense of precision. For this reason, no such attempts are made here.

4.0 QUANTIFICATION OF UTILITY-ASSOCIATED FIRE RISK WITHIN SCE'S SERVICE TERRITORY

As described in Section 1.2, wildland fire risk is "*The probability of a wildland fire occurring at a specified location and under specific circumstances, together with its expected outcome as defined by its impacts on the objects it affects*." This is closely related to the classic general definition of risk as probability times consequence. Therefore, in order to quantify fire risk within SCE's service territory, it is necessary to quantify probability (Section 4.1), consequence (Section 4.2), and their product (risk, Section 4.3).

4.1 Fire probability

In this work, ignitions are distributed randomly and uniformly within a buffer encompassing SCE's overhead electrical facilities. This inherently assumes that all electrical assets present similar ignition probabilities. However, given differences in protective measures on circuits and spatial variations in wind, fuels, canopy, etc. this may or may not be the case. Previous work that was conducted during the Fire Map 1 development process was unsuccessful at developing correlations between outages/ignitions and environmental variables.

For that reason, the probability leg of the risk equation is viewed here as the conditional probability that once a fire occurs it grows sufficiently rapidly that it escapes initial containment efforts. This is justified because most fires are controlled or extinguished while still small. It is a small percentage of fires – specifically those that escape initial attack and become extended attack or campaign fires – that are responsible for the majority of hectares burned in California. Fires are most likely to escape initial containment when fuels, weather, and topography lead to rapid fire spread, long flame lengths, and spotting that hinder control operations. Therefore, fire volume (the spatial integral of burned area and flame length) is used here as a proxy for probability of fire escaping initial containment efforts.

4.2 Fire consequence

Fire consequence is taken here as fire's impact on the objects it affects. As described earlier, the only assets at risk continued here are homes from the 2010 US Census. Impacts to homes are quantified for each modeled fire by calculating the spatial integral of fire area and structure density.

4.3 Fire risk

With probability and consequence now quantified, risk is now calculated as probability times consequence.

5.0 Model Outputs and GIS Data

Geospatial outputs from this analysis have been delivered to SCE via Citrix ShareFile. An initial data delivery was made on February 22 for all areas within CPUC Tier 2 & 3 with an additional ½ mile area. After that delivery, SCE requested that "Bulletin 322" areas outside of the previous footprint also be analyzed. These were delivered on March 5th. GIS data associated with these deliveries are described in Section 5.1.

After these initial deliveries, SCE requested fire perimeter data for all modeled fires. This type of data at the scale of SCE's service territory had not been generated in earlier work. Significant development efforts were required to generate these data, which were delivered to SCE via Citrix ShareFile on May 10th and are described in Section 5.2.

5.1 Fire area, volume, impacted structures, and risk

Outputs from this Monte Carlo fire modeling analysis were post-processed to quantify risk as the product of probability and consequence. Fire volume is used here as a proxy for probability because rapidly spreading fires with are most likely to escape initial containment efforts than slowly developing fires. Consequence (or impact) is quantified as the number of structures within a modeled fire perimeter. To limit the order of magnitude of risk scores to $\sim 10^4$, risk was calculated as $0.001 \times$ fire volume $\times$ impacted structures.

The ShareFile .zip archive includes the following GeoTiff rasters:

- `fire_area.tif`: Fire area (acres) at 30 m resolution
- `fire_area_smooothed.tif`: Fire area (acres) at 30 m resolution with smoothing kernel
- `fire_area_300m.tif`: Fire area (acres) resampled to 300 m resolution
- `fire_area_1000m.tif`: Fire area (acres) resampled to 1000 m resolution

- `fire_volume.tif`: Fire volume (acre-ft) at 30 m resolution
- `fire_volume_smoothed.tif`: Fire volume (acre-ft) at 30 m resolution with smoothing kernel
- `fire_volume_300m.tif`: Fire volume (acre-ft) resampled to 300 m resolution
- `fire_volume_1000m.tif`: Fire volume (acre-ft) resampled to 1000 m resolution

- `impacted_structures.tif`: Number of impacted structures at 30 m resolution
- `impacted_structures_smoothed.tif`: Number of impacted structures at 30 m resolution with smoothing kernel
- `impacted_structures_300m.tif`: Number of impacted structures resampled to 300 m resolution
- `impacted_structures_1000m.tif`: Number of impacted structures resampled to 1000 m resolution

- `structure_risk.tif`: Product of fire volume and impacted structures at 30 m resolution
- `structure_risk_smoothed.tif`: Product of fire volume and impacted structures at 30 m resolution with smoothing kernel
- `structure_risk_300m.tif`: Product of fire volume and impacted structures resampled to 300 m resolution
- `structure_risk_1000m.tif`: Product of fire volume and impacted structures resampled to 1000 m resolution

As shown previously in Figure 4, model outputs are natively generated as raster files with a resolution of 30 m. These rasters depict fire area/volume, number of impacted structures, and risk (defined later) for each modeled fire. Before outputs from the Monte Carlo fire spread simulations can be viewed and analyzed at scales approaching size of SCE's service territory, smoothing or resampling is required. Figure 6 shows a smoothing kernel applied to data from Figure 4, and Figure 7 shows the same data from Figure 4 resampled (averaged) to 300 m grids.

