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1 Technical Model Documentation

1.1 Purpose

The Office of Energy Infrastructure (OEIS) requires transparency in risk calculation methodologies supporting Wildfire Mitigation. Per the guidelines, OEIS has specific requirements for technical documentation, substantiation, and data governance of the models used in risk calculations for the WMP. This template outlines the required technical documentation and substantiation for the models, while the WMP Data Governance Framework covers the data governance requirements for the models.

1.2 Applicability

The applicability of the model documentation and governance applies to every model included in the Wildfire Mitigation Plan filed with the OEIS.

2 Technical Documentation

2.1 Problem or Function

2.1.1 Problem Modeled

Define the problem modeled for function performed by the program, for example, calculation of fire growth, smoke spread, people movement, etc.

The application of wildfire behavior modeling and risk analysis is used to quantify the potential impacts from possible electric utility infrastructure asset caused ignitions. The basis of this modeling is that not all ignitions (fires) are created equal, and each asset caused ignition can have substantially different consequence based on ignition location and related landscape characteristics.

The wildfire modeling and risk analysis derives a set of consequence metrics that quantify impacts. This includes potential acres burned, population impacted, number of buildings threatened, and estimated number of buildings destroyed. These are currently derived using an 8-hour simulation duration, based on a typical first burning period. Testing is underway to evaluate different fire durations based on suggestions in the most recent WMP Guidelines.

Technosylva's Wildfire Analyst™ (WFA) product is used to conduct the modeling, deliver modeling outputs, and monitor and visualize results with software applications.

The wildfire behavior modeling and risk analysis is applied to address two different, yet similar, scenarios. First, the modeling is used with historical re-analysis WRF weather data to support the mitigation planning process. The WFA FireSight, previously called Wildfire Risk Reduction Model (WRRM), is used to quantify risk metrics from millions of wildfire simulations using the numerous WRF weather scenarios defined. This wildfire consequence data is then combined with probability of failure and ignition analysis developed internally to define composite risk values to support prioritization decision making for asset hardening and related mitigation.

Secondly, the modeling is also used with daily WRF-based weather forecast data to calculate consequence based risk metrics for all assets as possible ignition sources to support operational requirements. Other key input datasets such as surface and canopy fuels, and live fuel moisture and dead fuel moisture, are developed daily using Machine Learning (ML) models to calculate the wildfire behavior outputs as part of the risk analysis model. Wildfire risk forecasts are derived daily, or sometimes twice daily, with a multi-day outlook on an hourly basis. This information is used as input into key decision making related to operational requirements, such as PSPS, resource allocation and deployment, field operations, etc.

Note that the Technosylva Wildfire Analyst™ product is comprised of three discrete applications – FireSim, FireRisk and FireSight. "FireRisk" is the new name for the application formerly called "FireCast". This was renamed to better meet platform functionality naming consistency. Accordingly, all references to FireRisk are identical to all functionality previously provided under the name "FireCast". Also note that the platform is now called Wildfire Analyst. "Enterprise" has been removed from the product platform name. To meet PacifiCorp requirements, a subscription to all three applications is required.[1] These include:

1. WFA FireRisk – daily asset-based risk forecasting to support operational needs, such as PSPS (previously called FireCast), including all situational awareness capabilities.
2. WFA FireSim – on-demand wildfire spread modeling to support real-time incident analysis and "what if" analysis for pending weather events to support operational needs.
3. WFA FireSight – risk analysis for assets using historical fire scenarios to ensure comprehensive understanding of asset ignition probability and consequence to support mitigation planning, such as WMP prioritization and development (previously called WRRM). FireSight includes integration of outage analytics, probability of outage/failure, and probability of ignition as well as built-in integrations to support calculations for risk reduction, mitigation effectiveness and risk spend efficiency.

FireRisk and FireSim support operational needs while FireSight supports enterprise risk management and mitigation planning needs. FireSight is implemented separately from FireRisk and FireSim.

2.2 Technical Description

2.2.1 Theoretical and Mathematical Foundations

Convey a thorough understanding of the theoretical and mathematical foundations, referencing the open literature where appropriate.

The basis of the wildfire risk modeling for electric utility assets lies in the published, proven and accepted fire science for wildfire behavior modeling. The Technosylva WFA product used to create risk metrics for both operational and planning initiatives utilizes the best-in-class fire science available. Technosylva has been able to operationalize proven wildfire behavior models and validate these models through on-going collaboration with CAL FIRE and the US Forest Service Missoula Fire Laboratory as the only unique vendor selected. This collaboration provides the operational platform to test and validate a suite of wildfire behavior and risk models that are utilized for statewide intelligence and operations by CAL FIRE, and by each IOU in California for operations and mitigation.

To support the model R&D and implementation, Technosylva regularly publishes peer reviewed and accepted articles regarding these models. Technosylva has been involved in 30+ publications over the past 24 months, with 11 as the principal investigator. Some of these publications are referenced on the Technosylva web site at https://technosylva.com/scientific-research/.

The published fire science provides the theoretical foundation for the operational models, tempered by validation analysis conducted on an on-going basis, to continually refine the models to match what occurs with observed wildfire behavior. The rest of this section provides a detailed description of the theoretical and mathematical foundation for the WFA models.

2.3 Theoretical Foundation

2.3.1 Phenomenon and Physical Laws (Model Basis)

Describe the theoretical basis of the phenomenon and the physical laws on which the model is based.

Fire is a self-sustained and usually uncontrolled sequence of processes basically carried out by the combination of fuel, oxygen and heat. In forest fires (also referred to as wildland fire or wildfire), the fuel is given by the vegetation layer composed of trees, bushes and all kinds of dead and living foliage (organic matter). The oxygen is abundantly present in the atmosphere and the heat is caused by the combustion of the flame and transported mainly by radiation and convection within the vegetation.

A quick review of the process involved could be described as follows. Consider a homogeneous flammable solid material like wood to which an external heat flux has been imposed. As the solid material absorbs the heat it raises its temperature at a rate dependent on the net heat capacity of the material (mix of all the components of the solid, including water). As the temperature increases, the moisture content in the solid diminishes and eventually dries up the solid. A further increase of the temperature causes the pyrolysis process of the wood (around 550 K), the organic material decomposes into a stream of volatile gasses (smoke, carbon and oxygen) and into solid remains like char (nearly pure carbon), and ashes (incombustible minerals like calcium, potassium, etc). The pyrolyzed fuel vapor convects and diffuses, mixing with the oxygen of the atmosphere and forming a combustible mixture. The high gas temperature favors the initiation of a gas phase combustion reaction in the combustible-oxidizer mixture. The compound molecules break apart, the atoms recombine with the oxygen to form water, carbon dioxide and some other products. The whole process is ruled by many factors, the types of char and volatile, the amount of oxygen and the exact chemical reactions taking place. The temperature difference between the gasses released in the pyrolysis process and the ambient air together with the gained temperature due to the oxidation reaction (around 1000 K), generates a buoyancy flow that raises up the hot combusting gas forming the characteristic flames of the fire.

In the wildland, fire behavior deeply depends on the vegetation (type, size and vertical arrangement), terrain, wind and moisture conditions of the vegetation (dead and living material). From a descriptive perspective, wildfires main observables are the fires Rate of Spread (ROS), flame length, flame intensity, heat per unit area, flame depth, and residence time. Depending on the behavior of the fire it may be classified as surface and crown fire. Surface fires burn loose needles, moss, lichen, herbaceous vegetation, shrubs, small trees and sampling that are at or near the surface of the ground. Crown fires burn forest canopy fuels, which include live and dead foliage/ branches, lichens in trees, and tall shrubs that lie well above the surface fuels. They are usually ignited by a surface fire. Crown fires can be passive or active. Passive crown fires involve the burning of individual trees or small groups of trees (often called torching). Active crown fires, or also referred to as running crown fires, present a solid wall of flame from the surface through the canopy fuel layers.

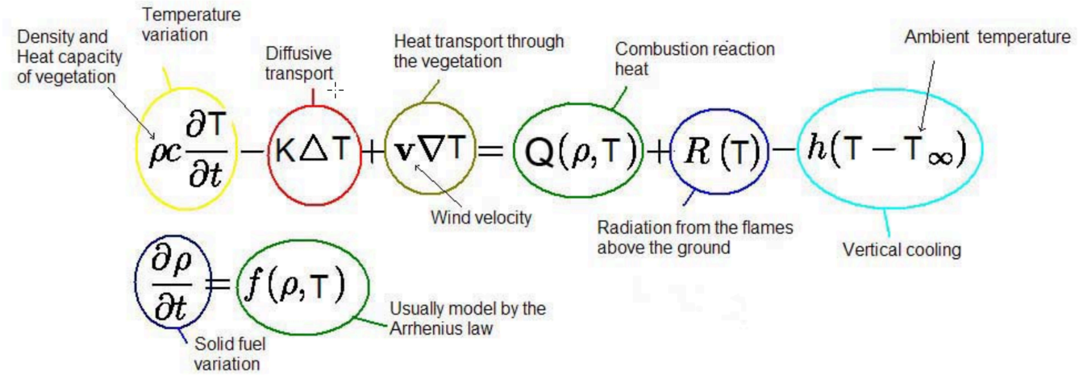
Fire growth from an ignition point can be split into four distinct phases (Fire science 2021), in the first phase the fire starts to burn slowly as the influx of air caused by the buoyancy flow of hot gasses causes the flames to tilt inwards. Once the fire has spread enough from the ignition point, wind is able to enter the already burned vegetation and pushes the flames away from the center and tilts them towards the unburned fuels, increasing the heat transfer, and therefore accelerating the fire. As the fire moves further away from the center, the acceleration of the fire depends more on the local characteristics of the curvilinear front. Finally, the fire may reach a steady-state when the fire line is uniform enough so that it can be considered of infinite length.

2.3.2 Governing Equations

Present the governing equations and the mathematical model employed.

Fire modeling is a highly challenging problem from both the physical and the numerical point of view, and consequently historical advances in this field have always been forced to a compromised position due to the desire of practical usefulness, computer capabilities, required input data, and existing numerical methods. It is only by the consideration of these requirements that the primary natural approaches to the problem can be understood. The primary broad approaches are physical models, quasi-empirical models, and empirical ones.

Physical models are the most complex and have the advantage to be more generally valid across different fuels and weather conditions (Cruz 2017). They are usually posed as a set of coupled differential equations derived from conservation laws and defined on a usually bidimensional domain representing the vegetation layer considered as a porous medium where the main variables develop. The degree of approximation of the initial semi-physical description of the problem, as well as the rest of physical effects considered in the modeling may vary greatly from one model to another. Despite these different approaches, a conventional 2D multiphase model, sketching vegetation temperature through a convection reaction diffusion equation, and a solid combustible material evolution in time may serve as a simple example for illustration purposes.



