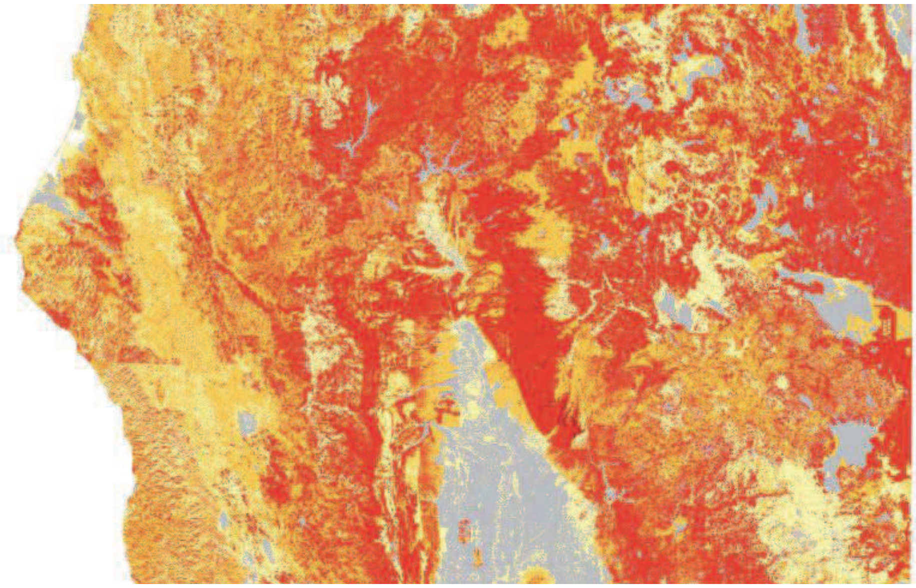
APPENDIX E

REAX REPORT

Reax Engineering Inc.
Job # 10-0134



Prepared for California CIP Coalition

Communication Infrastructure Provider Assets in the Wildland Setting

CIP Fire Threat Map

June 9, 2010

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1.0 INTRODUCTION

Per recently enacted changes to the Public Utilities Commission of the State of California (CPUC) General Order 95 (GO 95), the Fire Threat Map developed by the California Department of Forestry and Fire Protection (Cal Fire) is being used to identify areas in Southern California where Communication Infrastructure Providers (CIPs) are required to begin performing patrol inspections of their facilities that are co-located with electrical facilities. The CPUC is contemplating similar regulations for the remainder of California. However, Cal Fire's Fire Threat Map was not developed to characterize the fire threat associated with CIP facilities co-located with electrical facilities and is not appropriate for this use because it does not specifically address the steps that lead to fire initiation by CIP facilities co-located with electrical facilities.

For this reason, Reax Engineering Inc. has been retained by the California Coalition of Communication Infrastructure Providers (CIPs)[1] to develop a map that specifically characterizes the fire threat associated with wind-induced failures of CIP facilities co-located with electrical power lines in California. This new map builds upon Cal Fire's existing Fire Threat Map by considering state-wide spatial variations in wind and weather patterns during off-shore (Foehn) wind days that create the highest potential for fire initiation by CIP facilities co-located with electric power transmission lines. It does not address failures caused by mechanisms other than wind. Seven Southern California counties are specifically exempted from this study: Santa Barbara, Ventura, Los Angeles, Orange, San Diego, Riverside, and San Bernardino.

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[1] The coalition is comprised of the following companies: Pacific Bell Telephone Company dba AT&T California, Verizon California Inc., CTIA-The Wireless Association, Sunesys Inc., Frontier Communications, Calaveras Telephone Company, Cal-Ore Telephone Co., Ducor Telephone Company, Foresthill Telephone Co., Happy Valley Telephone Company, Hornitos Telephone Company, Kerman Telephone Co., Pinnacles Telephone Co., The Ponderosa Telephone Co., Sierra Telephone Company, Inc., The Siskiyou Telephone Company, Volcano Telephone Company, and Winterhaven Telephone Company.

2.0 SUMMARY OF PROPOSED RULEMAKING FOR INSPECTION OF CIP ASSETS

The GO 95 Interim Ordering Paragraph that requires inspection of CIP facilities in Southern California is reproduced below [1]:

> The term "Communication Infrastructure Provider" or "CIP" is defined as any entity that has attached facilities to an electric utility's poles for the purpose of providing communication services. Communication Infrastructure Providers shall begin performing patrol inspections of their facilities in designated Extreme and Very High Fire Threat Zones, as identified in Cal Fire's Fire and Resource Assessment Program Fire Threat Map, in the following Southern California counties: Santa Barbara, Ventura, Los Angeles, Orange, San Diego, Riverside, and San Bernardino. The boundaries of the Fire Threat Map shall be broadly construed, and CIPs should use their own expertise and judgment to determine if local conditions require them to adjust the boundaries of the map. The CIPs' patrol inspections shall encompass all of their overhead lines installed on joint use poles with electric distribution or transmission facilities, as well as those facilities that are one pole length away from joint use poles with electric distribution or transmission lines in the designated areas. The CIPs shall take appropriate corrective action of any safety hazards or violations of General Orders 95 that are identified during the patrol inspections. The patrol inspections shall be completed no later than September 30, 2010. CIPs shall maintain documentation which would allow Commission staff to verify that such inspections and corrective actions were completed, including the location of the poles/equipment inspected, the date of inspection, and the personnel that performed the inspection and corrective action. Such documentation shall be retained for five years. "Patrol inspection" shall be defined as a simple visual inspection of applicable communications infrastructure equipment and structures that is designed to identify obvious structural problems and hazards. Patrol inspections may be carried out in the course of other company business.

This paragraph requires patrol inspections in "Extreme" and "Very High" Fire Threat Zones as identified in Cal Fire's Fire Threat Map. The GO 95 adopted ordering paragraph that defines the Fire Threat Map is reproduced below [1]:

> Extreme and Very High Fire Threat Zones are defined by California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP) Fire Threat Map. The FRAP Fire Threat Map is to be used to establish approximate boundaries for purposes of this rule. The boundaries of the map are to be broadly construed and utilities should use their own expertise and judgment to determine if local conditions require them to adjust the boundaries of the map.

The Fire Threat Map, dated October 20, 2005, is available for download from FRAP's web site, both as a pdf document [2] and a GIS layer (GRID format) [3].

3.0 EXISTING FIRE THREAT AND FIRE HAZARD SEVERITY ZONE MAPS

A logical starting point for developing an alternative map that specifically characterizes the fire threat of co-located CIP facilities is to review Cal Fire's Fire Threat Map that has been adopted in GO 95 (see Section 2.0). For this reason, Section 3.1 below reviews Cal Fire's existing Fire Threat Map. As part of this work, Cal Fire's Fire Hazard Severity Zone Map [4] was also reviewed but is not specifically addressed in this report.

3.1 Cal Fire's Existing Fire Threat Map

The Fire Threat map combines fire frequency (as characterized by fire rotation) with potential fire behavior (as characterized by fuel rank) to develop the four-category Fire Threat Map (moderate, high, very high, and extreme). Table 1 shows how the four fire threat categories are determined [5]:

Table 1. Fire threat categories as calculated from Fuel Rank and Fire Rotation in Cal Fire's Fire Threat Map.

		Fuel Rank		
		1 (moderate)	**2 (high)**	**3 (very high)**
Fire Rotation	**1 (low)**	**moderate**	**high**	**very high**
	2 (moderate)	**high**	**very high**	**very high**
	3 (high)	**very high**	**very high**	**extreme**

The two factors that feed in to Cal Fire's Fire Threat Map (Fire Rotation and Fuel Rank) are described in greater detail in the following sections.

3.1.1 Fire Frequency: Fire Rotation

In Cal Fire's Fire Threat Map, fire frequency is characterized by fire rotation, a measure of the expected interval between fires at a given location. Lower fire rotation values (measured in years) correspond to a higher fire frequency. Cal Fire used post-1950 fire perimeter data to estimate fire rotation and identified the following fire rotation classes:

0. Undetermined
1. Low (fire rotation > 300 years)
2. Moderate (fire rotation between 100 and 300 years)
3. High (fire rotation < 100 years)

The Fire Rotation map can be download from the FRAP web site [6]. Cal Fire's Fire Rotation map (as presented in Ref. [5]) is reproduced in Figure 1.

