technosylva

Wildfire Analyst™ Enterprise

MODELS & INPUTS

March 14th, 2022

Wildfire ANALYST

Table of Contents

1. MODELS USED IN WILDFIRE ANALYST™

This section provides a list of the analytical models that are implemented in Technosylva's Wildfire Analyst product line.

The Wildfire Analyst™ Enterprise propagation core is comprised of a group of fire behavior libraries developed by Technosylva. These libraries are responsible for the fire simulation, weather data processing, and the processing of the main outputs of WFA. The main models used in the implementation of Wildfire Analyst™ Enterprise are shown in the table below.

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, to run in an operational scenario that requires real-time performance and visualization in desktop, web and mobile platforms. Most Technosylva custom-developed models are supported by journal publications as part of our corporate R&D program.

All these models have their own assumptions and limitations, as described in the original papers that are cited in Section 3. References[1]. As an example, the Surface Fire Propagation Model by Richard Rothermel (1972) is limited to surface fire and does not account for heat release due to combustion. The three-dimensional coupled effects that may happen on more extreme fires may be captured by other models such as WRF-SFIRE.

Also, Technosylva has implemented other models in the WFA-E platform, such as the Canadian Forest Fire Behavior Prediction Model, the Chilean Kitral model, and some of the Australian Models, as MacArthur, not included in this description, as it is more focused on the U.S. and European implementations.

Model	Model Reference	Notes
Surface Fire Propagation	Rothermel 1972, Albini 1976 Kitral IntecChile FBP, Canada	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 other countries, i.e., Chile, Canada, etc.
Coupled Fire Atmospheric Propagation	Mandel, Beezley & Kochanski 2013	WFA has integrated the Fire Atmospheric Coupled WRF-SFIRE model in collaboration with SJSU Fire Weather Lab in 2022
Surface Fuel Models	Rothermel 1972, Albini 1976, Scott & Burgan 2005	WFA supports both accepted surface fuel models, i.e., 1972 thirteen fuel models, and the more recent and readily used 2005 forty fuel models. Custom fuels models can also be defined to meet specific landscape

[1] For a comprehensive explanation of the Wildland Fire USFS RMRS models, we recommend a review of the synthesis by Patricia L Andrews (2018) "The Rothermel surface fire spread model and associated developments: A comprehensive explanation", available at https://www.fs.usda.gov/treesearch/pubs/55928

Model	Model Reference	Notes
		characteristics if desired. For example, Technosylva commonly delineates more classes for non-burnable fuels to support advanced urban encroachment algorithms requiring finer resolution data.
Time Evolution	Technosylva (Monedero, Ramirez 2011)	Minimum Travel Time algorithm with 12 degrees of freedom, 4 of which are automatically selected.
High Definition Wind	Forthoffer et al (2009)	High resolution wind model through obtained from the integration of the USFS WindNinja third party software. Note Technosylva is also the contractor for the USFS Fire Sciences Lab for the on-going enhancement and customization of the WindNinja software.
Wind Adjustment Factor	Andrews, 2012	
Fire Shape	Anderson 1982, Farsite (2004)	
Moisture Content	Rothermel1983)	
Crown Fire	Scott & Reinhardt 2011	As used in Behave. 0-Surface Fire: Fire spreads through the surface fuels that may include litter, grass, shrubs, and dead twigs. Surface fuels are generally defined to be less than about 6 feet (1.8 meters) deep. 1-Passive Crown Fire (Torching): Fire spreads through the surface fuels, occasionally torching overstory trees. Spotting may increase the spread rate, but the overall spread rate may be the same as the surface fire spread rate. 2-Conditional Crown Fire: A fire cannot transition into a crown fire in this area, but active crown fire is possible if the fire transitions to the overstory outside the area and burns into the canopy. 3-Active Crown Fire: Fire spreads through the overstory tree canopy.
Firebreaks	Technosylva (Monedero, Ramirez 2011)	This custom model can utilize firebreaks width in landscape units and hence is not based on data the cell size. This is a significant enhancement over previous methods.
Probabilistic Mode	Technosylva (Monedero, Ramirez 2013)	Inspired by the USFS Fire Sciences Lab FSPro software, Finney 2012.

Model	Model Reference	Notes
Adjustment Mode	Technosylva (Monedero, Ramirez 2011)	Allows for adjustment of ROS factors based on in-the-field fire observations. This allows the propagation model to continually adjust to match what occurs in the field resulting in more accurate simulation outputs. Described in Ramirez et al 2011, Cardil et al 2019.
Reverse Mode	Technosylva (Monedero, et al 2015)	Ability to calculate the propagation mode backwards in time based on a final perimeter to show fire progression and ignition location.
Evacuation / Exposure Mode	Cova (2005) Technosylva (Monedero, et al 2011)	Estimate fire arrival time from any point (i.e. asset) on the map. This is typically used to identify exposure sheds for key assets or values-at-risk, showing how long until a fire would reach those assets from any direction.
MTT (Fire Paths)	Finney (2005), Flammap	Showing fire progression paths identifying the key travel routes of a fire. Based on Finney (2005) as first implemented in USFS Flammap, with enhancements on performance and real-time calculations within Wildfire Analyst.
Campbell Analysis	Campbell (2009) Technosylva (Monedero, et al 2012)	Based on Campbell's concept of Alignment of Forces implemented as a standard output in Wildfire Analyst.
Safe Separation Distance	Butler 2014	
Ignition probability	Schroeder 1969	
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 that can be parameterized by the user. Based on research publications by NIST.
Spotting	Technosylva 2019	Spotting is implemented as a random process of new ignitions ahead the main fire front. The model uses the maximum spotting distance from wind-driven surface fires developed by (Albini 1983a; Albini 1983b; Chase 1984), together with some heuristic parameters.