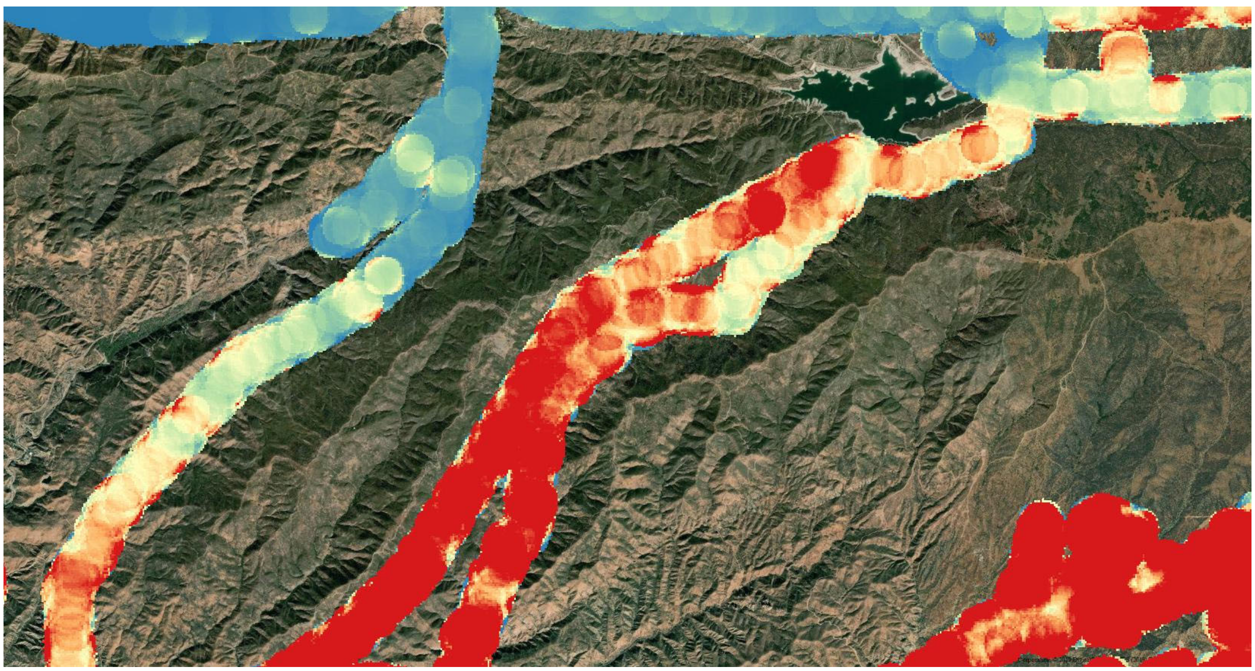


Figure 6. Smoothing kernel applied to data from Figure 4.