Example of a 2D multiphase model sketching vegetation temperature and solid combustible

Even though physical models are very promising, they are not easy to make operational because in many cases the detailed input data they need is not readily available, and because they require a lot of computer processing capability, as they usually use adaptive meshes to keep track of the burning front. Some numerical methods used for solving these models are the Finite Element Method (FEM), Finite Difference methods (FDM), etc.

Empirical and semi-empirical models are mainly based on experimental data: laboratory runs, controlled outdoor fires, or well documented wildland fires. The difference between the empirical and semi-empirical approach is that the former ones contain no physical basis at all and are generally statistical in nature, while the later use some form of physical framework on which the statistical model is based (Andrews 2018, Sullivan 2009). These models are largely developed to support decision making and are the main operational models used today.   They are typically able to predict the source dataset with mean absolute percent errors between 20 and 40% (Cruz et al. 2013)

Further review of existing fire modeling approaches can be found in Catchpole and De Mestre (1986), Weber (1991), Pastor et al. (2003), Sullivan (2009a,b,c)

2.3.3 Assumptions

Identify the major assumptions on which the fire model is based and any simplifying assumptions.

The following are some of major assumptions contained in the models

- The physical framework development is based on an idealized situation in steady state spread which may not fit some extreme behavior of fires.
- Fuels are assumed to be continuous and uniform for the scale of the input (typically between 10 to 30 meter (m) resolution)
- Fire characteristics at a point only depend on the conditions at that point (point-functional model). This means that there are certain non-local phenomena like:
    - Increase of ROS due to a concave front.
    - Fire interaction between different parts of the same fire or a different one
- Fire spread is assumed to be elliptical although there are several variations such as double ellipse, oval, egg-shape, etc.
- Weather is given hourly and is assumed to remain constant during that time. There is no interpolation in time to compute the evolution of weather between hours.
- Reliability of weather inputs in the mid-range forecast (2 to 5 days)
- Fire is not coupled with the atmosphere in any way. This may seem like a major limitation in the model as wind is a main contribution to fire spread and at present many models (specially physical ones) try to couple wind and fire. The main reasons for us not to consider the coupling is:
    - It would make it infeasible to run millions of simulations considering the coupling effect.
    - Empirical and semi-empirical models have been developed using an average wind speed as an input, so it is not clear that considering more granular wind at the front is advisable.
- Fire is always assumed to be fully developed. Fire acceleration, flashover, or decay is not considered.
- Atmospheric instability which may have a deep impact on ROS (beer 1991) is not considered in the model.
- Gusts are not considered in the model
- No interaction between slope and wind other than creating an effective or equivalent wind. This means that fire is assumed to have an elliptical shape no matter the alignment of wind and slope.
- Models have been developed with scarce empirical data. The abundance of today’s fire data sources, however, is allowing us to better adjust models to observed fire patterns.
- Fuel array description of the vegetation may not perfectly describe fuel characteristics.
- Spotting is only considered in surface fires

2.3.4 Independent Review Results (see Guide ASTM E 1355)

Provide the results of any independent review of the theoretical basis of the model. Guide E1355 recommends a review by one or more recognized experts fully conversant with the chemistry and physics of the fire phenomena but not involved with the production of the model.

The core models implemented in WFA form the basis of most operational propagation models in use today (Andrews et al 1980, Gould 1991). They have been implemented in well-known software like NEXUS (Scott and Reinhardt 2001), Fire and Fuels Extension to Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003), FARSITE (Finney 2004), Fuel Management Analyst (FMAPlus) (Carlton2005), FlamMap (Finney 2006) and BehavePlus (Andrews et al.2008). Nevertheless, forest fires are a very difficult phenomenon to simulate which depends on many different factors and typical simulations are able to predict the source dataset with mean absolute percent errors between 20 and 40% (Cruz et al. 2013)

One of the important facts in fire simulation is the definition of the fuel models, with analysis providing different results for different fuels and regions. For example, Sanders (2001) observed a pattern of over-prediction by FARSITE in fuel models 1,2, 5 by a large margin, moderate in fuel 10 and some underprediction for fuel model 8. Zigner et al (2020) used two case studies during strong winds revealing that FARSITE was able to successfully reconstruct the spread rate and size of wildfires when spotting was minimal. However, in situations when spotting was an important factor in rapid downslope wildfire spread, both FARSITE and FlamMap were unable to simulate realistic fire perimeters. Ross et al. (2006) used measurements from temperature sensors during prescribed burns in the Appalachian Mountains to recreate the fires and compared fire behavior simulated by FARSITE. They obtained a set of ROS adjustment factors that better represented the observed fire behavior obtaining a ROS adjustment factor of 1.5 and 2 for fuels 9 and 11 respectively, and a decreasing factor of 0.2 to the fuel type 6.

Apart from these reviews Technosylva has been constantly improving the accuracy and performance of the published fire models to better adjust the results to observed fire behavior. This includes a better definition of the fuel types, improved forecast of live fuel moisture content, modifications to the crown fire modeling initialization scheme, and automatic fire adjustment based on data assimilation techniques using ROS adjustment factor. In addition, Technosylva has implemented more than 21 additional models into the WFA platform to enhance accuracy and address known limitations of published fire models. These improvements include crown fire analysis, ember and spotting, urban / non-burnable area encroachment, consequence and impact quantification, etc. It is important to note that improvement of the fire modeling platform of choice necessitates not only improvements in mathematical algorithms but substantial improvements in the accuracy and resolution of input data sources. These work in concert to enhance the modeling and outputs to match observed and expected fire behavior. A robust operationalization of fire models requires constant and on-going research, testing, validation and implementation of both models and data sources.

2.4 Mathematical Foundation

2.4.1 Techniques, Procedures, Algorithms

Describe the mathematical techniques, procedures, and computational algorithms employed to obtain numerical solutions.

The fire propagation model in WFA is a point-punctual model where the fire characteristics at a given point (cell) only depends on the conditions at that cell (weather, terrain, vegetation). This fits well in fire simulation as most of wildfire characteristics mainly depend on local characteristics (Di Gregorio et al 2003), but excludes the effects of non-local phenomena.

The overall resolution is done using a Cellular Automata (CA) where space is discretized into cells (from 10 m to 30 m resolution), and physical quantities take on a finite set of values at each cell. The potential ROS at each cell at any time is given by the propagation models (surface and crown fire). CA models directly incorporate spatial heterogeneity in topography, fuel characteristics, and meteorological conditions, and they can easily accommodate any empirical or theoretical fire propagation mechanism, even complex ones (Collin et al. 2011)

Spotting is introduced as a random event where firebrands can be lifted and generate secondary ignition points ahead of the fire (in the direction of the wind).

The time evolution is done using a Minimum Travel Time (Fast-Marching) algorithm. This algorithm is similar to the well-known Dijkstra´s (1959) algorithm but more adapted to grids instead of the original model that uses graphs. This approach has been used with success in many forest fires propagation models like FlamMap (Finney 2002) and many others (CITES). The algorithm provides a solution of the Eikonal equation of a spreading curve subject to a given speed function ROS(**x**). This is done by searching for the fastest fire travel time along straight line transects of neighboring cells in the lattice. The number of neighboring cells considered determines the angle discretization of the spreading fire. The neighborhood or degrees of freedom, u, in WFA ranges from 8 cells (Moore neighborhood) to 32 cells.

2.4.2 References to Techniques and Algorithms

Provide references to the algorithms and numerical techniques.

The Technosylva WFA platform utilizes numerous models to address specific operational requirements. These models are integrated into an extendible platform that facilitates continued improvement as R&D advancements are made. The following table lists the primary models employed on WFA :

Model	Model Reference	Notes
Surface fire	Rothermel 1972, Albini 1976 Kitral IntecChile	WFA uses the core Rothermel model for fire propagation, however it can be configured for custom versions to support any empirical or semi empirical fire model. This has been done for different models employed in other countries, i.e. Chile, Canada, etc. In this regard, WFA platform is easily extended for use in unique geographies.
Crown Fire	Van Wagner (1977,1989,1993); Finney (1998); Scott and Reinhardt (2001)	Critical surface intensity and critical ROS for crown fire initialization. Expected ROS and flame intensity.
Time Evolution	Technosylva (Monedero, Ramirez 2011)	Fast-Marching method adapted to fire simulations. Minimum Travel Time algorithm with 32 degrees of freedom.

Model	Model Reference	Notes
High-Definition Wind	Forthoffer et al (2009)	High resolution wind model obtained through the integration of the USFS WindNinja software. Note: Technosylva is also the contractor for the USFS Missoula Fire Sciences Lab. for the on-going enhancement and customization of the WindNinja software. This provides Technosylva a unique understanding of the model science foundation and implementation approaches.
Wind Adjustment Factor	Andrews 2012	Wind speed conversion with height. Based on Albini and Baughman (1979); Baughman and Albini (1980); Rothermel (1983); Andrews (2012)
Fire Shape	Andrews 2018,	Unique ellipse based solely on the effective wind speed.
Live Moisture Content	Cardil et al.	Machine learning Algorithm based on historical NDVI weather reading
Dead Moisture Content	Nelson (2002)	
Spark Modeling	Technosylva	Ignition point displacement based on wind speed
Urban Encroachment	Technosylva 2016	Includes several variations of urban encroachment algorithms developed internally to facilitate spread of fires into non-burnable urban fuels. This incorporates a distance-based friction model. Based on research publications by NIST.
Spotting	Technosylva 2019	Surface spotting model for wind driven fires. Albini (1983a, 1983b); Chase (1984); Morris (1987)
Building Loss Factor	Technosylva (Cardil xxx)	Machine Learning algorithm taking into account building conditions. Based on historical damage inspection data on buildings affected by fires over the past 13 years

Many of these models were originally published from research by the USFS Missoula Fire Sciences Laboratory. Technosylva has implemented, and enhanced these models, in addition to developing new models. Most Technosylva custom developed models are supported by journal publications as part of our corporate R&D program. Some of these models are referenced on the Technosylva web site at https://technosylva.com/scientific-research/. Key references are provided below for many of the models employed in the WFA platform.