2. SUMMARY OF KEY INPUT DATASETS FOR WILDFIRE RISK ANALYSIS

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

This section is intended as a general summary and is not intended to be a comprehensive description of data or methods to derive key input datasets. There are numerous publications that describe the identified data. This document does not describe any detailed methods or data employed by Technosylva or its customers.

1. Landscape Characteristics

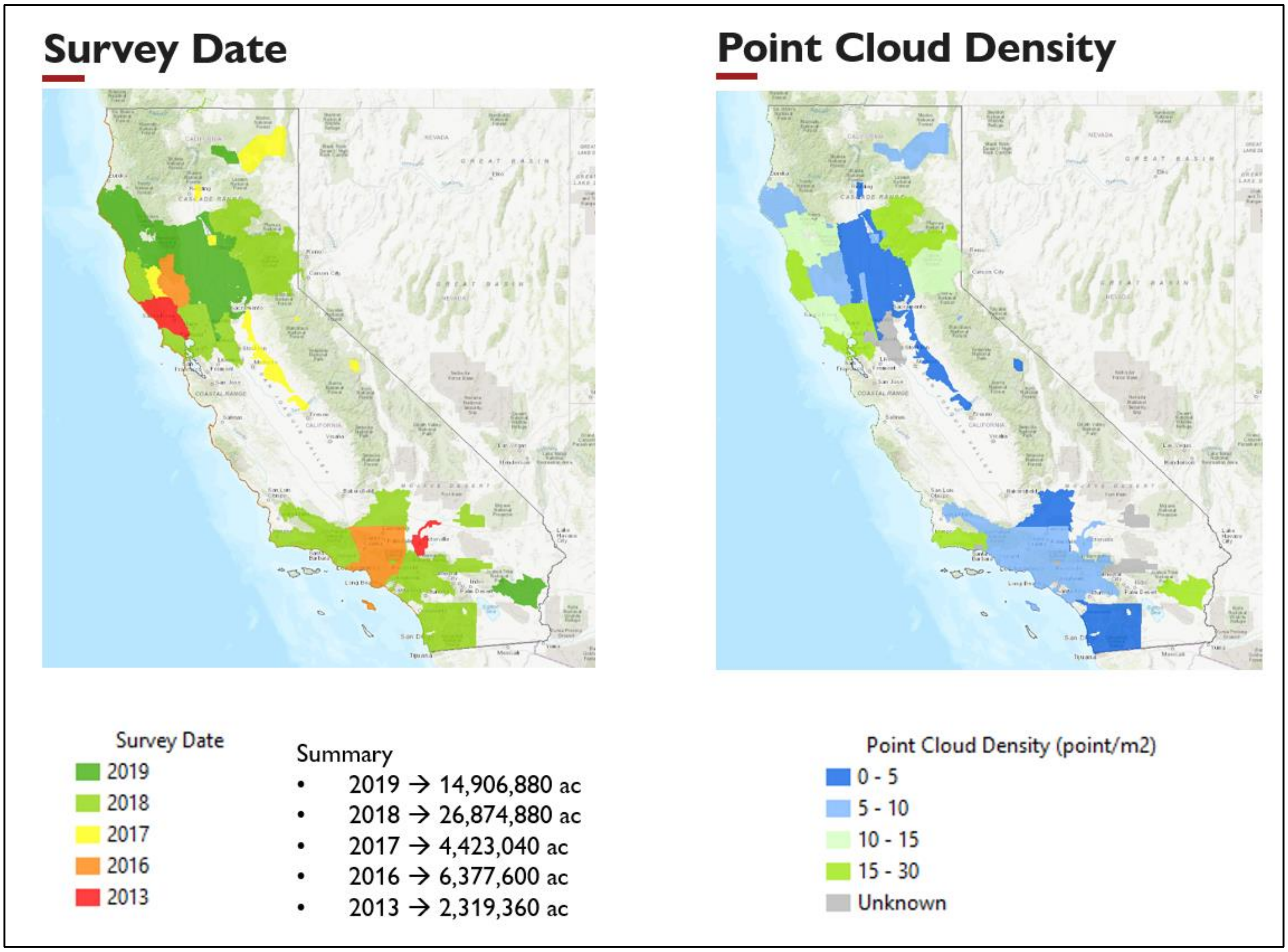
This includes a range of possible data that describe the characteristics of the landscape. The most important data are related to surface and canopy fuels, and vegetation. There are many publications available that describe these datasets, many from the USFS Missoula Fire Lab. Most use the Scott & Burgan 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 Non Forest Land Use classes (Technosylva, 2020)

Surface and Canopy Fuels

For these layers, our IOU customers use all the same source, enhanced data developed by Technosylva. We provide them an annual fuel updating subscription where we develop initial fuels using advanced remote sensing object segmentation methods using high resolution imagery, available LiDAR & GEDI, and other standard imagery sources, 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.