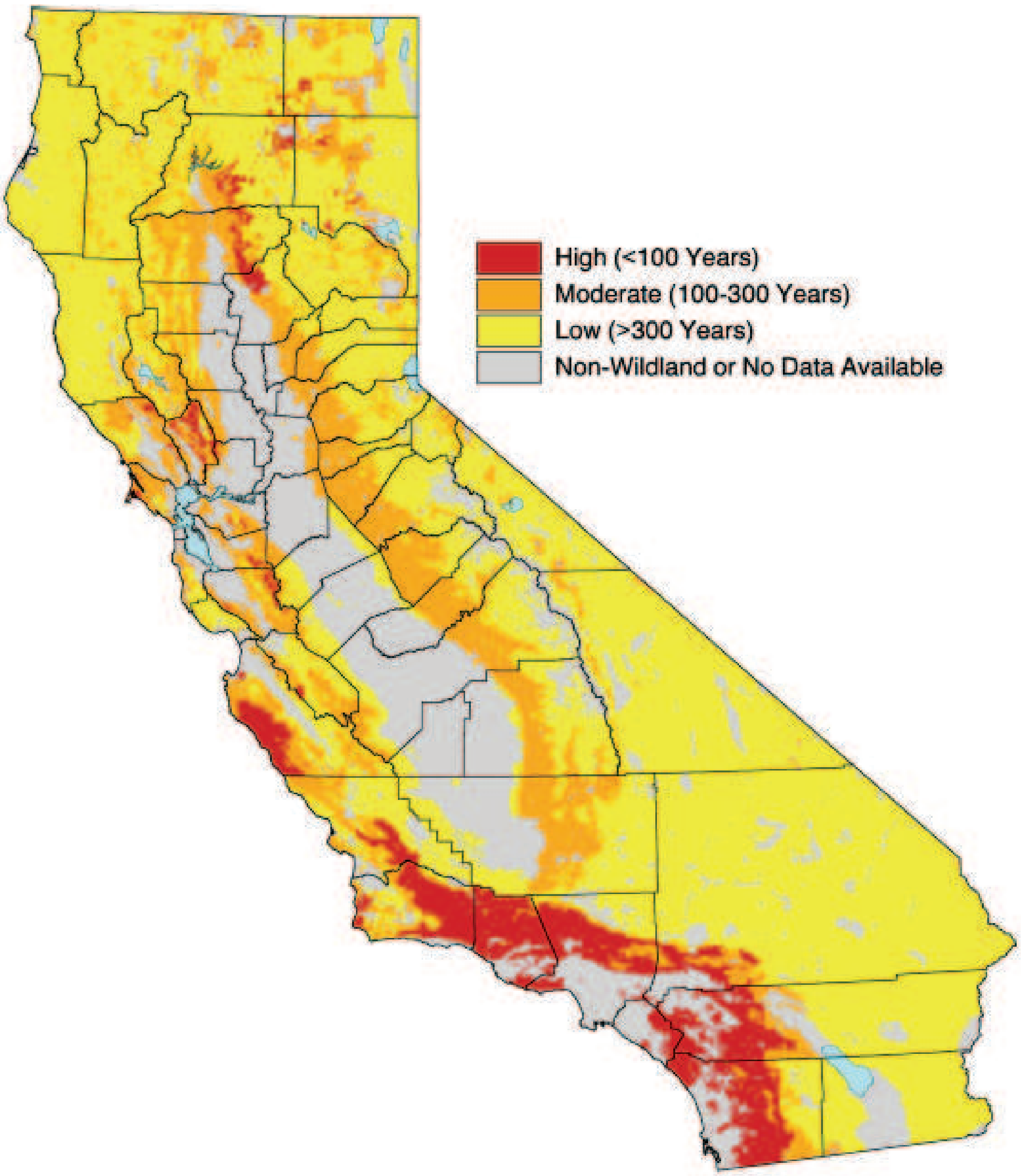

Figure 1. Cal Fire's Fire Rotation Map [5].

3.1.2 Potential Fire Behavior: Fuel Rank

In Cal Fire's Fire Threat Map, potential fire behavior is characterized by Fuel Rank, an integer index between 1 and 3 that is a relative measure of potential fire behavior:

1. Moderate
2. High
3. Very High

Fuel Rank has three components [7]:

1. Surface rank
2. Ladder index
3. Crown index

Surface rank is determined via wildland fire behavior modeling using the SURFACE module of the BEHAVE Fire Behavior Prediction System [8]. This modeling is based on surface fuel model type (as mapped by Cal Fire [9-10]) and slope (calculated from the USGS 7.5 minute Digital Elevation Model (DEM)). Spatial variations in wind speed, weather, and relative humidity are not taken into consideration; rather, uniform fire weather conditions are assumed for all of California.

Cal Fire identified three surface rank categories based on flame length [11], while also considering spread rate and heat per unit area. Figure 2 (copied verbatim from Ref. [11]) shows graphically how Cal Fire identifies these three categories. Below and to the left of the red line (4 ft flame length) is moderate surface rank; Between the red line (4 ft flame length) and either the green line (8 ft flame length) or blue line (11 ft flame length) is high surface rank, and flame lengths above this upper threshold are considered very high surface length. The reason for the 8 ft / 11 ft ambiguity is that the text in Ref. [11] suggests that 8 ft flame length was used as the demarcation point between high and very high surface rank, but Figure 2 (reproduced from Ref. [11]) suggests that 11 ft was used. It is worth noting that determination of whether a certain flame length is "high" or "very high" is a subjective call open to interpretation.

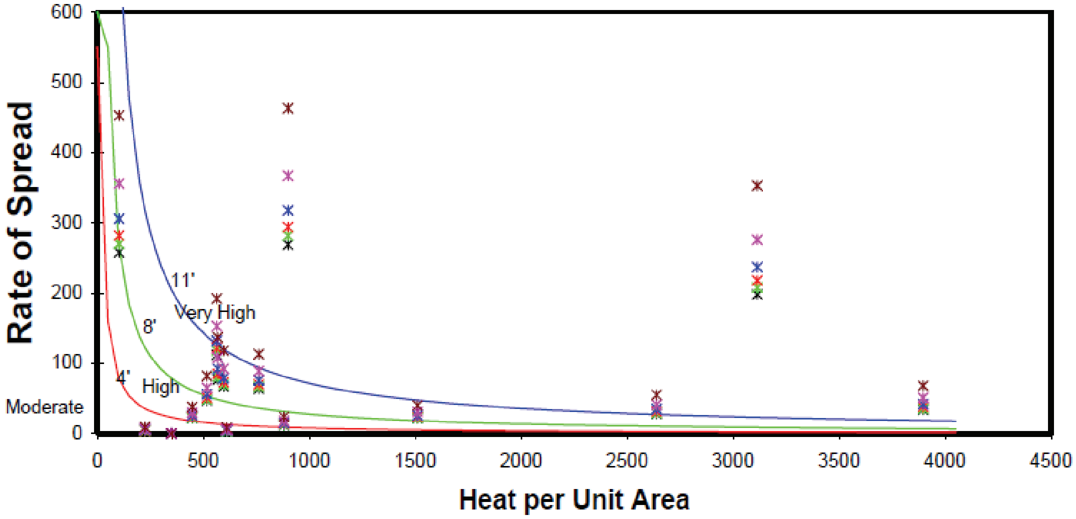

Figure 2. Cal Fire's identification moderate, high, and very high surface rank [11].
Note that there are no units on the x and y axes because Figure 2 is reproduced exactly as it appears in [11].

To summarize, Cal Fire's surface rank categories are as follows:

- Surface rank category 1: moderate (flame length less than 4 ft)
- Surface rank category 2: high (flame length between 4 and 8 or 11 ft)
- Surface rank category 3: very high (flame length greater than 8 or 11 ft)

Ladder index and crown index are determined based on the configuration of ladder and crown fuels as follows:

- Ladder/crown fuel index 0: ladder/crown fuels not present
- Ladder/crown fuel index 1: ladder/crown fuels present but spatially limited
- Ladder/crown fuel index 2: ladder/crown fuels widespread

If either the ladder or crown fuel index is 2, or the ladder and crown fuel indices are both one, then the surface rank category described above is increased by 1 to arrive at the final Fuel Rank. For example, if the surface rank category is 2 and the ladder and crown fuel indices are both 1, the final Fuel Rank category is 3. The resultant potential fire behavior map (as presented in Ref. [5]) is shown in Figure 3.