- Beer, T. The interaction of wind and fire. Boundary-Layer Meteorol 54, 287–308 (1991). https://doi.org/10.1007/BF00183958

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- Scott, J.H., and Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA For. Serv. Res. Pap. RMRS-RP-29.
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- Gould, James. (1991). Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. Proceedings of the Conference on Bushfire Modelling and Fire Danger Rating Systems. 51-64.
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- Zigner, K.; Carvalho, L.M.V.; Peterson, S.; Fujioka, F.; Duine, G.-J.; Jones, C.; Roberts, D.; Moritz, M. Evaluating the Ability of FARSITE to Simulate Wildfires Influenced by Extreme, Downslope Winds in Santa Barbara, California. *Fire* **2020**, *3*, 29. https://doi.org/10.3390/fire3030029
- Phillips, Ross J.; Waldrop, Thomas A.; Simon, Dean M. 2006. Assessment of the FARSITE model for predicting fire behavior in the Southern Appalachian Mountains. Proceedings of the 13th biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 521-525

2.4.3 Equations and Implementation

Present the mathematical equations in conventional terminology and show how they are implemented in the code.

Summary

The mathematical model used to simulate surface fire spread is the model developed by Rothermel (1972) with some modifications from Albini (1976) and some minor adjustments from Technosylva. It accepts the initial 13 fuel models (Anderson 1982) as well as Scott and Burgan's (2005) dynamical fuels where there is a transfer load between the herbaceous and dead classes. Among other outputs this model provides the surface fire rate of spread, flame length and flame intensity in the direction of maximum spread (head front). Crown fire is implemented using the model developed by Van Wagner (1977,1993) which computes the transition viability to crown fire, as well as the expected ROS and intensity in active crown fires. Spotting is modeled as a pseudo random event. The maximum expected spotting distance from the fire is obtained using the wind-driven model developed by (Albini 1983a; Albini 1983b; Chase 1984) and then embers are generated randomly on the front of the fire and the actual traveled distance is computed also randomly based on the maximum distance available. In this modeling there is no tracking of individual embers in the air. Wind speed profiles at different heights (2m, 10m, 20ft) are obtained through a logarithmic wind profile found in Andrews (2012). Fire is assumed to spread following an elliptical shape only dependent on the effective wind speed (Andrews 2012). The time evolution is done using a Fast-Marching method on a regularly spaced landscape grid of a Cellular Automata.

Surface Fire

The default propagation engine implemented in WFA is Rothermel's (1972) surface model with the modifications proposed by Albini (1976) and the requirements to accept Scott and Burgan (2005) fuel models. The basic equation in the model predicts the heads fire rate of spread without wind or slope:

$$R_0 = I_R \xi / \rho_b \varepsilon Q_{ig}$$

Here I_R is the reaction intensity (energy released rate per unit area of the fire front), ξ the propagating flux ratio, ρ_b the bulk density, ε the effective heating number, and Q_{ig} the heat of ignition. The equation is derived by applying the energy conservation to a unit volume of fuel ahead of a steadily advancing fire in a homogeneous fuel bed. In this model, the ROS may be viewed as the ratio between the heat flux received by the unburned fuel ahead of the fire (numerator) and the heat required to ignite it (denominator).

The input parameters to compute the ROS in the case of no wind or slope are the moisture content and the characteristics of the vegetation. Moisture content is given by the 1h, 10h and 100h dead moisture content, and the woody and herbaceous live moisture content. Fuels are assumed to be a mixture of different vegetation types depending on their class (dead or live) and size (less than 0.25 inch, 0.25-1 inch, 1-3 inch), with each class having different surface to volume ratio and loads. The inputs required to define a fuel type is given in the following table:

			LOAD				SAV					
Fuel	1h	10h	100h	herb	woody	1h	herb	woody	Dyn	Depth	MoistExt	heat

Table: input variables for each fuel type.

Here Dyn (dynamic) is a boolean variable to define if there should be a transfer between the herbaceous load and the dead one based on the herbaceous content. In general, SAV values (the fineness of the fuel) strongly affects the ROS and flame length of the fire, while the fuel load does not affect the rate of spread but can have a strong effect on the flame length.

The effect of wind and slope can be incorporated in the model through a couple of dimensionless parameters depending on the midflame wind speed U and the terrain angle θ:

$$ROS= R_0 (1+\Phi_w+ \Phi_s)$$

with

$$\Phi_s= 5.275\ \beta\text{-}0.3\ (\tan \theta)$$

$$\Phi_w= C * U^{B} (\beta / \beta_{op})^{-E}$$

Where β_{op} and β are the optimum and standard packing ratios respectively, and C, B, and E are parameters depending on the surface to volume ratio σ:

$$C = 7.47 * \exp(-0.133\ \sigma^{0.55});$$

$$B = 0.02526\ \sigma^{0.54}$$

$$E = 0.715 * \exp(-0.000359 * \sigma)$$

The slope and wind factors are summed together to obtain the final ROS. If they are not aligned the resultant vector defines the direction of maximum spread (which will be between the direction of wind and the direction of slope). This final slope-wind factor can also be used to compute an equivalent or effective wind speed causing the same effect as the combined effect of wind and slope. To do that we simply inverse the equation of the wind factor to obtain:

$$U_e= [\ \Phi_e (\beta / \beta_{op})^{E} / C\ ]^{-B}$$

The Rothermel model predicts fire characteristics (ROS, flame length, etc) only in the direction of maximum spread (head front) obtained from the combined effect of wind and slope. To compute the ROS in a direction different from the direction of maximum spread, and to be able to use the model in a 2D landscape it is assumed that a free burning fire perimeter from a single ignition point has an elliptical shape. There are several different approaches to compute the ellipse (or ellipses) eccentricity based on wind and slope (Albini [2], Anderson 1983 [6], Alexander, etc). The present implementation follows the equations in Andrews (2008) depending on the effective wind speed U_e in mi/h in the direction of maximum spread. The length to width ratio is given by:

$$L/W = 0\ .1+ 0.25\ U_e$$

Or equivalently the eccentricity e is given by

$$e= (Z^2 – 1)^{0.5} / Z$$

so that the ROS in any direction ϕ is given by

$$ROS(\phi)=ROS\ (1\text{-}e) / (1+e)$$

One of the most important variables of fire is the amount of heat it generates as this is the main contributor to fire spread and fire severity. The amount of heat can be measured using different variables like the reaction intensity (IR), the Heat per Unit Area (HPA) or the fireline intensity. The Reaction intensity is the rate of energy release per unit area within the flaming front (with units of energy/area/time), heat per unit area is the amount of heat energy released per unit are within the flaming front (units of energy/area), fire line intensity is the rate of heat energy released per unit time per unit length of the fire front (units of energy/distance/time). Fireline intensity is independent of the depth zone and It is calculated as the product of the available fuel energy and the ROS of the fire (Byram 1959):

$$I_B = HA \cdot ROS$$

Where The heat per unit area depends on the reaction intensity of the fire (IR) and the time that the area is in the flaming front (residence time tr)

$$H_A = I_R \cdot tr = 384 \cdot I_R / \sigma$$

In this model the flame length and Byram's intensity are closely related by:

$$FL = 0.45\ I^{0.46}$$

Where the flame length is in feet and the intensity in Btu/ft/sc.

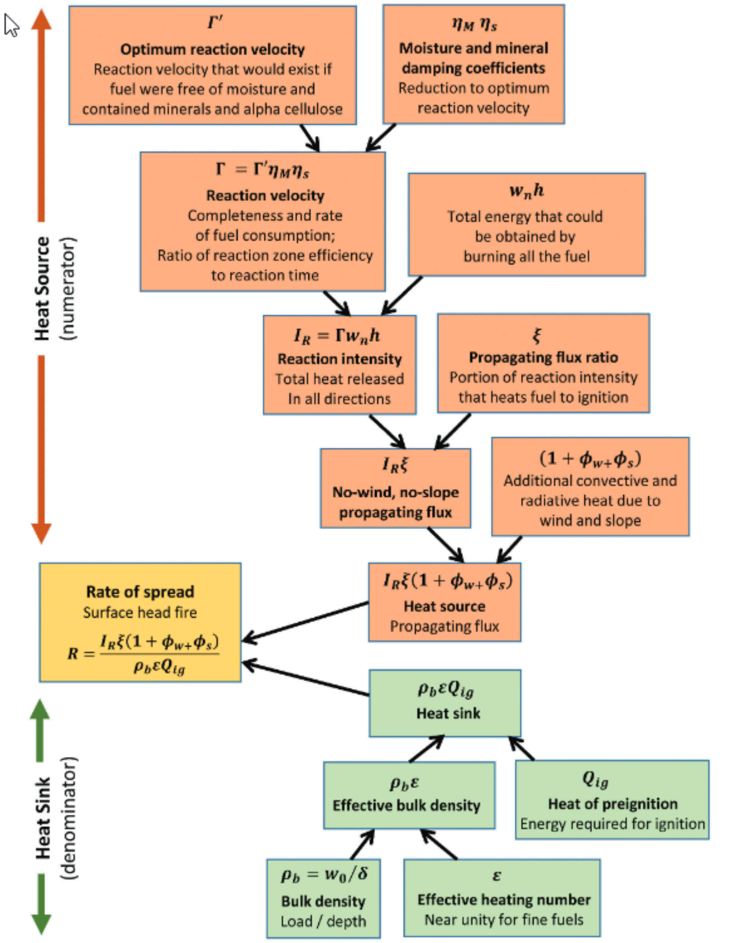


Fig X: Flow of Calculation provided in Andrews (2018)

For a much more in-depth discussion of the Rothermel surface model please read Andrews (2018) and Rothermel (1972).

Crown fire

Crown fires burn forest canopy fuels. They are usually generated by surface fires and represent a major change in fire behavior due to an increased rate of spread and heat released. Crown fires can be passive, active or conditional based on the capacity of the surface fire to move into areal fuels, and to the capacity of the burning canopy to move between individual trees.

Crown fire initiation occurs when the surface fire provides enough heat to raise the temperature of the canopy fuel to ignition temperature. In Van Wagner (1977) model, this minimum intensity is given by:

$$I_{ini}= (0.01 *CBH (460 + 25.9 FMC))^{1.5}$$

Where CBH is the canopy base height (m) and FMC is the foliage moisture content of the canopy cover. Foliar moisture content (FMC) is usually not known, but it is assumed that for most species old foliage should be around 100 percent and this value has been used as a default value when no other information is available (Scott 2001). This approach however does not consider any known humidity conditions of the site and in WFA the FMC is computed based on the 100h moisture content as follows:

$$FMC = 75 + 2 \cdot m100h$$

Once the fire has transitioned to the canopy it is necessary to have a critical mass-flow rate for the fire to be self-sustained. Vang Wagner found this critical mass to be 0.05 kg m-2 sec-1 (Scott 2001) which can be used to determine a minimum crown fire rate of spread only dependent on the Canopy Bulk Density (CBD) and given by

$$R_{active} = 3 / CBD$$

Other existing models not used in WFA are Alexander (1998) which is very similar to Van Wagner (1977) but includes additional inputs like flaming residence time, plume angle and fuel bed characteristics, Cruz et at. (1999) fire transition model, and Cruz et al. (2002) crown fire spread model given by:

$$ROS = c1\, U^{c2}\, CBD \cdot C3 \cdot e^{c4xEFM}$$

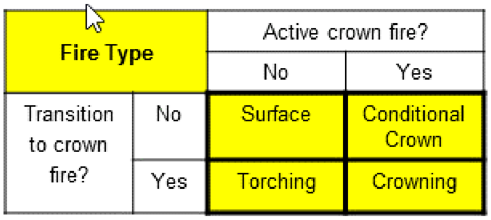
Where U is the wind at 10m, CBD the canopy bulk density, EFM is the fine dead moisture content, and C1, C2, C3, C4 are a set of regression coefficients.