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.

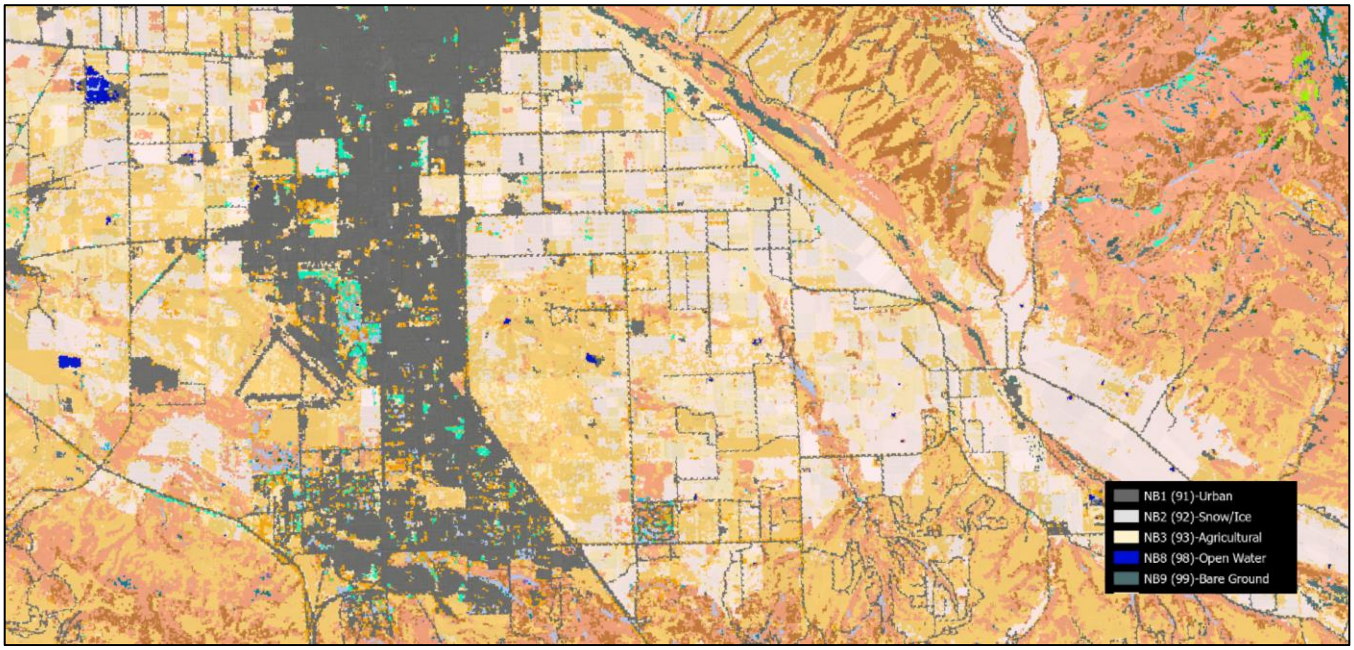
We continually test new fuels datasets that become available from other sources, such as LANDFIRE, federal risk assessment regional projects, and independent sources, such as California Forest Observatory data. Unfortunately, the publicly available data does not perform at the level required when confronted with operational testing. In general, it did 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, we are able to test this data, and other fuels data including our 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 is 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.