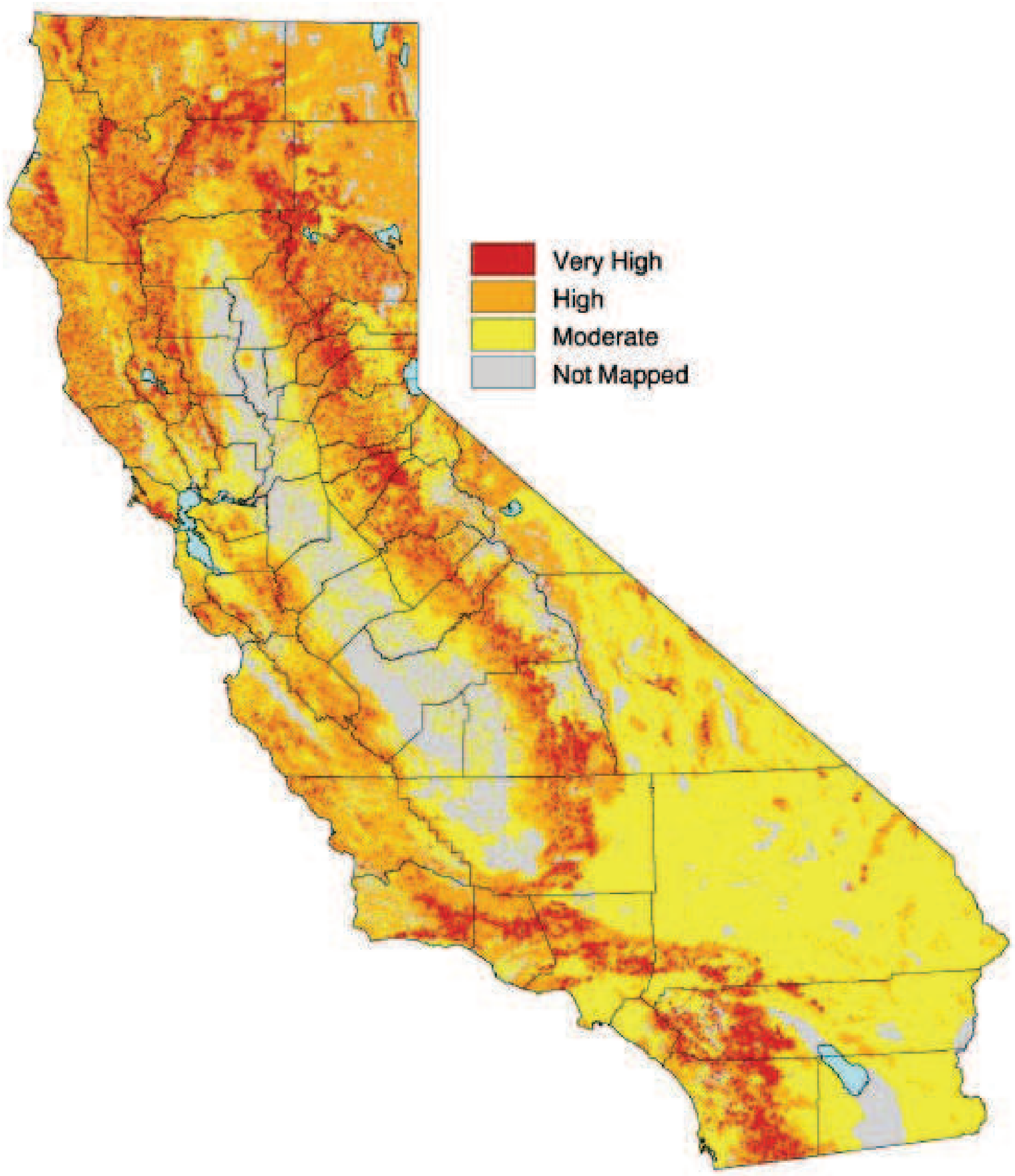

Figure 3. Cal Fire's Potential Fire Behavior Map [5].

Cal Fire's Fire Threat Map is rendered by using Table 1 to combine the Fire Rotation Map (Figure 1) with the Potential Fire Behavior Map (Figure 3). The resultant Fire Threat Map (as presented in Ref. [5]) is shown below in Figure 4.

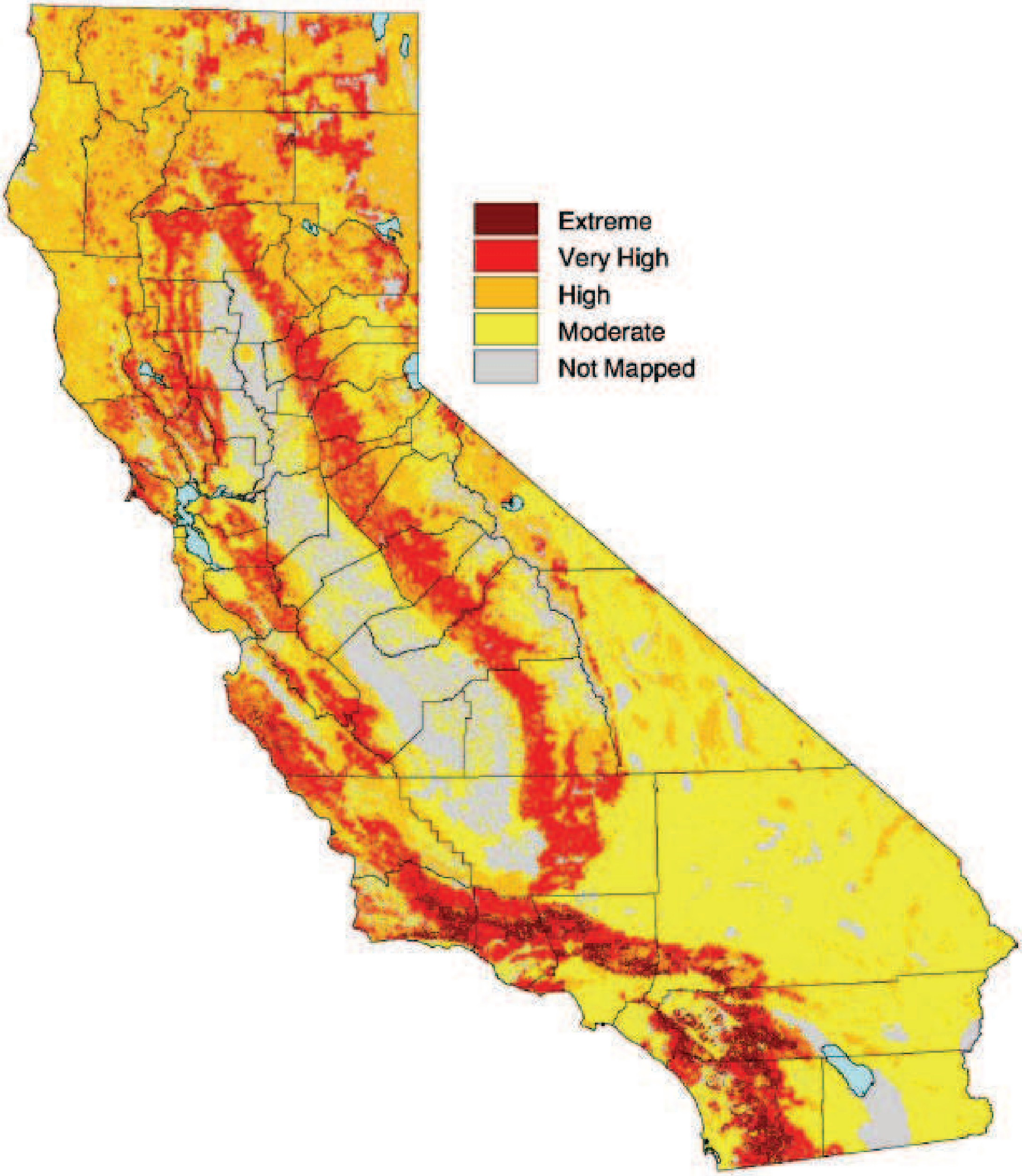

Figure 4. Cal Fire's Fire Threat Map [5].

3.2 Deficiencies of Existing Fire Threat Map for Scheduling Inspections of CIP Facilities

There are several reasons why Cal Fire's existing Fire Threat Map is not an appropriate tool for scheduling inspections of CIP facilities co-located with electrical facilities. Among the most significant are:

1. The Fire Threat Map's fire rotation component (essentially, a proxy for ignition/burn probability) is based on historical fire perimeters. These fire perimeter data include fires initiated by all causes, including lightning and human activity (which account for the majority of wildland fire ignitions), and are in no way correlated to the likelihood that a CIP facility co-located with electrical facilities could ignite a fire.
2. In order for CIP facilities co-located with electrical facilities to ignite a wildland fire, a failure of these facilities must occur in a way that a competent ignition source is generated (more on this in Section 4.0). This type of failure, although unlikely in absolute terms, has a higher relatively likelihood of occurring under high winds. Since Cal Fire's Fire Threat Map does not specifically address local (or even regional) wind patterns, it is not an appropriate measure of the likelihood that a CIP facility co-located with electrical facilities could ignite a fire.
3. For a given fuel type and slope steepness, two of the most important factors controlling potential fire behavior are fuel moisture content and wind speed/direction. Thus, spatial variations in wind and weather patterns (wind velocity, wind direction, air temperature, and relative humidity—which control fuel moisture content) have a significant effect on potential fire behavior. Consequently, potential fire behavior may vary significantly across California, even for the same fuel type and slope. However, Cal Fire's Fire Threat Map does not specifically address spatial variations in wind and weather patterns and therefore does not capture local or regional variations in potential fire behavior.

The new CIP Fire Threat Map developed here specifically addresses each of these deficiencies.

4.0 METHODOLOGY FOR DEVELOPMENT OF A NEW CIP FIRE THREAT MAP

Development of the new CIP Fire Threat map begins by examining the sequence of events that must occur in order for CIP assets that are co-located with electrical power lines to cause a propagating fire:

1. A failure must occur in a way that generates a potential ignition source (generation of an ignition source does not necessarily mean that a fire is ignited). The index that characterizes the relative likelihood of failure will be denoted θ_{failure}.
2. The potential ignition source must come into contact with a fuel bed and be sufficiently competent to cause ignition. The index that characterizes the relative ignition likelihood of a particular fuel bed will be denoted θ_{ignition}.
3. A self-sustaining fire must propagate away from the point of fire origin. The faster the resultant fire spread, and the greater the fire's intensity, the less likely the fire is to be extinguished at an incipient stage. The index that characterizes relative fire behavior will be denoted θ_{behavior}.