The model for the ROS of crown fires was computed by Rothermel (1991) through a linear regression between observed crown ROS and the surface fire model. It states that the crown fire of an active ROS is 3.34 times the rate of spread of the surface model 10 assuming a 0.4 wind reduction factor.

$$R = 3.34(R_{10})_{40\%}$$

Based on these conditions, crown fire may be classified as:

- Surface fire if neither the intensity nor the minimum crown ROS is met
- Passive Crown fire (torching): Fire spreads through the surface fuels, occasionally torching overstory trees. Overall ROS is that of the surface fire.
- Conditional Crown: Fire cannot transition to crown, but active crown fire is possible if there was a fire transition to crown by other means
- Active Crown: Fire spreads through the overstory tree canopy if both conditions are meet



Fire Type		Active crown fire?	
		No	Yes
Transition to crown fire?	No	Surface	Conditional Crown
	Yes	Torching	Crowning

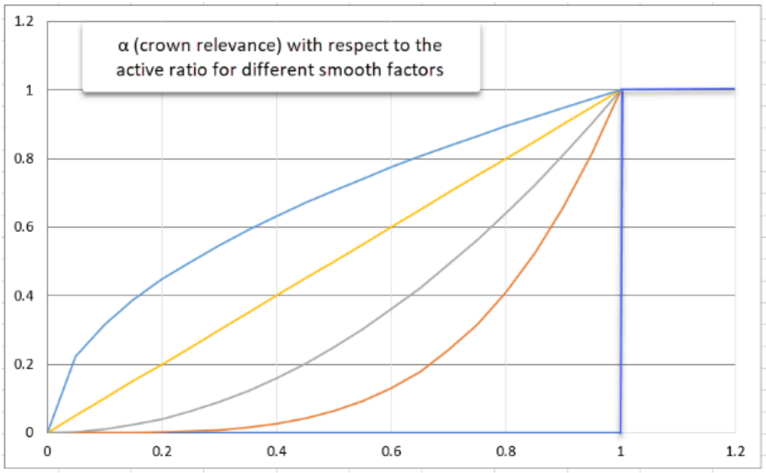
Crown fire classification as shown in BehavePlus

Van Wagner's crown fire transition and propagation models are well known and used operationally but have shown to have a significant underprediction bias when used in assessing potential crown fire behavior in conifer forests of western North America (Cruz et al. 2010). To try to correct this bias Technosylva has introduced two new parameters in the model that have been adjusted based on the analysis carried out by the scientific team using data from the last two fire seasons in California. The model introduces two new parameters 1) a crown factor multiplier for the Canopy Bulk Density (CBD) which decreases the minimum crown ROS required to have an active crown fire, and a factor that forces a smooth transition between the surface and the crown fire behavior. The final ROS of the overall fire when crown fire type is conditional or crowning is a weighted average of surface and crown ROS

$$\mathrm{ROS} = \mathrm{surfROS} * (1-\alpha) + \alpha * \mathrm{crownRos}$$

Where the value α ranges from 0 to 1 and depends on the **active ratio** in the following way:

$$\alpha = \mathrm{activeRatio}^{1/\mathrm{smoothFactor}}$$



Example effect of the smooth factor (0 blue, 0.25 red, 0.5 gray, 1 yellow) in the crown contribution for active ratios lower than 1

At present, with WFA the crown CBD factor is set to 1.2 and the smooth factor to 0.4. This approach to provide a gradual transition in the fire's rate of spread (and flame length) from the initial onset of crowning similar to the crown fraction burned (CFB) (Alexander 1998) used in other modeling systems like FlamMap, FARSITE or Nexus, with the main difference being the smoothing function itself. Cruz et al. observes that there is no evidence of such a smooth transition between surface and crown fire regimes in the experimental data but rather an abrupt transition is observed far more commonly. In our context, however, where the main aim is to produce a forecast risk and not to simulate an individual fire we consider that it is important to reflect the fact that the fire conditions are close to generate an active crown fire.

For a more in-depth discussion of the crown fire models please read Cruz et al (2010) Scott et al. (2006)

Wind adjustment factor

Fire simulations require wind speed at midflame to compute surface fire spread and at 20ft to compute crown fire characteristics. To convert the wind between the two heights, WFA uses the wind adjustment factor (WAF) found in Andrews (2012) and implemented in the software BehavePlus and Farsite. The model is based on the work of Albini and Baughman (1979) and Baughman and Albini (1980), using some assumptions made by Finney (1998). This implementation considers two different models for sheltered and unsheltered conditions from the overstory. As described in Andrews (2012), the unsheltered WAF is based on an average wind speed from the top of the fuel bed to a height of twice the fuel bed depth. The sheltered WAF is based on the assumption that the wind speed is approximately constant with height below the top of a uniform forest canopy. Sheltered WAF is based on the fraction of crown space occupied by tree crowns. The unsheltered WAF model is used if crown fill portion is less than 5 percent. Midflame wind speed is the 20-ft wind multiplied by the WAF.

Unsheltered WAF depends on the surface fuel bed depth (in feet):

$$WAF = \frac{1.83}{\ln ln\left(\frac{20+0.36H}{013H}\right)}$$

Sheltered WAF:

$$WAF = \frac{0.555}{\sqrt{fH}*\ln ln\left(\frac{20+0.36H}{0.13H}\right)}$$

With H, the canopy height, and f ,the crown fill portion, depending on the canopy cover (CC) and the crown ratio (CR):

f = CC*CR / 3

CR = (CH-CBH) / CH

CR is the ratio of the crown length to the total height of a tree.

Time evolution

The fire models can predict the potential ROS of the front at any point and direction but are not able to compute the evolution of the fire perimeter in time. The main models to do that are:

1) Using Huygens principle of wave propagation like in Farsite (xxx) and discretizing in time
2) Using a Minimum Travel Time Algorithm or Fast Marching method, and discretizing in space
3) Using the more general but usually slower Level Set Method.

In the context of wildfires, Huygens principle states that each point on a fire front is in itself the source of an elliptical wavelet (fire) which spreads out in an independent way in the forward direction. This approach is numerically solved by splitting the perimeter into a set of nodes, computing the evolution of those nodes in the direction normal to the perimeter based on the ROS given by the propagation model and a given time steps, and then reconstructing the front based on the position of the transported nodes. The main weakness of vector-based approaches is the need for a computationally costly algorithm for generating the convex hull fire-spread perimeter at each time step, especially in the presence of fire crossovers and unburned islands (Ghisu et al. 2014). Raster based implementations are computationally more efficient (Glasa et al. 2008), but can suffer from significant distortion of the produced fire shape if the number of neighboring cells considered (number of possible spread directions) is low.

Spotting

Wildfires can create powerful updrafts which launch burning firebrands into the atmosphere, these firebrands are then carried horizontally by the wind landing some distance downwind from the source and creating a new ignition. Due to its unpredictable nature, fire-spotting modeling, here, is considered through a statistical approach.

Encroachment

Encroachment is a critical component in the WFA fire modeling simulations as it affects the number of buildings, assets, facilities and population impacted. It does not have a relevant effect on other impact metrics. To take advantage of enhanced algorithms for spread encroachment using adjacent fuels and fire behavior data, the non-burnable (and especially urban) fuel classification needed to be updated to provide better granularity and characterization of the type of urban/WUI. Accordingly, to test these methods an enrichment of the current fuels data was developed by Technosylva to delineate urban fuels into different types of urban and also a level of density of buildings. This enhancement of the basic Scott and Burgan fuel models is used in combination with enhanced encroachment algorithms to more accurately calculate potential impacts to buildings and population.

Urban areas have been classified into classes depending on their structure (roads, urban core, isolated, sparse) and their surrounding fuels, characterized as high versus low fire behavior fuels). Specific encroachment factors can then be applied to each grouping.

Spark Modeling

Electrical failures can cause sparks and produce an ignition meters away from the asset location. To take this into account, the WFA allows the ignition point location to be displaced if the underlying vegetation type is either non-combustible or WUI. This displacement is in the direction of the wind and is proportional to the wind speed. The displacement distance and wind speed algorithm has been developed using expert opinion from electric utility engineers familiar with asset failure and ignition probability.

Weather

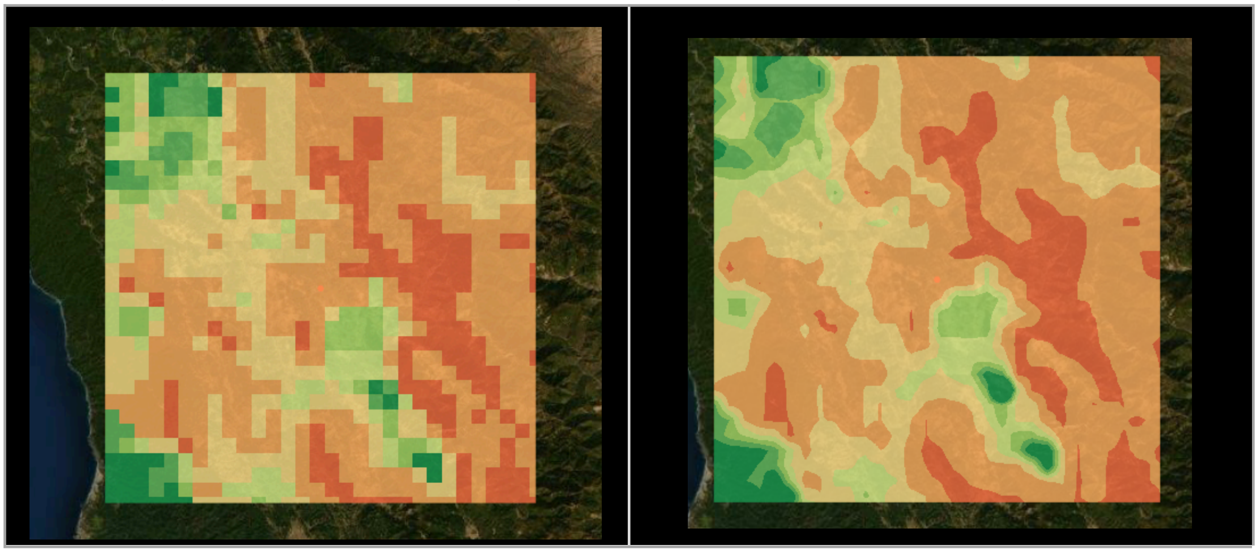
WFA requires historical daily weather data to run the fire simulations. The minimum required variables are the wind speed at 10m, the dead moisture content, and the live moisture content. More explicitly:

- Northward 10m wind speed
- Eastward 10m wind speed
- Dead moisture content 1hr
- Dead moisture content 10hr
- Dead moisture content 100hr
- Herbaceous moisture content

- Woody moisture content

The dead moisture may be given by the client or may be computed based on the Nelson model. Similarly, the herbaceous moisture content may be provided by the client or may be computed using Technosylva's Machine Learning algorithm based on historical NDVI weather reading. The Technosylva DFM model has been developed to meet customer needs using the latest modeling approaches. The input wind speed required by the propagation model is 20ft; to convert the initial 10m wind speeds to 20ft, we use a logarithmic profile from Andrews (2012) leading to a 13% wind speed reduction.