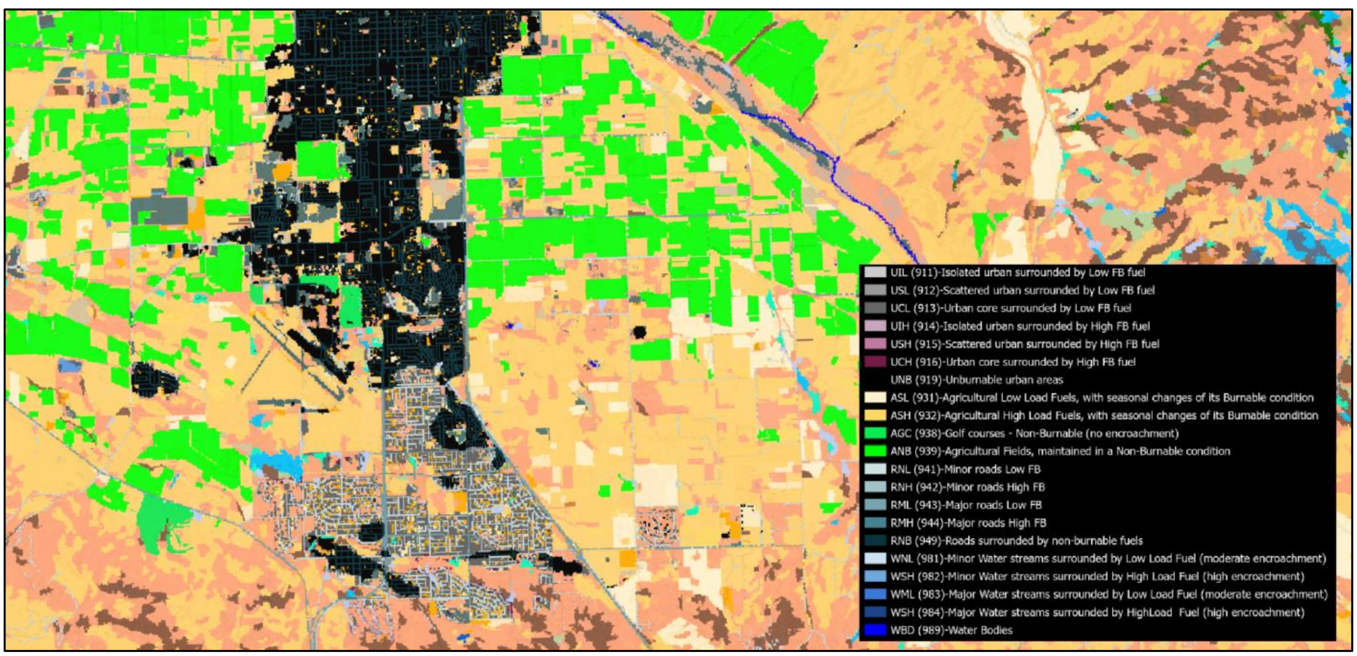
Each of our IOU customers subscribe to our fuels updating program and, in this regard, have the same source.

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. In combination with the Surface Fuels, provide 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 by our IOU customers.



LandFire Fuels – Non Burnable Classes



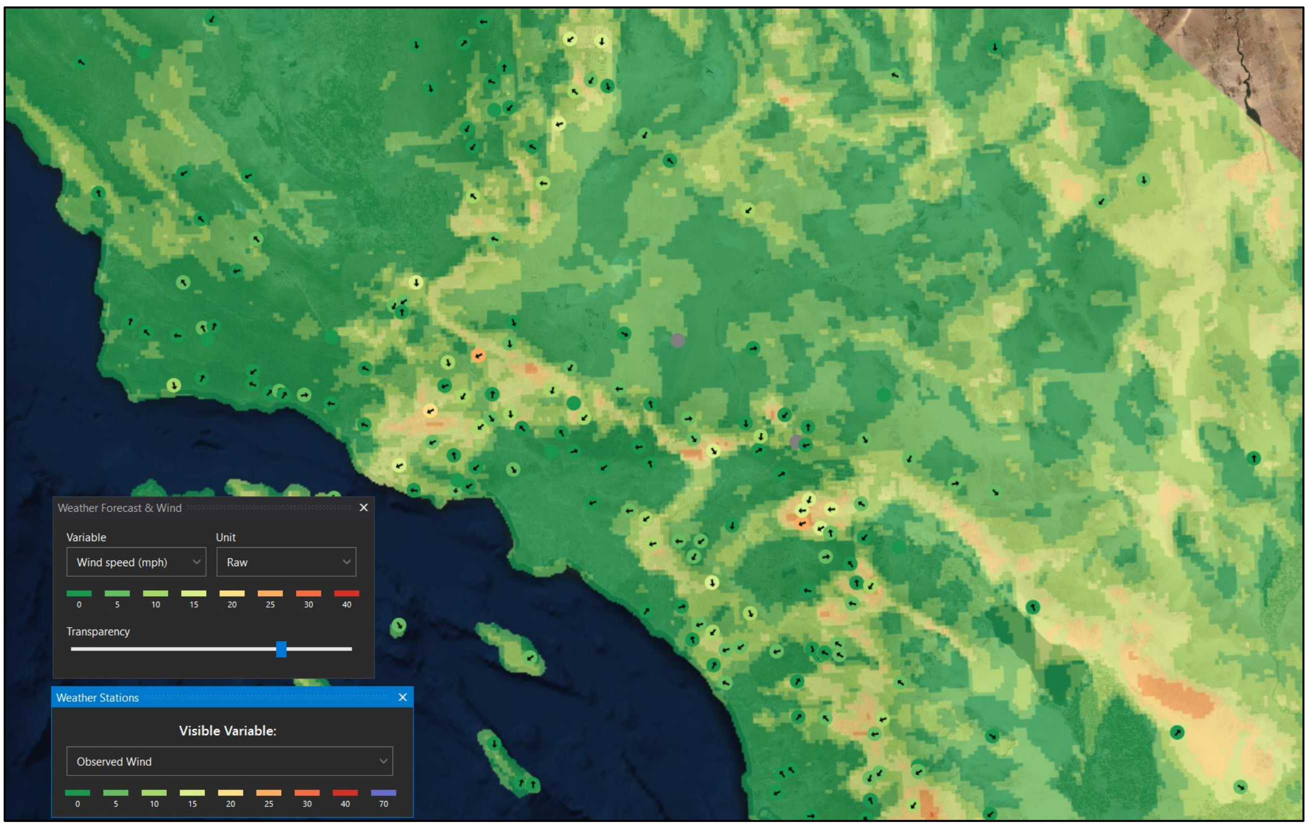
Technosylva Fuels Dec 2021 – WUI and Non-Forest Fuels Classes

2. Weather and Atmospheric Data

Each of our IOU customers produces an advanced WRF weather data prediction dataset. IOUs develop this data internally and with third party weather and predictive services experts. Typically, the data is 2 km spatial resolution and hourly (temporal) for a multi-day period, up, to five days. Multiple forecasts are generated daily. Details on the attributes and technical details of this weather prediction data should be obtained from the IOUs directly.