The new CIP Fire Threat Map developed here assigns each of the three θ indices a value of 1, 2, or 3, where 1 represents the lowest threat and 3 represents the highest threat (thus, there are 27 possible combinations). Sections 4.1, 4.2, and 4.3 explain how the failure index (θ_{failure}), ignition index (θ_{ignition}), and fire behavior index (θ_{behavior}) are determined, respectively.

As shown previously (Figure 4), in Cal Fire's Fire Threat Map, different combinations of Fire Rotation and Fuel Rank are used to develop a four category ranking (moderate, high, very high, and extreme). The new CIP Threat Map also uses an analogous four category ranking system, but specific descriptions are not assigned to each category (due to the arbitrary nature of differentiating "high" from "very high", for example). Instead, Category 1 represents the lowest CIP fire threat, and Category 4 represents the highest CIP fire threat.

Table 2 shows how the three θ indices (failure, ignition, and fire behavior) are combined to produce a relative CIP fire threat ranking between 1 and 4.

Table 2. CIP Fire Threat categories defined.

Combination #	$\theta_{failure}$	$\theta_{ignition}$	$\theta_{behavior}$	CIP Fire Threat
1	1	1	1	1
2	1	1	2	1
3	1	1	3	1
4	1	2	1	1
5	1	2	2	1
6	1	2	3	2
7	1	3	1	1
8	1	3	2	2
9	1	3	3	2
10	2	1	1	1
11	2	1	2	2
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	3
16	2	3	1	3
17	2	3	2	3
18	2	3	3	3
19	3	1	1	2
20	3	1	2	3
21	3	1	3	3
22	3	2	1	3
23	3	2	2	3
24	3	2	3	4
25	3	3	1	3
26	3	3	2	4
27	3	3	3	4

Generation of the new CIP Fire Threat Map involves determining the spatial variation in each θ index across California. The following sections describe the methodology through which each of the θ indices is determined.

4.1 Relative Threat of Failure Index ($\theta_{failure}$)

For the purposes of developing the new CIP Fire Threat Map, the failure mechanism is considered to be generic (non-specific) wind-induced failure of CIP facilities co-located with utility power lines in a way that could generate an ignition source (the relative likelihood that this ignition source may ignite a fire is a separate issue that is addressed by the ignition likelihood index discussed in Section 4.1). We are unaware of any data in the open literature that has quantified the effect of wind on failure rates of CIP assets, so in this work wind velocity is used as a proxy for the relative likelihood of failure. This is consistent with outage data from electrical utilities that suggests an increase in outages as wind speed increases [12], but it is important to note that this outage data is for electrical, not CIP, facilities and that outages do not necessarily cause fires. It is also important to note that the specific failure mechanism is not addressed in this work and the relative failure threat index does not reflect an actual (absolute) probability of failure but only provides a relative measure of failure threat.

Most treatments of forces on communication and power lines and their associated supports and hardware use some variant of a relationship between wind speed and force, often expressed as a force per unit area [13]:

$$\frac{F_{wind}}{A} = 0.00256V^2 \tag{1}$$

In Equation 1, F_{wind} (wind force) has units of lb, A (object area) has units of ft^2, and V (wind velocity) has units of mph. This relationship is valid for forces that act on trees, branches, and debris exposed to wind forces. Forces will vary based on the area and shape of object but increases in force with increasing wind speed will be similar for all objects in a given wind field. The methods used to calculate wind related risk of failure are based on well developed equations for forces and strengths of poles and wires given in regulatory and guidance documents produced by the California Public Utilities Commission [14], American Society of Civil Engineers (ASCE) [15-16], Institute of Electrical and Electronics Engineers (IEEE) [13], and the American National Standards Institute (ANSI) [17]. However, prediction of wind induced absolute failure rates for any specific failure mode and pole configuration (material, age, condition) is beyond the scope of this analysis. Noting this caveat, the relative probability of failure, calculated using the methods described above, is tabulated in Table 3 as a function of wind speed and plotted in Figure 5 (along with electrical facilities outage data [12]).

During the Foehn wind days analyzed in this work, typical wind speeds are lower than 40 mph, which is significantly less than the 56 mph design criterion from GO95. This suggests that there is no meaningful fire hazard associated with CIP facilities during the Foehn winds analyzed in this work. However, conservative wind velocity thresholds are selected here only for the purpose of identifying areas with higher relative threat of failure, even though the absolute likelihood of failure at these wind velocities is extremely small.

Three classes of delimiting wind velocities are identified based on two wind speeds: 20 mph and 28 mph. For 1-hour average wind speeds below ~20 mph, the risk of damage to structures is extremely low and the literature suggests that failures, as measured by outages of electrical utilities, are unlikely [12]. Above ~20 mph, outages start to occur [12], and around a threshold 1-hour wind velocity of ~28-30 mph, the number of electrical outages increases dramatically [12] and unstable trees or weak branches may begin to break [18]. Therefore, 20 mph and 28 mph are used here as delimiting wind velocities for determining the relative CIP asset failure likelihood index (θ_{failure}) by filtering the calculated wind velocity field as follows:

$$\theta_{\text{failure}} = \begin{cases} 1 & \text{for } 0\text{ mph} \le \text{V}_\text{c} \le 20\text{ mph} \\ 2 & \text{for } 20\text{ mph} < \text{V}_\text{c} \le 28\text{ mph} \\ 3 & \text{for } \text{V}_\text{c} > 28\text{ mph} \end{cases} \tag{2}$$

where V_c represents a characteristic wind speed determined via weather modeling (see Section 5.2) over the time frame analyzed. See Section 6.0 for a description of how characteristic wind speeds are extracted from the weather modeling.

Table 3. Effect of wind velocity on relative likelihood of failure.

1-hour wind speed (mph)	3 second wind gust (mph)	Relative likelihood of failure (-)	Relative likelihood of failure normalized to 56 mph (-)
5	6.0	0.00008	0.0009
10	12.0	0.00010	0.0010
15	18.1	0.00014	0.0015
20	24.1	0.0002	0.0023
25	30.1	0.0004	0.0041
30	36.1	0.0008	0.0082
35	42.2	0.002	0.0181
40	48.2	0.004	0.0431
45	54.2	0.011	0.1102
50	60.2	0.029	0.2971
55	66.3	0.081	0.8190
56	67.5	0.099	1.0000

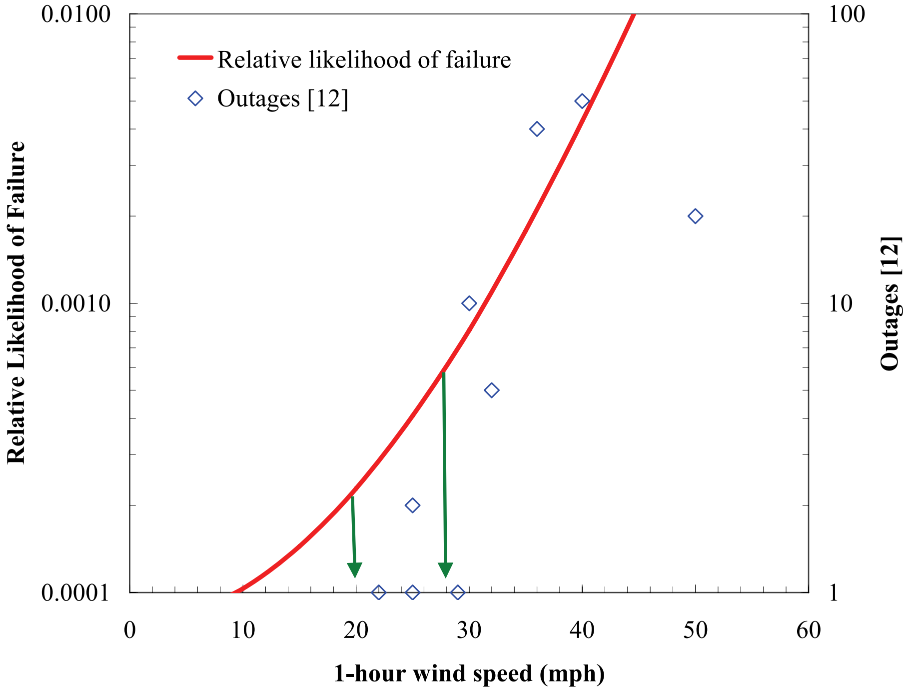

Figure 5. Effect of wind speed on relative likelihood of failure.

4.2 Ignition Likelihood Index ($\theta_{ignition}$)

Ignitability of wildland fuels by embers and heated particles/surfaces depends primarily on fine-fuel (1-hour) moisture content (and fuel type, i.e. whether or not fine fuels are present). Secondary factors include air temperature, relative humidity, and wind speed. The IGNITE module of the BEHAVE Fire Behavior Prediction System [8] uses the methodology of Schroeder [19] to calculate the probability of ignition by firebrands. Schroeder's [19] ignition probabilities are given in Table 4 as a function of fuel temperature and fine fuel moisture content. It can be seen from Table 4 that the ignition probability is much more sensitive to fine fuel moisture content than fuel temperature.

Table 4. Ignition probability by firebrands as tabulated by Schroeder [19].