Weather data is obtained from the Weather Research and Forecasting (WRF) Model weather forecast data. The forecast weather has a 2 km resolution which can lead to sharp changes in weather conditions between neighboring cells. In order to increase accuracy and meet the underlying 30m cell size resolution of the fuels data, weather data is interpolated spatially using a bilinear interpolation scheme. The smoothing of the source weather data ensures that integration with the wildfire behavior models results in outputs that do not have hard edges in the data.



Left: Initial weather definition. Right interpolated weather definition

Impact and consequence value calculation

Wildfire spread modeling is undertaken with asset ignition locations to derive potential impacts. The output impact values (risk metrics) are assigned back to the asset ignition point location. Using this approach allows us to differentiate between the risk output associated with different assets (and their ignition locations) using the same weather data although weather values may vary based on spatial location and time of day (hourly). For both operational and mitigation applications, the wildfire spread modeling is conducted using High Performance Computers (HPC) and typically involves hundreds of millions of spread simulations. The amount of simulation will vary depending operational use with daily forecasts versus mitigation planning use with hundreds of weather scenarios.

The main goal for the WFA simulations is to create a forecast risk associated to each ignition point and surrounding area. This is done by running individual simulations and associating the following main risk metrics back to each ignition point. The following baseline risk metrics are calculated from the spread simulations

- Acres Burned (referred to as Fire Size Potential)
- Number of Buildings Threatened
- Estimated Number of Buildings destroyed
- Population impacted

Numerous conventional fire behavior outputs are also calculated, the most important being:

- Rate Of Spread (ROS)
- Flame Length (FL)
- Fire Behavior Index (FBI) – combination of ROS and FL

2.4.4 Limitations (see Guide ASTM E 1895)

Identified the limitations of the model based on the algorithms and numerical techniques.

The Technosylva WFA platform Is an integration of numerous speciality models designed to address specific scientific requirements and methods.

The following assumptions applied to the models used in WFA:

- The physical framework development is based on an idealized situation in steady state spread
- Rate Of Spread at a point only depends on the conditions at that point (point-functional models). This means that there is no increase in speed due to non-local contributions of the fire front.
- Fire model is not directly coupled with the atmosphere. Fire will not modify local atmosphere. However, this is being addressed with seamless integration with the WRF-SFIRE model in development at San Jose State University, Wildfire Interdisciplinary Research Center. WRF-SFIRE is an option available to WFA customers to address specific convection based fire scenarios.
- Fire is always assumed to be fully developed with fire acceleration, flashover, or decay not being considered.
- Atmospheric instability, which may have a deep impact on ROS (Beer 1991), is not considered in the model in any way.
- Gusts are not considered in the model
- No interaction between slope and wind other than creating an effective or equivalent wind. This means that fire is assumed to have an elliptical shape no matter the alignment of wind and slope.
- Experimental data is scarce and the empirical adjustment of models have been based on wind tunnel experiments and a few well documented fires
- Fuel array description of the vegetation may not perfectly describe fuel characteristics.
- Spotting is only considered in surface fires

2.5 Data Libraries

Provide background information on the source, contents, and use of data libraries.

This section provides a brief summary of the key input datasets required for wildfire behavior analysis and risk analysis. The following categories of input data are:

1. Landscape characteristics
2. Weather and atmospheric data

3. Fuel moisture
4. Values at risk (highly valued resources and assets)
5. Possible ignition sources
6. Fire activity

2.5.1 Landscape Characteristics

This includes a range of possible data that describe the characteristics of the landscape. The most important data are related to surface and canopy fuels, and vegetation. There are many publications available that describe these datasets, many from the USFS Missoula Fire Lab. Most use the Scott & Burgan 2005 Fuels Model Set standard for classification of fuels data.

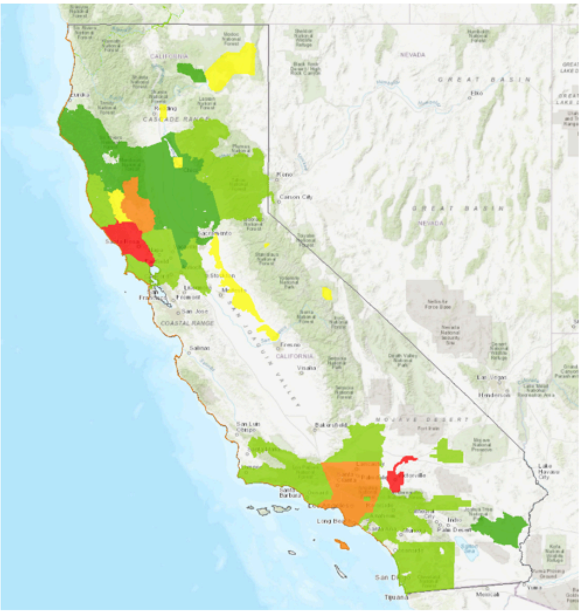
Standard fire behavior analysis input layers are:

1. Terrain – elevation, slope, aspect
2. Surface fuels (Scott & Burgan 2005)
3. Canopy fuels
   a. Canopy height
   b. Canopy base height
   c. Canopy bulk density
   d. Canopy closure
4. WUI and and Non Forest Land Use classes (Technosylva, 2020)

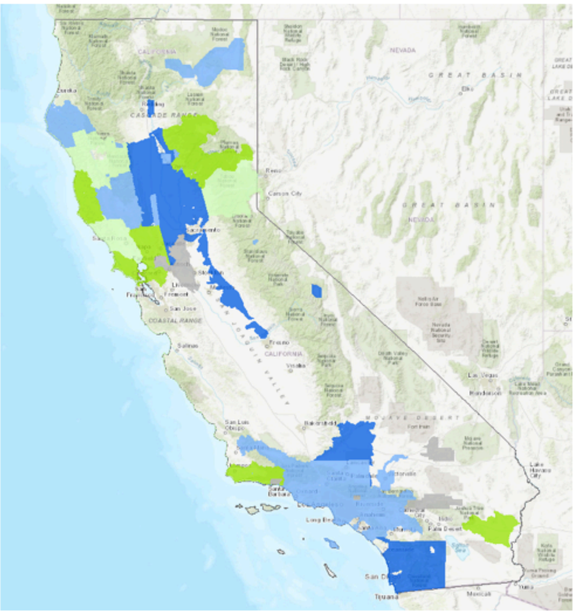
2.5.2 Surface and Canopy Fuels

For these layers, data developed by Technosylva is used. Technosylva provides an annual fuel updating subscription where initial fuels is developed using advanced remote sensing object segmentation methods using high resolution imagery, available LiDAR & GEDI, and other standard imagery sources, such as NAIP , Sentinel 2 and Landsat. This is supplemented with in-the-field surveys to verify the fuels for possible areas of concern and to validate the fuels classification. Surface and canopy fuels data is critical for accurate fire behavior modeling, so it is paramount that this data is up-to-date, and when used, results in the observed and expected fire behavior.

Survey Date



Point Cloud Density



Survey Date

- 🟩 2019
- 🟩 2018
- 🟨 2017
- 🟧 2016
- 🟥 2013

Summary

- 2019 → 14,906,880 ac
- 2018 → 26,874,880 ac
- 2017 → 4,423,040 ac
- 2016 → 6,377,600 ac
- 2013 → 2,319,360 ac

Point Cloud Density (point/m2)

- 🟦 0 - 5
- 🟦 5 - 10
- 🟩 10 - 15
- 🟩 15 - 30
- ⬜ Unknown

LIDAR Data used for Technosylva Fuels 2021, with capture date and points density

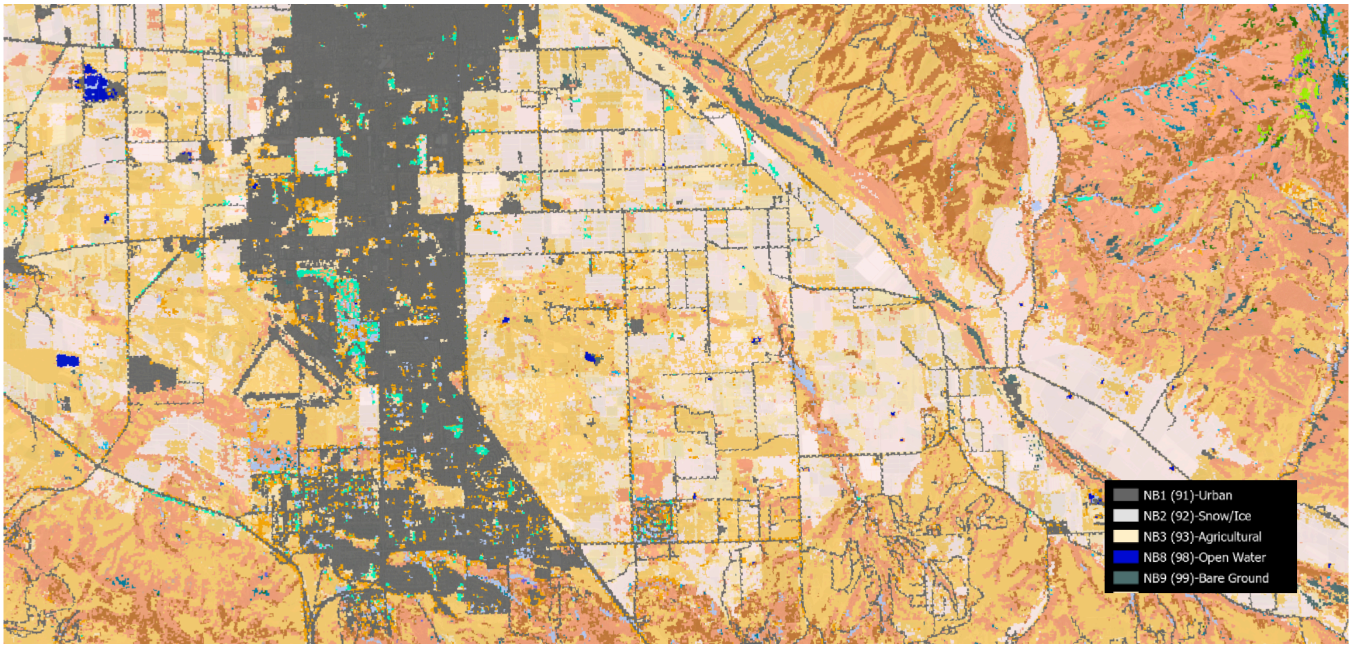
Surface and canopy fuels are updated throughout the year, to accommodate changes to the fuels, typically monthly during fire season. This ensures that all major disturbances, such as fires, urban growth, landslides, etc. are updated in the fuels data. A variety of methods, including burn severity analysis, are used to update the fuels. Up to date fuels data is critical to ensuring the fire behavior outputs from our modeling are accurate, as it is a key input into risk analysis.