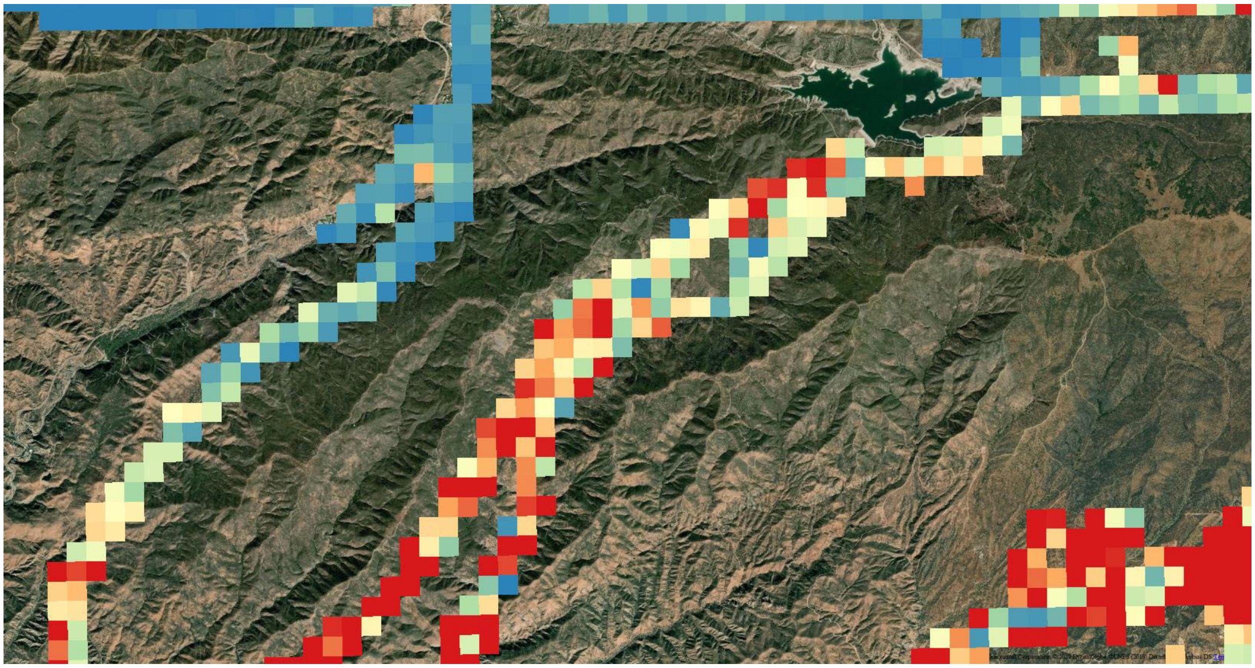


Figure 7. Data from Figure 4 resampled to 300 m resolution.

5.2 Fire perimeter data

SCE's territory was divided into 30 km by 30 km tiles. Those tiles containing overhead electrical facilities located within the high fire threat district (taken here as CPUC Tier 2 and Tier 3 with a ½ mile buffer plus SCE's Bulletin 322 areas) were identified. A map showing these tiles along with a four-digit identifier is presented in Figure 1. Analogous GIS data can be found in the ESRI shapefile tiles.shp in the root of the Sharefile .zip archive.