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

Since moisture content is the dominant factor controlling ignitability of wildland fuels, several authors have attempted to relate ease of ignition to fuel moisture content alone, without considering secondary factors (air temperature, wind velocity, relative humidity, wind speed). For example, Chuvieco *et al*. [20] defined an "ignition potential" based on fuel moisture content and the "moisture of extinction" (the threshold moisture content above which a fire cannot be sustained). A similar approach was taken by Dimitrakopoulos *et al.* [21]. In the present work, only moisture content is taken into consideration when addressing ignition potential, and secondary less important factors are neglected.

Experimental data showing the effect of fine-fuel moisture content on the ignitability of pine needles by glowing embers in a controlled laboratory setting is shown in Figure 6 [22].

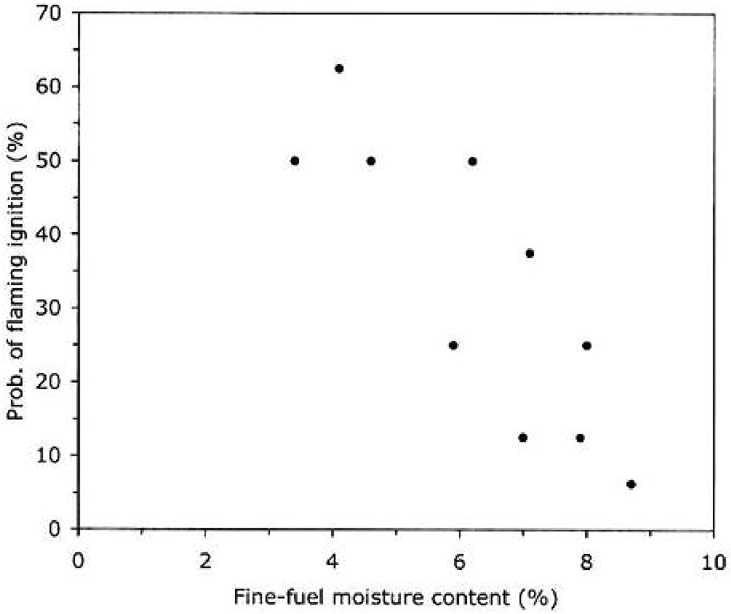

Figure 6. Effect of fine-fuel moisture content on the ignitability of pine needles from small glowing embers [22].

It can be seen from Figure 6 that below ~5% moisture content, the ignition probability is greater 50%. This is consistent with Table 4 above, which indicates that for a representative fuel temperature of 85 °F, the ignition probability at 5% moisture content is approximately 60%. Figure 6 suggests that above 9% moisture content, the ignition probability approaches zero. However, the limiting moisture content (i.e. the moisture content above which ignition does not occur) is higher in Table 4 than in Figure 6, falling to approximately 15% above 12% moisture content.

Based on the above discussion, the relative ignition likelihood index is determined by filtering the 1-hour fuel moisture content field as:

$$\theta_{\text{ignition}} = \begin{cases} 1 & \text{for } M_{1,c} > 9\,\% \\ 2 & \text{for } 5\,\% < M_{1,c} \le 9\,\% \\ 3 & \text{for } 0\,\% \le M_{1,c} \le 5\,\% \end{cases} \tag{3}$$

In Equation 3, $M_{1,c}$ is a characteristic moisture content of 1-hour timelag fuels (such as grasses and small twigs) as calculated from weather modeling data (Section 5.2), using the procedure described in Section 5.4. See Section 6.0 for a description of how characteristic 1-hour timelag fuel moisture contents are established.

It should be noted that the heated particles that could be generated by interactions between CIP facilities and electrical utilities may have different energetics (temperature, size) than firebrands. However, due to the relatively small size of sparks/heated particles that may be generated by interactions between CIP facilities and electrical utilities, it is felt that firebrand studies are conservative and are therefore the best available metric for determining a relative ranking of ignition probability based on moisture content.

4.3 Fire Behavior Index (θ_{behavior})

Several metrics could be used to quantify potential fire behavior. These include flame length, fireline intensity, fire spread rate (velocity), and heat per unit area. Cal Fire's existing Fire Threat map uses flame length (while also considering heat per unit area and spread rate) to demarcate moderate, high, and very high fire behavior (see Section 3.1.2 for details). For consistency with Cal Fire's existing Fire Threat Map, flame length is also used here to identify three different fire behavior categories. Specifically, the relative fire behavior index is calculated by filtering the calculated flame length field as follows:

$$\theta_{\text{behavior}} = \begin{cases} 1 & \text{for } 0 \le L_{f,c} \le 4\text{ ft} \\ 2 & \text{for } 4\text{ ft} < L_{f,c} \le 10\text{ ft} \\ 3 & \text{for } L_{f,c} > 10\text{ ft} \end{cases} \tag{4}$$

Where $L_{f,c}$ is a characteristic flame length calculated with the Rothermel surface fire spread model as implemented in the BEHAVE fire modeling system. See Section 6.0 for a description of how characteristic input parameters are established to determine characteristic flame lengths using BEHAVE. The two flame length delimiters used here (4 ft and 10 ft) are considered fire suppression points, meaning that ground crews can attack the head of a fire for flame lengths below ~ 4 ft, ground equipment can be used for flame lengths between 4 ft and 10 ft, and above 10 ft other methods (such as aerial attack) may be necessary.

The inputs necessary to calculate flame length with BEHAVE include fuel model type, slope, wind speed, dead fuel moisture content (1-hour, 10-hour, and 100-hour timelag), live herbaceous moisture content, and live woody moisture content. These inputs are addressed in detail in Section 5.0.

The fire behavior modeling conducted here conservatively assumes that wind always blows in the uphill direction. For example, for a West-facing slope with winds out of the east, BEHAVE is run as if the wind is in the uphill direction. Although slope aspect and wind directionality information are available, it is felt that due to turbulent fluctuations in wind direction and local terrain effects not captured in the weather modeling (i.e. features smaller than 1.5 km) that making the conservative assumption that wind is always in the uphill direction is the best approach.

One important difference between Cal Fire’s Fuel Rank map (see Section 3.1.2) and the Fire Behavior Index ($\theta_{behavior}$) determined here is that the presence or absence of crown and ladder fuels is not explicitly considered here. More specifically, $\theta_{behavior}$ is based only on fire behavior of *surface* fuels, whereas Cal Fire’s Fuel Rank map considers not only surface fire behavior but also the degree to which ladder and crown fuels are present (not present, present but spatially limited, present and widespread). While a ladder/crown fuel component could be included in $\theta_{behavior}$, it is felt that this is unnecessary because the aim of the present work is to identify areas that have the highest relative threats for wind-induced ignition of fires by co-located CIP facilities, with resultant fire behavior playing a secondary role.

5.0 MAP INPUT DATA SETS / GIS LAYERS

As described above, the CIP Fire Threat map is calculated from three indices that characterize the relative likelihoods of CIP asset failure (θ_{failure}), ignition of wildland fuels (θ_{ignition}), and potential fire behavior (θ_{behavior}). These θ indices in turn depend on wind speed, hourly temperature, and hourly relative humidity variations as summarized in Figure 7:

$$\theta_{\text{failure}} \to \text{wind speed}$$

$$\theta_{\text{ignition}} \to \text{dead } 1-\text{hr MC} \to \begin{cases} \text{Hourly temperature variations} \\ \text{Hourly relative humidity variations} \end{cases}$$

$$\theta_{\text{behavior}} \to \text{Flame length} \to \left\{ \begin{array}{l} \left. \begin{array}{l} \text{dead } 1-\text{hr MC} \\ \text{dead } 10-\text{hr MC} \\ \text{dead } 100-\text{hr MC} \\ \text{live herbaceous MC} \\ \text{live woody MC} \end{array} \right\} \to \left\{ \begin{array}{l} \text{Hourly temperature variations} \\ \text{Hourly relative humidity variations} \end{array} \right. \\ \text{fuel type} \\ \text{slope} \\ \text{wind speed} \end{array} \right.$$

Figure 7. θ factor dependencies.

From Figure 7, it can be seen that in order to calculate each of the θ factors (and the resultant CIP Fire Threat Map from Table 2) the following GIS layers are needed as input or must calculated as an intermediate step:

1. Fuel model type
2. Slope (terrain steepness)
3. Wind speed
4. Dead fuel moisture content – 1-hr
5. Dead fuel moisture content – 10-hr
6. Dead fuel moisture content – 100-hr
7. Live herbaceous fuel moisture content
8. Live woody fuel moisture content
9. Hourly temperature variations
10. Hourly relative humidity variations
11. Flame length

Each of these 11 quantities is determined at a resolution of 100 m by 100 m across California, except for the 7 Southern California Counties that are specifically exempted from this study (Santa Barbara, Ventura, Los Angeles, Orange, San Diego, Riverside, and San Bernardino). A resolution of 100 m was chosen for consistency with Cal Fire's current Fire Threat Map. Given that the area of California is just over 420,000 sq km, each of the above quantities must be determined for approximately 40 million individual locations (raster) points. Some quantities (particularly wind and weather related quantities) have been determined to an accuracy of less than 100 m and must be "upsampled" to 100 m resolution for consistency with other layers. Each input data set, and the degree of upsampling/downsampling, is described in greater detail below.