Technosylva continually tests new fuels datasets that become available from other sources, such as LANDFIRE, federal risk assessment regional projects, and independent sources, such as the California Forest Observatory data. Unfortunately, the publicly available data does not perform at the level required when confronted with operational testing. In general, these publicly available data do not result in fire behavior outputs that facilitated accurate predictions. Ultimately with any fuels dataset, the quality and accuracy of the fuels is measured on whether it produces ‘observed and expected fire behavior’. Fortunately, Technosylva is able to test this data, and other fuels data including their custom data, operationally on a daily basis with CAL FIRE and the IOUs against active wildfires to see how it performs.

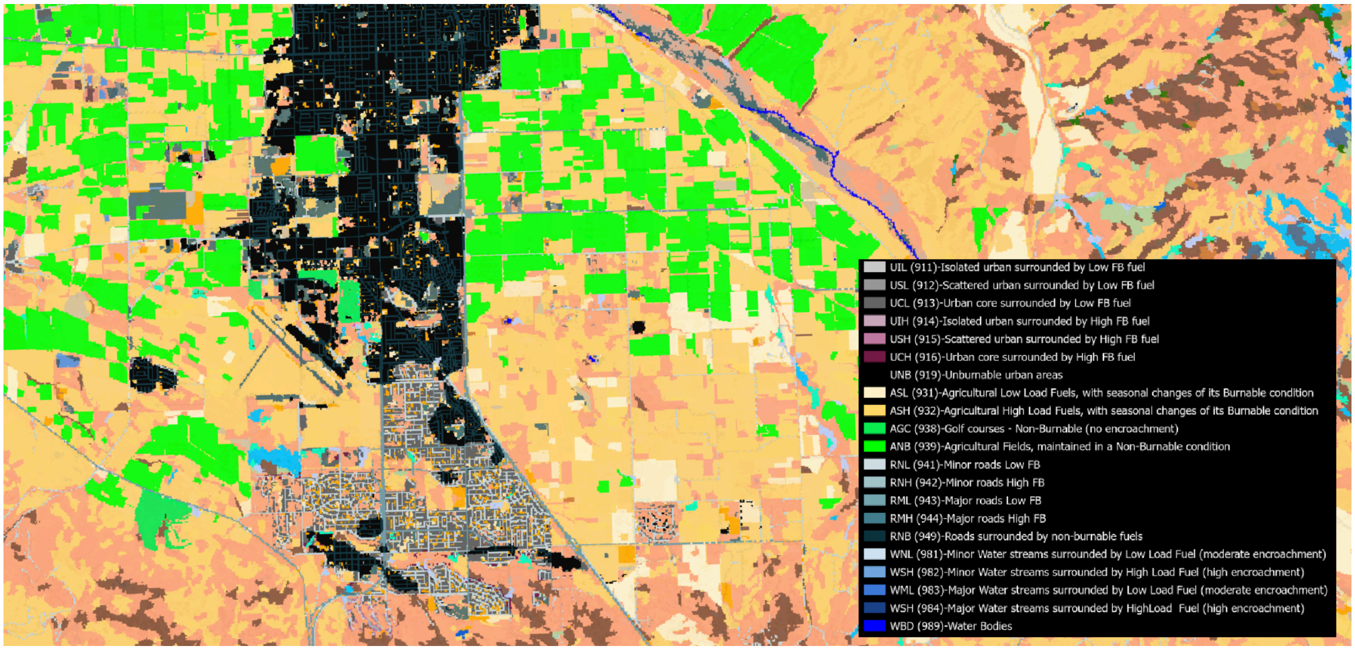
Updates to the fuels, and algorithms that use the fuels data for fire behavior modeling are on-going with us, as we continue to enhance the data and algorithms to match observed fire behavior across the state. These methods and algorithms are proprietary.

WUI and Non-Forest Fuels Land Use classes are based on a Technosylva proprietary method that characterizes WUI and other land uses classes that have been a typical limitation of the Scott and Burgan classification, as they are defined in general non burnable classes. In combination with the Surface Fuels, this provides a solid foundation for fire behavior and impact analysis.

The following two figures present an example of publicly available LANDFIRE data commonly used for fire modeling, and the custom Technosylva fuels used.



LandFire Fuels – Non Burnable Classes



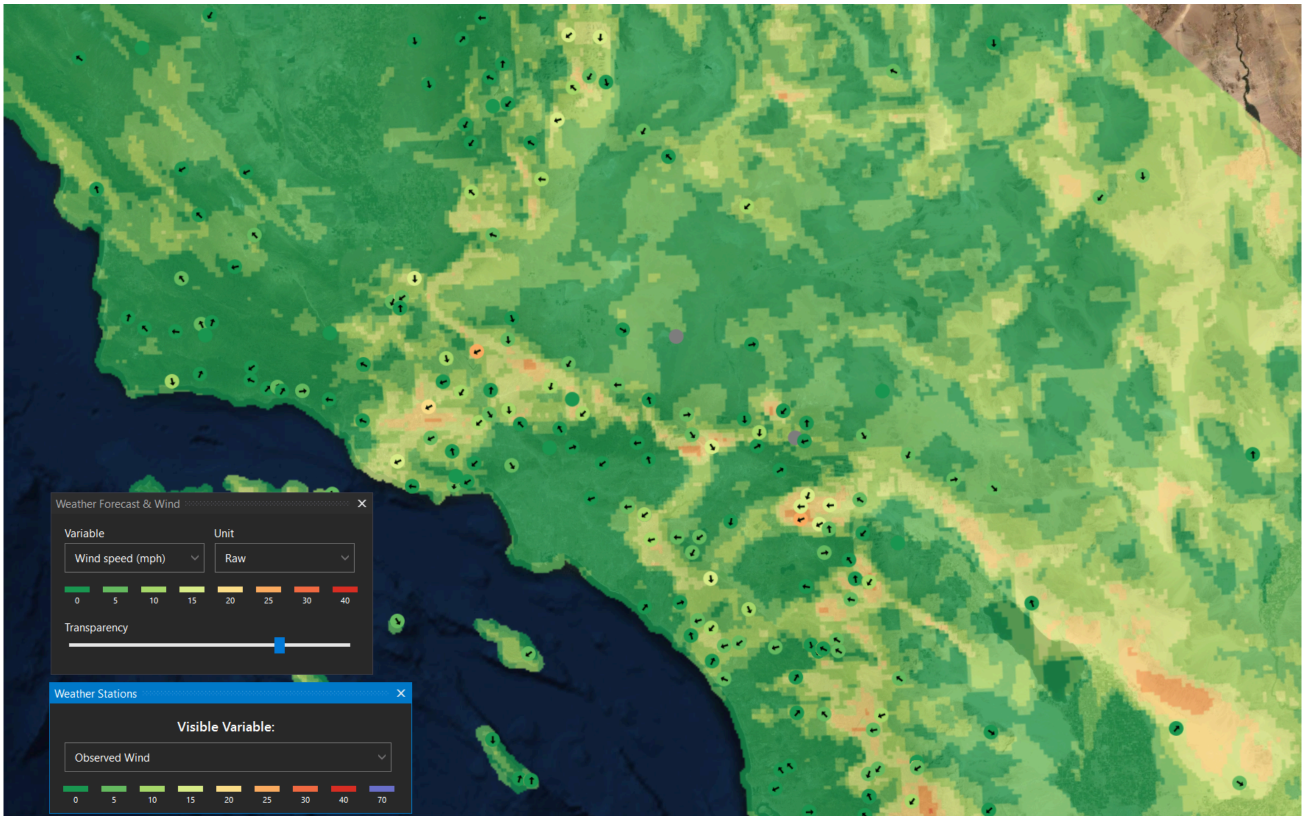
Technosylva Fuels Dec 2021 – WUI and Non-Forest Fuels Classes

2.5.3 Weather and Atmospheric Data

WRF data is developed using third party weather and predictive services experts available through commercial providers. Data is 2 km spatial resolution and hourly (temporal) for a multi-day period, up to five+ days. Multiple forecasts are generated daily.

Weather observation data can also be used along with, or independently, to support fire behavior analysis. This data is typically available through published weather stations on MesoWest, or through commercial providers, such as Synoptic. The methods of how this data can be integrated within the Technosylva software and processes is proprietary.

The following figure shows a typical 2km WRF model of wind speed overlaid with weather stations data (WFA software example).