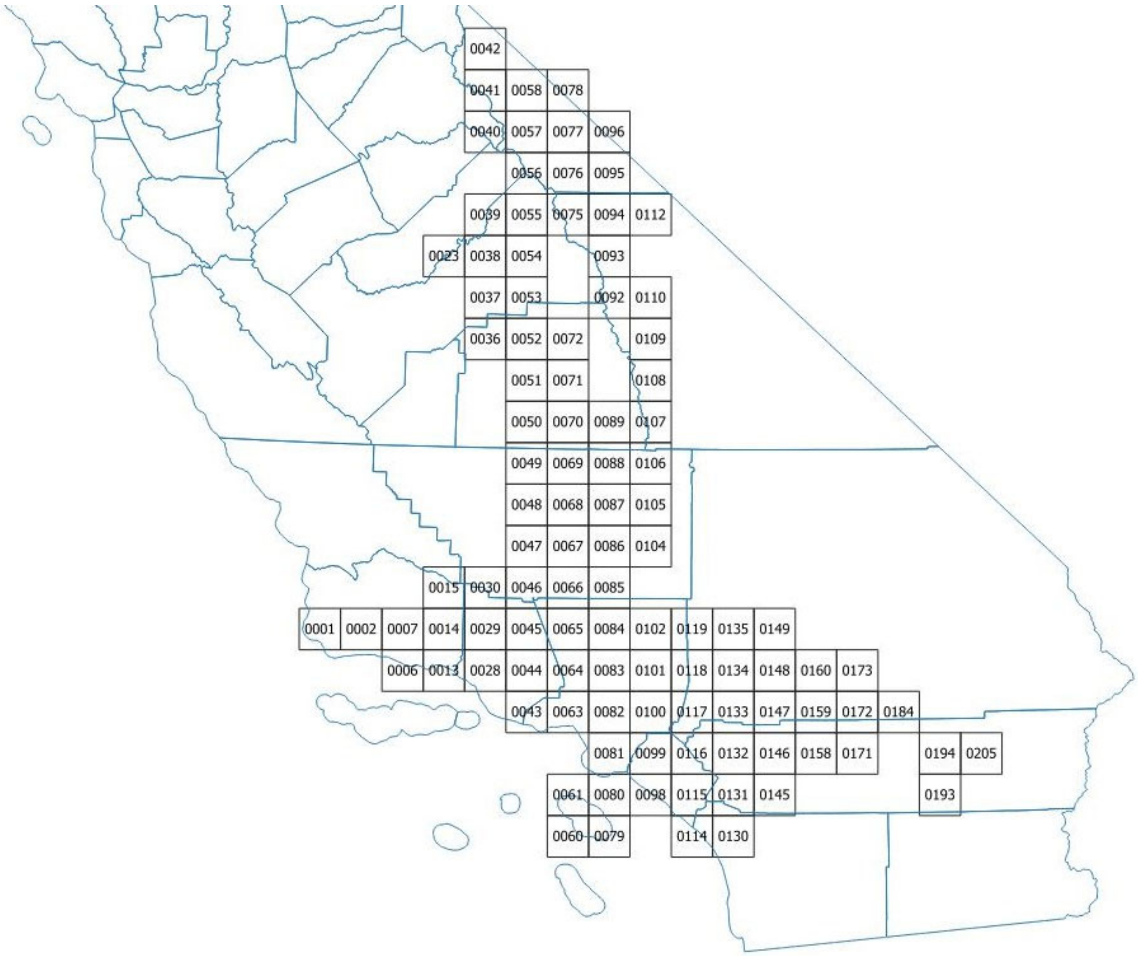


Figure 1. 30 km master tiles containing SCE facilities located within the high fire threat district.

Every 30 km master tile was broken into 10,000 sub-tiles (each subtile is 300 m by 300 m). The naming convention for subtiles within a master tile used here, and as the naming convention in GIS output files, is:

####_XXX_YYY

Here, #### is the four digit tile identifier shown in Figure 1, XXX is a three digit integer describing the subtile's *x* (East/West) offset from the lower-left corner of the master tile, and YYY is a three digit integer describing the *y* (North/South) offset from the lower left corner of the master tile. As an example, subtile 0046_030_025 is the subtile in master tile 0046 with its lower left corner offset by an *x* distance of (30 – 1) × 300 m = 8700 m from the lower left corner of the master tile and its lower left corner offset by a *y* distance of (25 – 1) × 300 m = 7200 m from the lower left corner of the master tile.

A Monte Carlo fire spread analysis comprising approximately 1.2 million ignitions distributed randomly and uniformly within a buffer surrounding SCE overhead electrical facilities was initiated to facilitate calculation of conditional burn probability from all ignitions occurring in each

300 m subtile. Although the underlying fire spread simulations are run on a 30 m grid, conditional burn probability is tabulated on a 300 m grid. This process generated approximately 100,000 GeoTiff rasters containing conditional burn probabilities from all ignitions within each 300 m subtile containing SCE overhead facilities.

GIS data can be found in the “tifs” directory within the .zip archive. The subfolders within the tifs directory correspond to the master tiles shown in Figure 1. Individual tif files are named using the convention described above.

6.0 CONCLUDING REMARKS

While the modeling analysis described herein is based on the best available inputs and fire modeling technology, the analysis is subject to several limitations, including:

- All fire models – including ELMFIRE – lack capabilities to model fire spread through built up or urban areas, which are typically marked as nonburnable in LANDFIRE.

- Structure density data were obtained from the 2010 census and do not reflect development that has occurred since 2010. Structure density data are at the census block level and do not reflect precise locations of individual structures.

- Structure impacts are calculated as the spatial integral of fire area and structure density at the census block scale. Factors that may affect survivability such as firewise practices or compliance with Chapter 7A of the California Building Code are not included.

- Fuels inputs were obtained from the most recent LANDFIRE product (LANDFIRE 2014 / LF 1.4.0). This data product includes disturbances, such as fires, through 2014 but does not reflect fire activity from 2015-2018. For that reason, near-term fire risk will be over-estimated in recently-burned areas and it is recommended that near-term risk in recently burned areas be analyzed on a case by case basis after considering the level of regrowth. An ESRI Shapefile with fire perimeters from 2015-2018 is included in the .zip archive (`fire_perimeters_2015-2018.shp`).

- By distributing ignitions randomly and uniformly within a buffer surrounding overhead facilities, it is inherently assumed that ignition likelihood is equal at all locations within the analyzed area. Other factors that may affect ignition likelihood such as protective devices on circuits, presence or absence of canopy, and highly localized wind patterns are not considered in this analysis.

- Fires are modeled for a duration of 6 hours; consequently, impacts beyond 6 hours of spread are not addressed.

- Suppression or firefighting activities are not modeled.

- LANDFIRE data products tend to over-estimate fire behavior in desert areas. Desert fuels typically do not burn due to lack of fuel continuity. However, in years where rainfall has been plentiful, an herbaceous surface layer capable of supporting propagating fires may be present. LANDFIRE inputs for desert areas reflect fuel conditions when an herbaceous surface layer is present.

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