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-E software example).



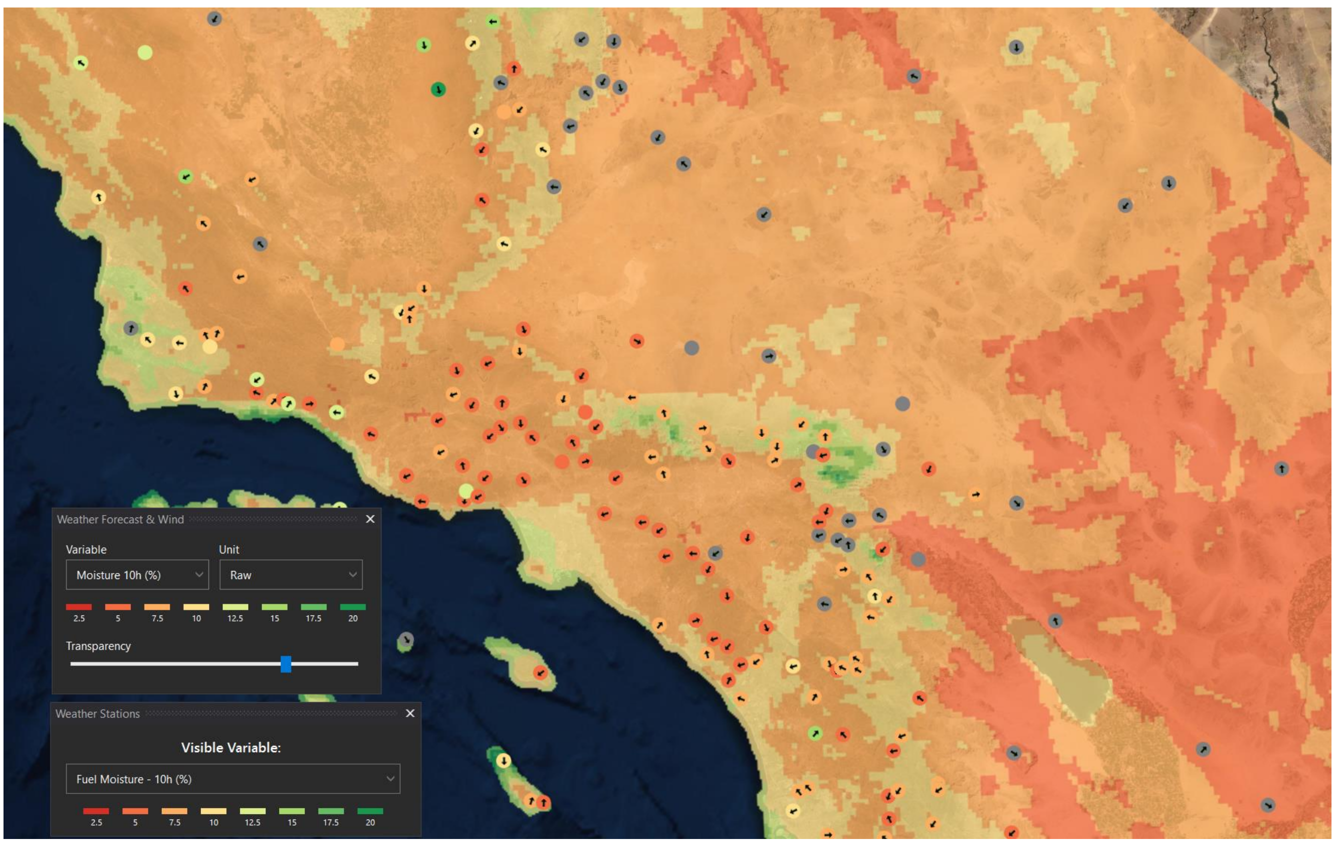
Predicted (WRF model) and Observed Wind (Weather Stations, Synoptic)

3. 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-E software example).