Variable: Wind speed (mph)
Unit: Raw

Visible Variable: Observed Wind

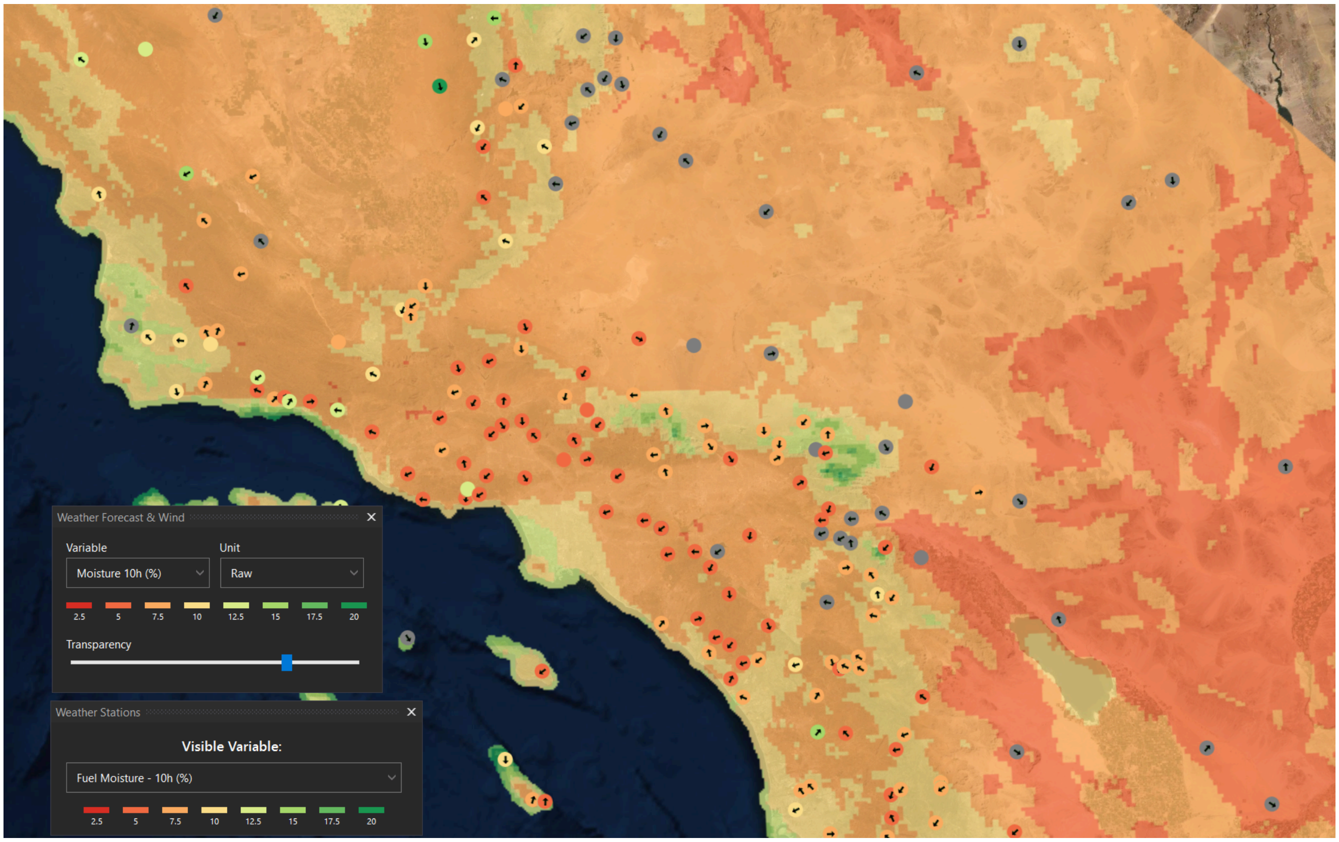
Predicted (WRF model) and Observed Wind (Weather Stations, Synoptic)

2.5.4 Fuel Moisture

Fuel moisture data is also a key input into fire behavior modeling. Fuel moisture can be characterized as either Dead or Live fuel moisture. Standard methods for measuring and quantifying fuel moistures are well documented in publications by the USFS Missoula Fire Lab and other research agencies.

However, to date the ability to accurately predict live and dead fuel moistures at high resolution has been limited. Only a few IOUs and commercial vendors are producing daily estimates that can be integrated into fire modeling. Technosylva produces both a dead and live fuel moisture data product that combines historical and current sample data with remotely sensing imagery in a machine learning model to estimate daily data products. These methods are proprietary although they are substantiated with several publications and on-going collaboration between the IOUs, Technosylva and fire weather and behavior research agencies. This fuel moisture data product is used by CAL FIRE and several IOUs across seven western US states.

The following figure shows the Technosylva Dead Fuel Moisture overlaid with weather stations data (WFA software example).



Variable: Moisture 10h (%)

Unit: Raw

Visible Variable: Fuel Moisture - 10h (%)

Predicted (WRF model) and Observed 10-hr Fuel Moisture (Weather Stations, Synoptic)

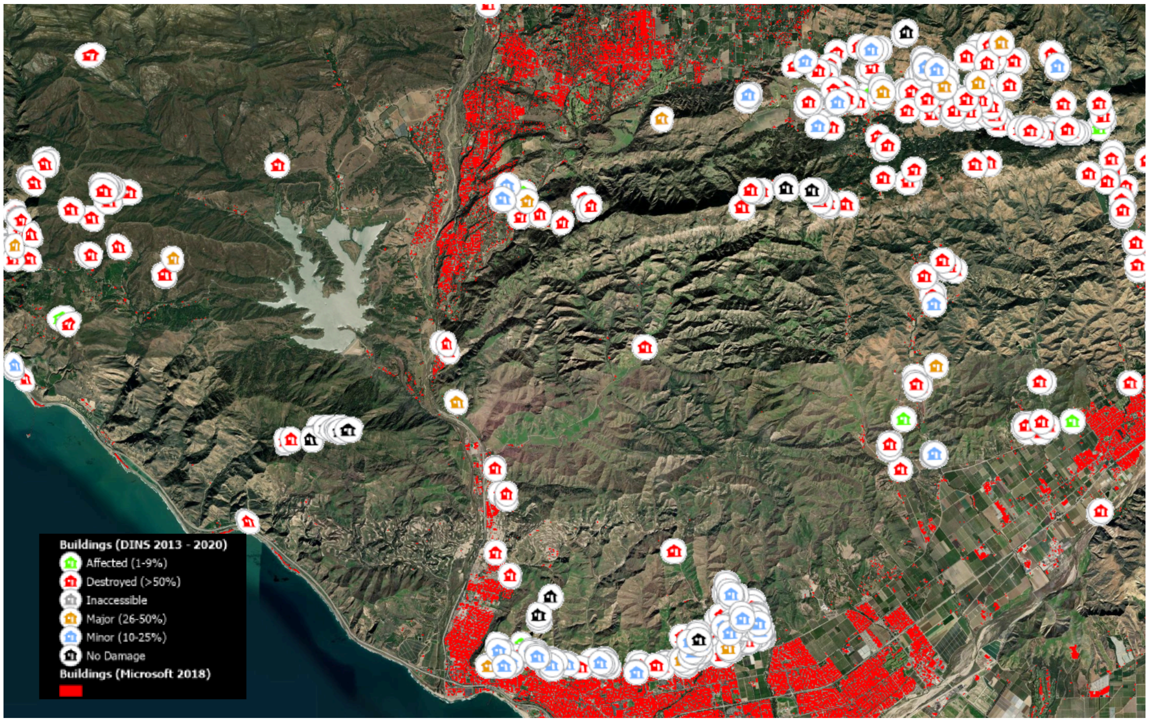
2.5.5 Values at Risk

Values-at-Risk data reflects the resources and assets that exist across that landscape that we are concerned about. Typically, ‘resources’ refers to natural items while ‘assets’ refers to man made items. Wildfire modeling is used to identify the “risk” associated with resources and assets, with risk representing the possibility of loss or harm occurring due to wildfire.

VAR data is typically characterized into public safety or financial impacts. Technosylva IOU customers use similar input datasets for VAR, such as population count (location), building footprints, and critical facilities. A variety of datasets exist to define the location and characteristics of these VAR, each with varying temporal and spatial accuracy. Census data is a common source for population data along with ORNL LandScan data (population count). LandScan has become a de facto standard for static wildfire risk assessments across the Nation in the past 10 years. It is available through the Dept. of Homeland Security HSIP program for certified vendors of government agencies, or the agencies themselves. It is typically updated every 2 years with a 90 meter spatial resolution of population count. Technosylva currently uses the latest 2021 LandScan data for calculating population impacts.

The Microsoft Buildings Footprint dataset is a publicly available free data source used as a starting point by many vendors and agencies. Technosylva has taken this data and updated it using local high resolution imagery data sources to enhance the data. The original Microsoft data is a good starting point, however it does have holes with missing data and some misrepresentation of buildings with natural features. This data was updated in 2020 by Microsoft. This provides the primary source for the buildings data used by Technosylva.

Population and buildings are the two primary datasets used as input into wildfire risk analysis, although most IOU customers add confidential data to derive more detailed consequence metrics. These are proprietary to the IOUs and cannot be shared by Technosylva.



Buildings (Microsoft 2020) and Damaged Inspections data (DINS) from CAL FIRE

2.5.6 Possible Ignition Sources

Wildfire ignition data varies greatly depending on the organization and purpose of the wildfire risk analysis. Traditionally, agency driven risk assessments will use historical fire location data to create Historical Fire Occurrence datasets, reflecting ignition density over a specific time period. This data is obtained from federal and state fire reporting systems.

IOUs are often concerned with using their assets as possible ignition sources, in equipment failure scenarios or extreme weather events, where a spark from an electric utility asset may cause a fire ignition. Risk can be assessed related to the probability of ignition for electric utility assets, or more commonly with the potential spread and impacts of a wildfire ignited by an asset. Technosylva provides integration of both ignition and spread analysis to derive risk metrics using VAR data. This focuses on assigning possible consequence back to the electric utility assets to identify those assets more prone to having significant impacts should a wildfire ignite. Different proprietary methods exist to integrate and model probability of ignition data for electric utility assets with consequence modeling. Referred to as “asset wildfire risk” this information can be used to support operational decisions, such as PSPS, resource allocation and placement, and stakeholder communication, in addition to short and long term mitigation planning efforts, reflected in IOU WMPs. The weather and fuels inputs will vary depending on the purpose of these risk analyses.