5.1 Topography: Elevation, Slope, and Aspect

Native resolution:	10 m
Downsampled resolution:	100 m

CA topography information is obtained from the USGS Digital Elevation Maps (DEM) and in particular the National Elevation Dataset (NED) at a resolution of 10 m. This dataset is processed to generate separate GIS raster layers for elevation, slope, and aspect accurate to a resolution of 100 m (only slope feeds directly into the fire behavior modeling conducted here).

5.2 Weather: Wind, Temperature, and Relative Humidity

Native resolution:	1500 m
Upsampled resolution:	100 m

Due to the limited coverage of California by RAWS and NWS COOP weather stations, a short-term weather forecasting model (COAMPS – Coupled Ocean/Atmosphere Numerical Weather Prediction System [23], developed by the US Navy) is used to develop detailed spatially resolved fields of wind velocity, temperature, and relative humidity during Foehn (offshore) wind days from 2006 – 2008. Weather modeling was conducted for consecutive "blocks" of 4-6 days during which Foehn winds occurred. Table 5 lists the weather blocks that modeled as well as the number of days in each block.

COAMPS takes as input actual historical weather observations and uses state-of-the-art weather forecasting techniques to provide temporally and spatially resolved weather predictions; essentially, it takes actual observations and uses weather modeling to "fill in the gaps". Calculations are conducted with a spatial resolution of 1.5 km and weather data are calculated for approximately 190,000 raster points across California, each having an area of 2.25 km^2. Calculations are performed on a High Performance Computational Cluster to determine hourly "observations" of wind velocity, air temperature, and relative humidity at a resolution of 1.5 km. The weather simulations are then post-processed to determine characteristic values of wind velocity, air temperature, and relative humidity and derivative quantities such as fuel moisture contents (see Section 6.0 for a description of how this is done); these data then feed into the fuel moisture content modeling and fire behavior modeling described elsewhere. Wind velocities at 2 m above ground level are used here, meaning that $\theta_{failure}$ and $\theta_{behavior}$ are calculated from wind data at the same height (2 m above ground level).

Table 5. Number of Foehn wind days between September and November 2006 - 2008 analyzed in this work.

Block	# Days in Block
2006 block 1	4
2007 block 1	5
2007 block 2	4
2007 block 3	5
2008 block 1	5
2008 block 2	6
2008 block 3	4
2008 block 4	5

Moritz *et al.* [24] recently investigated severe fire weather in Southern California using a mesoscale weather model at a resolution of 36 km^2. The numerical weather modeling conducted in our work has a resolution of 2.25 km^2, or 16 times finer than Moritz *et al.* [24], and is conducted for all of California.

5.3 Vegetation Type: Fuel Model

Native resolution: 30 m
Downsampled resolution: 100 m

Cal Fire has published a surface fuel map [10] based on the original 13 standard fuel models. These 13 standard fuel models are summarized in Table 6 (adopted from Anderson [25]). Cal Fire's surface fuel map is used here after downsampling to 100 m resolution.

Table 6. Standard fuel models used in this work (from Anderson [25])

Fuel Model	Typical fuel complex	Fuel loading (tons/acre)				Fuel bed depth (ft)	Moisture of Extinction (%)
		1-hr	10-hr	100-hr	live		
	Grass and grass dominated						
1	Short grass (1 foot)	0.74	0.00	0.00	0.00	1.0	12
2	Woodland w/ grass understory	2.00	1.00	0.50	0.50	1.0	15
3	Tall grass (2.5 feet)	3.01	0.00	0.00	0.00	2.5	25
	Chaparral and shrubs						
4	Chaparral (6 feet)	5.01	4.01	2.00	5.01	6.0	20
5	Brush (2 feet)	1.00	0.50	0.00	2.00	2.0	20
6	Dormant brush, hardwood slash	1.50	2.50	2.00	0.00	2.5	25
7	Southern rough	1.13	1.87	1.50	0.37	2.5	40
	Timber litter						
8	Closed timber litter	1.50	1.00	2.50	0.00	0.2	30
9	Hardwood litter	2.92	41	0.15	0.00	0.2	25
10	Timber (litter and understory)	3.01	2.00	5.01	0.00	1.0	25
	Logging slash						
11	Light logging slash	1.50	4.51	5.51	0.00	1.0	15
12	Medium logging slash	4.01	14.03	16.53	0.00	2.3	20
13	Heavy logging slash	7.01	23.04	28.05	0.00	3.0	25

5.4 Dead Fuel Moisture Content: 1-hour, 10-hour, and 100-hour Fuels

Native resolution: 1500 m (derived from weather modeling data described in Section 5.2)
Upsampled resolution: 100 m

For representative fire modeling runs, dead fuel moisture content is calculated for three fuel size classes (1-hour, 10-hour, and 100-hour fuels) by numerically integrating (using the Crank-Nicholson method) the following first order ordinary differential equation:

$$\frac{dM}{dt} = \frac{M_{eq} - M}{\tau_c} \tag{5}$$

Here, τ_c is the time lag constant for the corresponding fuel size class (1-hour, 10-hour, or 100-hour). Essentially, fuels with a 1-hour timelag adjust to changes in relative humidity in roughly 1-hour, fuels with a 10-hour timelag adjust to changes in relative humidity in 10 hours, and so on.

Numerical solution Equation 5 requires specification of an initial condition (the initial moisture content M_0) and an initial moisture content of 7% is assumed here.

Since ~100 hours of continuous weather data is processed to determine representative fuel moisture content values (see Section 6.0), the assumed initial fuel moisture contents for the 1-hour and 10-hour timelag fuels has a negligible effect on calculated characteristic fuel moisture contents. The characteristic moisture contents calculated for the 100-hour timelag fuels will depend somewhat on the assumed initial condition because the length of the weather stream analyzed (96 – 144 hours) is of comparable magnitude to the 100-hour timelag. However, 100-hour fuels do not have a strong influence on surface fire behavior and therefore the effect of the initial condition is considered negligible.

The equilibrium fuel moisture content in Equation 5 is calculated following Simard [26] as cited in Goodrick [27]:

$$M_{eq} = \begin{cases} 0.03 + 0.28 \times \mathrm{RH} - 0.00058 \times \mathrm{RH} \times \mathrm{T} & \text{for RH} < 10\% \\ 2.23 + 0.16 \times \mathrm{RH} - 0.0148 \times \mathrm{T} & \text{for } 10 \le \mathrm{RH} < 50\% \\ 21.1 - 0.4944 \times \mathrm{RH} + 0.00557 \times \mathrm{RH}^2 - 0.00035 \times \mathrm{RH} \times \mathrm{T} & \text{for RH} \ge 50\% \end{cases} \tag{6}$$

In Equation 6, which is used in the Fosberg Fire Weather Index, RH is the relative humidity in percent and T is the temperature in degrees Fahrenheit. RH and T values are obtained from the weather modeling as a function of space and time (1-hour intervals) to calculate fuel moisture content values as a function of space and time. Characteristic fuel moisture contents are then determined at each 1500 m raster point and up-sampled to 100 m for use in fire behavior modeling.

As an example of how Equations 5 and 6 are used to calculate dead fuel moisture content, 10 days of hourly observations from the Santa Rosa RAWS station (starting August 1, 1992) were used to calculate fuel moisture contents for 1, 10, and 100 hour time lag fuels. The hourly observations of temperature and relative humidity are plotted in Figure 8, showing the typical diurnal variation where relative humidity peaks at night and reaches its minimum during the day, while temperature does the opposite. The calculated equilibrium fuel moisture content and 1, 10, and 100 hour timelag fuel moisture contents are plotted in Figure 9. Note that the smaller the fuel time lag class, the more closely the fuel moisture content "tracks" the equilibrium value.

In the CIP Fire Threat map that is developed here, modeled hourly observations of temperature and relative humidity (see Section 5.2) are used to calculate fuel moisture contents for each 1500 m raster point in lieu of weather station (RAWS) data as was done in this example, but the method is identical.

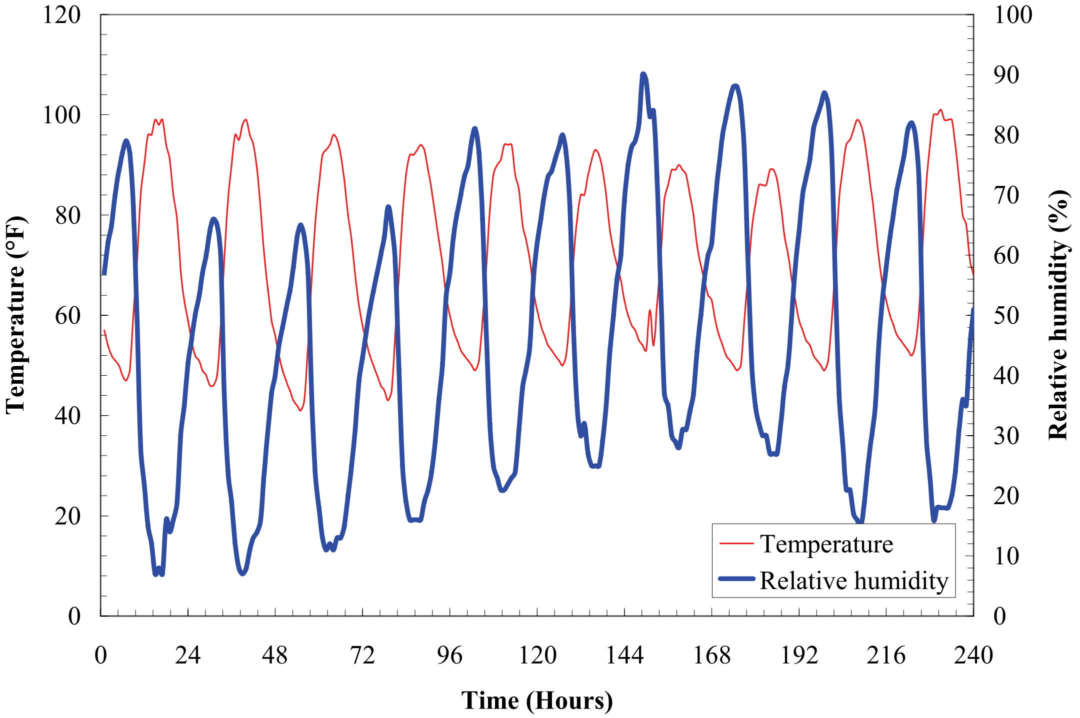

Figure 8. Hourly temperature and relative humidity observations for a 10 day period in August 1992 – from RAWS data for Santa Rosa, CA.