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

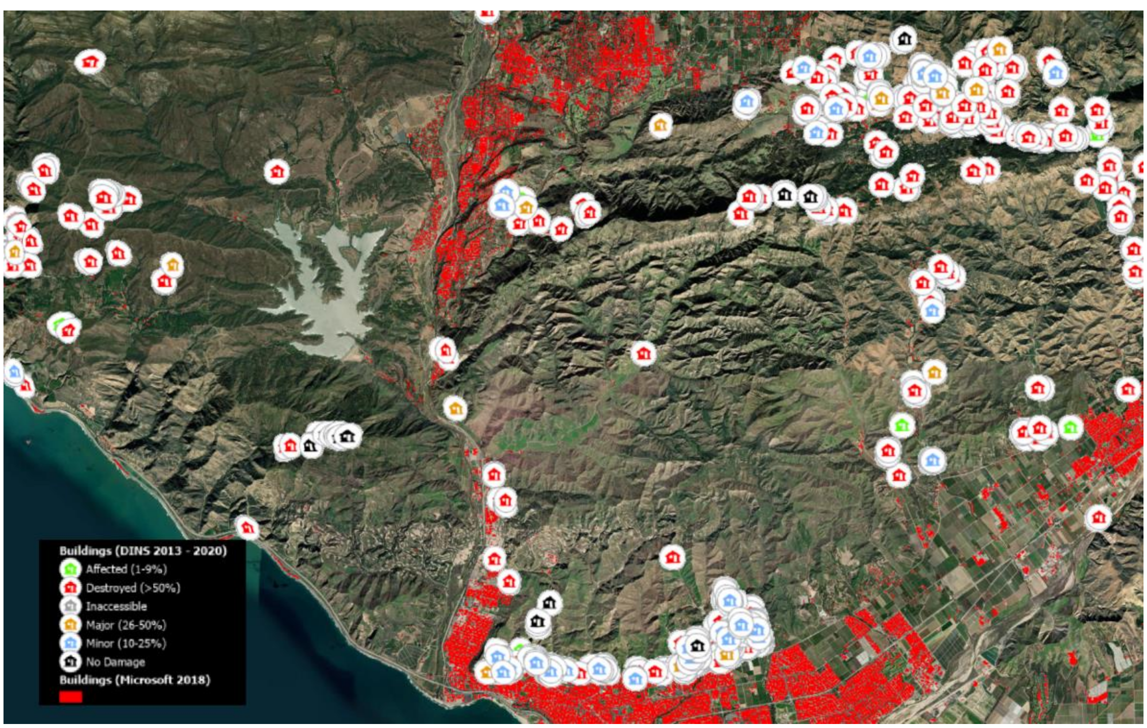
4. Values at risk (highly valued resources and assets)

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 manmade 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.

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.

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

5. 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.

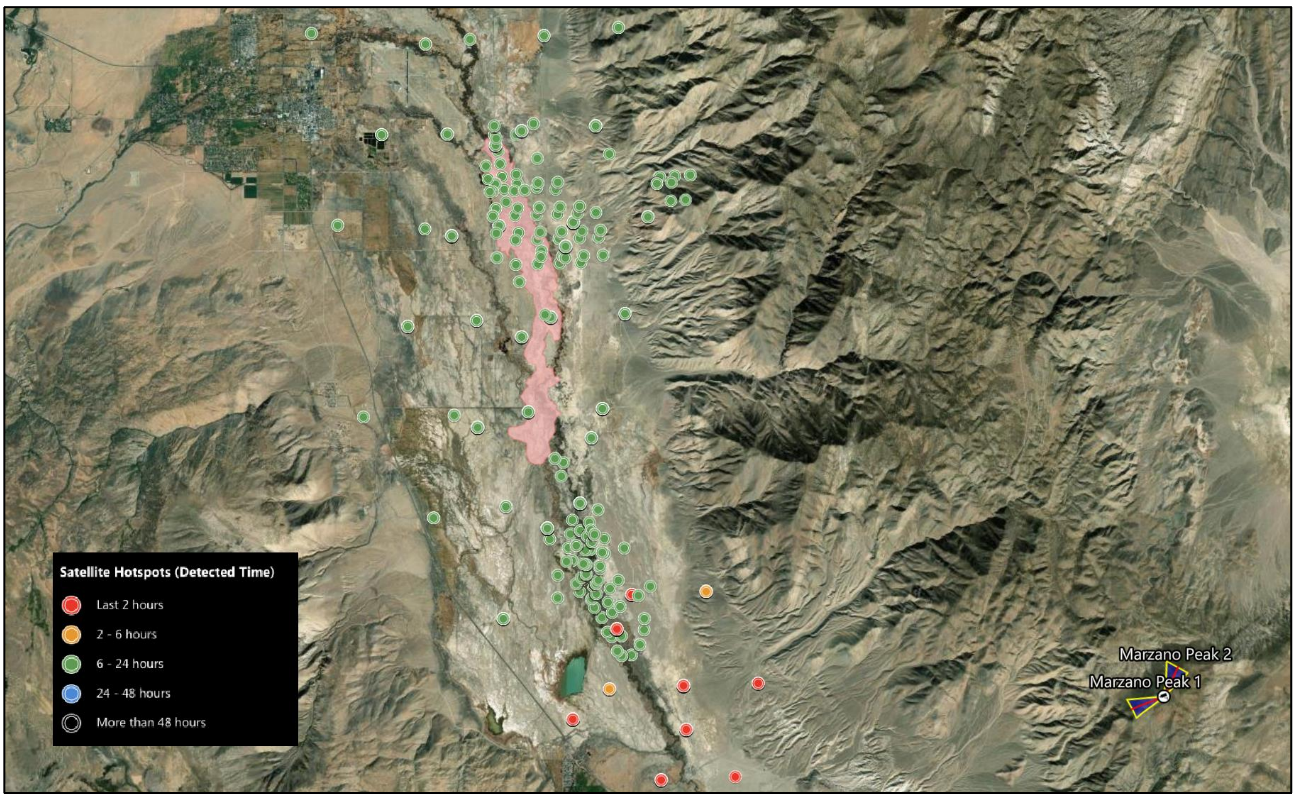
IOUs and agencies are also concerned with non-asset wildfire ignitions and the risk associated with these ignitions due to possible spread and potential impacts. Technosylva has developed proprietary methods for deriving territory wide risk that integrates millions of possible ignition points with wildfire 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.