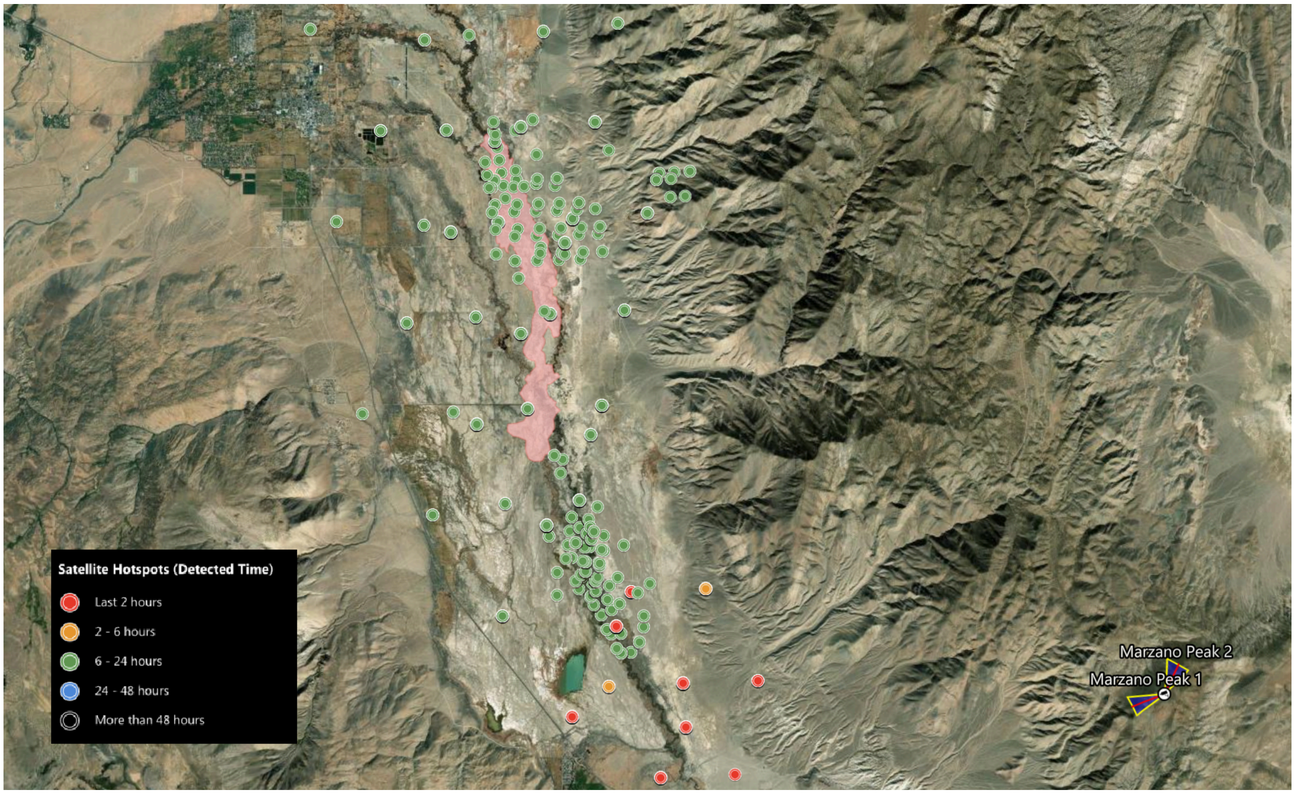
IOUs and agencies are also concerned with non-asset wildfire ignitions and the risk associated with these ignitions due to possible spread and potential impacts. Technosylva has developed proprietary methods for deriving territory wide risk that integrates millions of possible ignition points with wildfire spread modeling to derive standard risk outputs, similar to “asset risk” metrics. These output metrics vary greatly depending on the customer and purpose for using the risk data. The methods and outputs are proprietary.

2.5.7 Fire Activity

The fire activity data used to support operational situational awareness is captured from different sources:

- VIIRS and MODIS Satellite hotspots, from public sources (FIRMS)
- GOES 16 and 17 data based on agreement with providers to the IOUs
- Lighting data also from IOU’s providers
- Fire Perimeters from Open Wildfire data from NIFC
- Fire activity from National Guard data from Fire Guard program
- Alert Wildfire Cameras integration

The following figure shows an example of Fire Activity data integrated into the Technosylva WFA system. All data is temporal and displayed color coded based on a selected time from the software timeline.



Hotspots, Fire Perimeters and Alert Wildfire Cameras

2.5.8 Summary of Input Data Sources

The following table presents a summary of the data sources used in the wildfire risk analysis. Some data varies slightly depending on mitigation versus operational use.

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
Landscape Characteristics				
TERRAIN	10	YEARLY		USGS
SURFACE FUELS	30/10	PRE FIRE SEASON, MONTHLY UPDATE IN FIRE SEASON, END OF FIRE SEASON	2020	TECHNOSYLVA
WUI AND NON FOREST FUELS LAND USE	30/10	TWICE A YEAR	2020	TECHNOSYLVA
CANOPY FUELS (CBD,CH,CC,CBH)	30/10	PRE FIRE SEASON, MONTHLY UPDATE IN FIRE SEASON,	2020	TECHNOSYLVA

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
		END OF FIRE SEASON		
ROADS NETWORK	30	YEARLY		USGS
HYDROGRAPHY	30	YEARLY		USGS
CROPLANDS	30	YEARLY	1997	USDA
Weather and Atmospheric Data				
WIND SPEED	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
WIND DIRECTION	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
WIND GUST	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
AIR TEMPERATURE	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
SURFACE PRESSURE	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
RELATIVE HUMIDITY	2000	HOURLY / 124 HOUR FORECAST	1990	TECHNOSYLVA
PRECIPITATION	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
RADIATION	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
WATER VAPOR MIXING RATIO 2m	2000	HOURLY / 124 HOUR FORECAST	1990	ADS/DTN
SNOW ACCUMULATED - OBS	1000	DAILY	2008	NOAA
PRECIPITATION ACCUMULATED - OBS	4000	DAILY	2008	NOAA
BURN SCARS	10	5 DAYS	2000	NASA/ESA
WEATHER OBSERVATIONS DATA	Points	10 MIN	1990	SYNOPTIC
Fuel Moisture				
HERBACEOUS LIVE FUEL MOISTURE	250	DAILY / 5-DAY FORECAST	2000	TECHNOSYLVA

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
WOODY LIVE FUEL MOISTURE	250	DAILY / 5-DAY FORECAST	2000	TECHNOSYLVA / ADS
1 hr DEAD FM	2000	HOURLY / 124 HOUR FORECAST	1990	TECHNOSYLVA / ADS
10 hr DEAD FM	2000	HOURLY / 124 HOUR FORECAST	1990	TECHNOSYLVA / ADS
100 hr DEAD FM	2000	HOURLY / 124 HOUR FORECAST	1990	TECHNOSYLVA / ADS

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
Values at Risk				
BUILDINGS	Polygon footprints	YEARLY	2020-21	MICROSOFT/TECHNOSYLVA
DINS	Points	YEARLY	2014-21	CAL FIRE
POPULATION	90	YEARLY	2019	LANDSCAN,ORNL
ROADS	Vector lines	YEARLY	2021	CALTRANS
SOCIAL VULNERABILITY	Plexels	YEARLY	2021	ESRI GEOENRICHMENT SERVICE
FIRE STATIONS	Points	YEARLY	2021	ESRI, USGS
BUILDING LOSS FACTOR	Building footprints	YEARLY	2022	TECHNOSYLVA
CRITICAL FACILITIES	Points	YEARLY	2021	FRAP – CAL FIRE
Potential Ignitions locations				
IOU DISTRIBUTION & TRANSMISSION LINES	Linear segments	Updated quarterly	2022	IOUs
IOU POLES & EQUIPMENT	Points	Updated quarterly	2022	IOUs
Fire Activity				
HOTSPOTS MODIS	1000	TWICE A DAY	2000	NASA
HOTSPOTS VIIRS	375	TWICE A DAY	2014	NASA
HOTSPOTS GOES 16/17	3000	10 MIN	2019	NASA
FIREGUARD	Polygons	15 MIN	2020	NATIONAL GUARD
FIRE SEASON PERIMETERS	Polygons	DAILY	2021	NIFS
HISTORIC FIRE PERIMETERS	Polygons	YEARLY	1900	CAL FIRE
ALERT WILDFIRE CAMERAS	Live Feeds	1 min	Real Time	AWF Consortium
LIGHTING STRIKES	1000	1 MIN	Real Time	EARTH NETWORKS / OTHERS

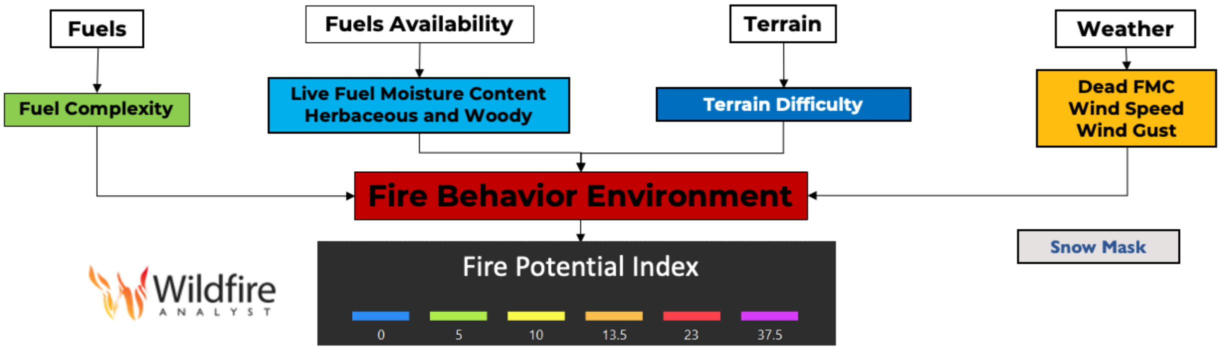
2.5.9 Fire Potential Index (FPI)

FPI quantifies the fire activity potential over the territory aiming to assist operational decision-making to reduce fire threats and risks. FPI allows agencies to easily analyze the short-term fire danger that could exist across the service territory and better communicate the wildfire potential on any given day and time, promoting safe and reliable operations.

Hexel-based (h3) FPI is a forecast product, which is produced on a daily basis, calculated every 3 hours at different h3 resolutions from level 4 to 8 (182 ac and 1km resolution approximately). One of the main advantages of this index is that it was calibrated with real fires (2012 to 2022) using VIIRS hotspots as a proxy of fire activity.

FPI estimates the expected daily number of VIIRS hotspots in a h3-hexel level 6.

FPI comprises several variables including fuels, terrain and weather:



Technosylva has integrated FPI into its operational decision-making WFA enterprise to facilitate its use operationally.

FPI promotes proactive and reactive operational measures through standard operating procedures aiming to reduce the likelihood facilities and assets will be the source of ignition for a fire when FPI is high or extreme.

FPI can be used to inform operation decisions (restrictions on the type of work being performed), as an input to PSPS decision-making and to make risk informed mitigation decisions.

Fire Potential Index products developed for electrical utilities usually include weather data: wind speed, wind gusts, and both dead and live fuel moisture content. Technosylva's FPI also includes the Fuel Complexity (fuel structure, load and age) and Terrain Difficulty. These are key inputs of the classical fire triangle that explain fire behavior.

Technosylva's Fire Potential Index (FPI) has been empirically trained and validated with real fire activity. The product is hexel-based (h3) allowing a better temporal and spatial analysis of outcomes, including the analysis by district or any administrative division.