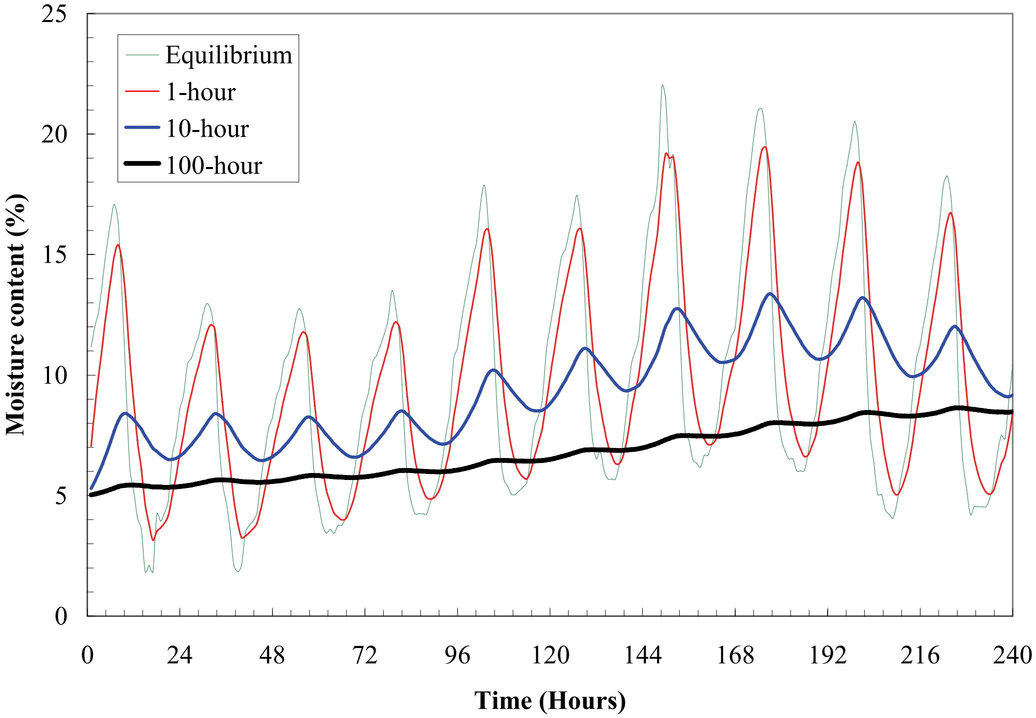

Figure 9. Calculated (with Equations 5 and 6) dead fuel moisture contents for a 10 day period in August 1992 for temperature and humidity data shown in Figure 8.

5.5 Live Fuel Moisture Content: Herbaceous and Woody Fuels

Native resolution: N/A
Upsampled resolution: 100 m

Of the 13 standard fuel models used in this work, live fuel moisture content applies only to fuel models 2, 4, 5, 7, and 10. Live fuel moisture is affected by seasonal weather patterns and longer-term climate trends such as multi-year drought. For example, Burgan [28] suggests relating live fuel moisture content to a modified 1000-hour (42-day) timelag dead fuel moisture content. Since we are analyzing only ~5 day weather "blocks" in this work, use of this type of long-term metric is not possible. Instead, the following live fuel moisture contents, representative of severe fire weather conditions, are assumed:

- Fuel model 2 live herbaceous moisture content: 40%
- Fuel model 4 live woody moisture content: 60%
- Fuel model 5 live woody moisture content: 60%
- Fuel model 7 live woody moisture content: 60%
- Fuel model 10 live woody moisture content: 60%

These moisture content levels are conservative and, with the exception of fuel model 4 (chaparral), live fuel moisture content has a relatively minor effect on fire behavior [29]. The 60% value for fuel model 4 is justified as a near worst-case value based on field measurements in Northern California by Stephens *et al.* [30].

5.6 Fire Behavior: Flame Length

Native resolution: 10 m (slope), 30 m (fuels), 1500 m (wind, fuel moisture content)
Upsampled resolution: 100 m

The C library "FireLib" [31], an implementation of the surface fire behavior routines in BEHAVE, is used to calculate fire behavior parameters for each 100 m raster point (although spread rate, fireline intensity, reaction intensity, etc. are calculated, only flame length is used in development of the CIP Fire Threat Map). FireLib was implemented as a subroutine in mixed Fortran/C program that was written specifically for this project to extract relevant data from the appropriate GIS input layers and generate output GIS layers for various fire behavior quantities. Parallel processing on a 16-core Linux cluster was used to reduce run times, and the CIP Fire Threat Map can be generated for California's ~40 million raster points in less than 10 minutes.

6.0 CALCULATING CHARACTERISTIC VALUES FROM WEATHER MODELING

As described in Section 5.2 (see Table 5), weather modeling is conducted for 38 historical Foehn wind days between 2006 and 2008. The weather modeling was conducted for continuous temporal "blocks" between 4 and 6 days in length, with a nominal length of 5 days (120 hours). Multi-day blocks were modeled to facilitate calculation of 10-hour and 100-hour timelag fuel moisture contents, which would not be possible when considering only one day at a time. Wind velocity, temperature, and relative humidity values were output at hourly intervals (consistent with weather stations) at a spatial resolution of 2.25 km^2.

In order to apply the deterministic modeling methods described earlier, it is necessary to reduce this large amount of weather modeling data (and derivative quantities such as fuel moisture contents) to establish "characteristic" (or representative) values. Essentially, the 8 weather blocks modeled here must be processed separately and then merged together to generate characteristic values (i.e., composite maps).

The procedure used here to establish characteristic quantities is as follows:

1. For each weather block, calculate fuel moisture contents using the methodology described in Section 5.4.
2. For each weather block, rank the following hourly observations from low to high: wind speed, temperature, relative humidity, 1-hour timelag moisture content, 10-hour timelag moisture content, 100-hour timelag moisture content.
3. For each weather block, determine the 98th percentile values of the quantities identified in step 2 above. For a typical 120-hour block, this 98th percentile value corresponds to the third most severe hourly observation (e.g., the third highest wind speed or the third lowest fuel moisture content)
4. After processing all weather blocks separately as described in steps 1-3 above, the worst-case values of the quantities identified in step 2 are determined across all weather blocks to establish composite (or characteristic) maps of each quantity. In this way, the characteristic values at a particular location may be derived from multiple weather blocks.
5. The values of each quantity determined in step 4 are then considered characteristic values, and each of the θ factors (see Sections 4.1 – 4.3 above) is determined using these characteristic values. For example, fire behavior modeling is calculated using the characteristic values of wind speed, temperature, relative humidity, 1-hour timelag moisture content, 10-hour timelag moisture content, and 100-hour timelag moisture content determined here.

7.0 THE MAPS

Maps are formatted to letter sized paper in this report, but high resolution maps (jpg format) are available for download from the following locations:

- 300 dpi (48 MB): http://reaxengineering.com/cip/2010-05-28_300dpi_maps.zip
- 1200 dpi (490 MB): http://reaxengineering.com/cip/2010-05-28_1200dpi_maps.zip

Note that the second file (1200 dpi maps) has a file size ten times that of the 300 dpi file and may take more than an hour to download. In the maps below, the corresponding filename of each high resolution map in the zip archives identified above is listed in parentheses at the end of the Figure caption.

The maps developed in this work and presented below are summarized in Table 7.

Table 7. Maps developed in this work.