6. Fire Activity

The fire activity 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-E 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

List of Wildfire Analyst™ Enterprise Inputs

The following table lists the inputs used in the Technosylva Wildfire Analyst™ Enterprise production environment.

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
Landscape Characteristics				
TERRAIN	10	YEARLY		USGS
SURFACE FUELS	30/10*	PRE FIRE SEASION, 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 SEASION, MONTHLY UPDATE IN FIRE SEASON, END OF FIRE SEASON	2020	TECHNOSYLVA
ROADS NETWORK	30	YEARLY		USGS
HYDROGRAPHY	30	YEARLY		USGS
CROPLANDS	30	YEARLY	1997	USDA

*Depends on customer

DATASET	SPATIAL RESOLUTION (meters)	TEMPORAL RESOLUTION	DATA VINTAGE	SOURCE
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
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

**note that data is resampled to 30 meters during modeling to eliminate edges and seamlines

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

3. REFERENCES

This section provides a list of references for wildfire behavior models including the models used in Technosylva's Wildfire Analyst Enterprise software product.

3.1 Model References

This list has been extended from Patricia L Andrews (2018) "The Rothermel surface fire spread model and associated developments: A comprehensive explanation", available at https://www.fs.usda.gov/treesearch/pubs/55928.

- Albini, Frank A. 1976a. Computer-based models of wildland fire behavior: A user's manual. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 68 p.
- Albini, Frank A. 1976b. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.
- Albini, Frank A. 1984. Wildland fires. American Scientist. 72: 590–597.
- Anderson, Hal E. 1969. Heat transfer and fire spread. Res. Pap. INT-69. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 20 p.
- Anderson, Hal E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.
- Anderson, Hal E. 1983. Predicting wind-driven wild land fire size and shape. Gen. Tech. Rep. INT-305. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 26 p.
- Andrews, Patricia L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system—BURN subsystem, part 1. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 130 p.
- Andrews, Patricia L. 2012. Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model. Gen. Tech. Rep. RMRSGTR-266. Fort Collins, CO: U.S. Department of Agriculture, Forest Service. 39 p.
- Andrews, Patricia L. 2014. Current status and future needs of the BehavePlus fire modeling system. International Journal of Wildland Fire. 23(1): 21–33.
- Andrews, Patricia L.; Queen, Lloyd P. 2001. Fire modeling and information system technology. International Journal of Wildland Fire. 10(3/4): 343–352.
- Andrews, Patricia L.; Rothermel, Richard C. 1982. Charts for interpreting wildland fire behavior characteristics. Gen. Tech. Rep. INT-131. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 21 p.

- Andrews, Patricia L.; Anderson, Stuart A. J.; Anderson, Wendy R. 2006. Evaluation of a dynamic load transfer function using grassland curing data. In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels management—How to measure success: Conference Proceedings. 2006 March 28–30; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 381–394.
- Andrews, Patricia L.; Cruz, Miguel G.; Rothermel, Richard C. 2013. Examination of the wind speed limit function in the Rothermel surface fire spread model. International Journal of Wildland Fire. 22(7): 959–969.
- Andrews, Patricia L.; Finney, Mark; Fishetti, Mark. 2007. Predicting wildfires. Scientific American. (August): 47–55.
- Andrews, Patricia L.; Heinsch, Faith Ann; Schelvan, Luke. 2011. How to generate and interpret fire characteristics charts for surface and crown fire behavior. Gen. Tech. Rep. RMRS-GTR-253. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 40 p.
- Bradshaw, Larry; McCormick, Erin. 2000. FireFamily Plus user's guide, version 2.0. Gen. Tech. Rep. RMRS-GTR-67WWW. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 122 p.
- Bradshaw, Larry S.; Deeming, John E.; Burgan, Robert E.; [et al.], comps. 1984.
- The 1978 National Fire Danger Rating System: Technical documentation. Gen. Tech. Rep. INT-169. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 44 p.
- Brown, Arthur A.; Davis, Kenneth P. 1973. Forest fire control and use. 2nd ed. New York: McGraw-Hill Book Co. 163 p.
- Brown, James K.; Simmerman, Dennis G. 1986. Appraising fuels and flammability in western aspen: A prescribed fire guide. Gen. Tech. Rep. INT-205. Ogden, UT:
- U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 48 p.
- Burgan, Robert E. 1979a. Estimating live fuel moisture for the 1978 National Fire
- Danger Rating System. Res. Pap. INT-226. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 16 p.
- Burgan, Robert E. 1979b. Fire danger/fire behavior computations with the Texas Instruments TI-59 calculator: User's manual. Gen. Tech. Rep. INT-61. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 25 p.
- Burgan, Robert E. 1987. Concepts and interpreted examples in advanced fuel modeling. Gen. Tech. Rep. INT-238. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 40 p.