Figure #	Page	Description	Filename
Figure 10	24	Elevation	elevation.jpg
Figure 11	25	Slope	slope.jpg
Figure 12	26	Fuel model type	fuel_model.jpg
Figure 13	27	Characteristic wind velocity	wind_velocity.jpg
Figure 14	28	1-hour timelag fuel moisture content	m1.jpg
Figure 15	29	10-hour timelag fuel moisture content	m10.jpg
Figure 16	30	100-hour timelag fuel moisture	m100.jpg
Figure 17	31	Characteristic flame length	lf.jpg
Figure 18	32	Failure index ($\theta_{failure}$)	theta_failure.jpg
Figure 19	33	Ignition index ($\theta_{ignition}$)	theta_ignition.jpg
Figure 20	34	Fire behavior index ($\theta_{behavior}$)	theta_behavior.jpg
Figure 21	35	New CIP Fire Threat Map	cip_fire_thrt.jpg
Figure 22	36	Difference between FRAP and CIP fire threat map	cip_delta.jpg
Figure 23	37	FRAP threat class 3 and 4 map	three_4_frap.jpg
Figure 24	38	CIP threat class 3 and 4 map	three_4_cip.jpg
Figure 25	39	Difference between FRAP & CIP threat class 3 & 4 map	three_4_delta.jpg

Figure 21 presents the new CIP Fire Threat map developed here. Figure 22 presents the difference in Fire Threat between the new CIP Fire Threat map and Cal Fire's Existing Fire Threat map. Positive values indicate an increase in fire threat in the new map, and negative values indicate a decrease in fire threat.

Figure 23 shows the areas of the FRAP Fire Threat map falling into very high and extreme fire threat areas (i.e., fire threat classes 3 and 4). Figure 24 presents the analogous CIP map showing threat class 3 and 4 areas. Figure 25 presents the difference between these CIP and FRAP threat class 3 and 4 maps.

Fire behavior modeling, CIP Threat Map generation, and inspection map generation are not conducted for the Southern California counties of Santa Barbara, Ventura, Los Angeles, Orange, San Diego, Riverside, and San Bernardino.

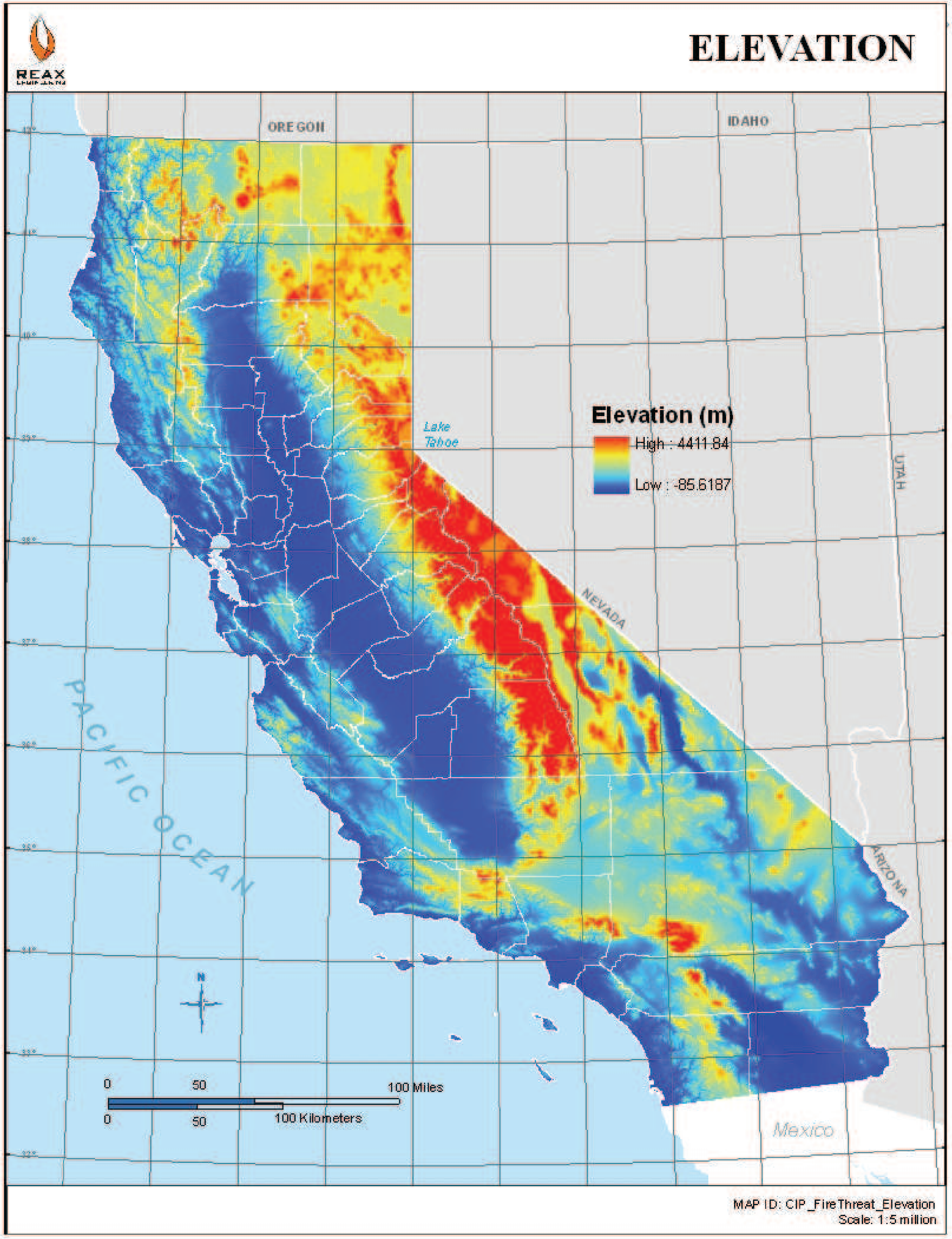

Figure 10. Map of elevation. (elevation.jpg)

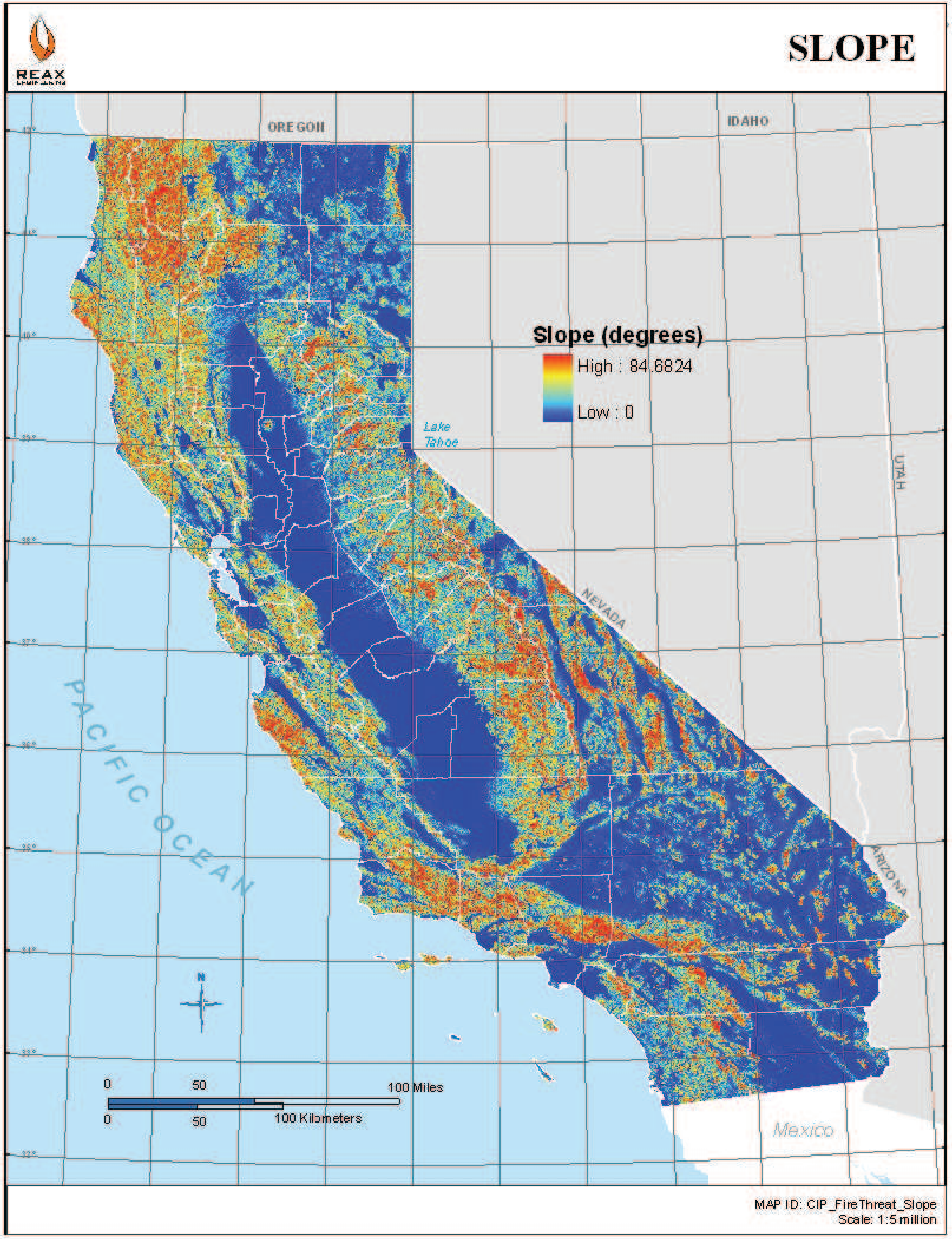

Figure 11. Map of slope. (slope.jpg)