- Burgan, Robert E. 1988. 1988 Revisions to the 1978 National Fire Danger Rating System. Res. Pap. SE-273. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 144 p.
- Burgan, Robert E.; Rothermel, Richard C. 1984. BEHAVE: Fire behavior prediction and fuel modeling system—FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 110 p.
- Byram, George M. 1959. Combustion of forest fuels. In: Davis, Kenneth P. Forest fire control and use. New York, NY: McGraw-Hill Book Co.: 61–89.
- Catchpole, E. A.; deMestre, N. J.; Gill, A. M. 1982. Intensity of fire at its perimeter. Australian Forest Research. 12: 47–54.
- Cohen, Jack D. 1985. Should the 1978 national fire danger rating system be updated: A technical comparison to fire behavior prediction. In: Donoghue, Linda R.; Martin, Robert E., eds. Weather—The drive train connecting the solar engine to forest ecosystems. Proceedings of the Eighth Conference on Fire and Forest Meteorology; 1985 April 29–May 2. Detroit, MI: Society of American Foresters: 163–168.
- Cohen, Jack D.; Deeming, John E. 1985. The National Fire Danger Rating System: Basic equations. Gen. Tech. Rep. PSW-82. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 16 p.
- Deeming, John E. 1973. Fuel modeling: The key to applying Rothermel's mathematical fire spread model to fire-danger rating. In: Papers presented at the 1973 spring meeting, Western States Section, the Combustion Institute; 1973 April 16–17. Tempe, AZ: Arizona State University. 10 p.
- Deeming, John E.; Brown, James K. 1975. Fuel models in the National Fire Danger Rating System. Journal of Forestry. 73(6): 347–350.
- Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. 1977. The National Fire Danger Rating System—1978. Gen. Tech. Rep. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 63 p.
- Deeming, John E.; Lancaster, James W.; Fosberg, Michael A.; [et al.]. 1972. National Fire Danger Rating System. Res. Pap. RM-84. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 165 p.
- Finney, Mark A. 1998. FARSITE: Fire Area Simulator—Model development and evaluation. Res. Pap. RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.
- Finney, Mark A. 2006. An overview of FlamMap fire modeling capabilities. In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels management—How to measure success: Conference Proceedings. 2006 March 28–30; Portland, OR. Proceedings RMRS-P-41. Fort

Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213–220.

- Fons, Wallace L. 1946. Analysis of fire spread in light forest fuels. Journal of Agricultural Engineering Research. 72(3): 93–121.
- Fosberg, Michael A.; Schroeder, Mark J. 1971. Fine herbaceous fuels in fire-danger rating. Res. Note. RM-185. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experimental Station. 7 p.
- Frandsen, William H. 1971. Fire spread through porous fuels from the conservation of energy. Combustion and Flame. 16(1): 9–16.
- Frandsen, William H. 1973. Using the effective heating number as a weighting factor in Rothermel's fire spread model. Gen. Tech. Rep. INT-10. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 7 p.
- Frandsen, William H.; Andrews, Patricia L. 1979. Fire behavior in non-uniform fuels. Res. Pap. INT-232. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34 p.
- Heinsch, Faith Ann; Andrews, Patricia L. 2010. BehavePlus fire modeling system, version 5.0: Design and features. Gen. Tech. Rep. RMRS-GTR-249. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 111 p.
- Hough, Walter A.; Albini, Frank A. 1978. Predicting fire behavior in palmettogallberry fuel complexes. Res. Pap. SE-174. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 44 p.
- Jolly, W. Matt. 2007. Sensitivity of a surface fire spread model and associated fire behaviour fuel models to changes in live fuel moisture. International Journal of Wildland Fire. 16(4): 503–509.
- Mandel, J. D. Beezley, and A. K. Kochanski, Coupled atmosphere-wildland fire modeling with WRF 3.3 and SFIRE. 2011, Geoscientific Model Development (GMD) 4, 591-610, 2011, doi:10.5194/gmd-4-591-2011
- Mandel, J.; S. Amram, J. D. Beezley, G. Kelman, A. K. Kochanski, V. Y. Kondratenko, B. H. Lynn, B. Regev, M. Vejmelka. 2014. Recent advances and applications of WRF–SFIRE, Natural Hazards and Earth System Science, 14, 2829-2845, 2014, doi:10.5194/nhess-14-2829-2014
- McArthur Alan G. 1969. The Tasmanian bushfires of 7th February 1967 and associated fire behaviour characteristics. In: Mass Fire Symposium: The Technical Cooperation Programme, 1969 February 10–12; Canberra, Australia. Volume 1, Paper A7. Melbourne, Australia, Defence Standards Laboratories. 23 p.
- Rothermel, Richard C. 1968. Mechanisms of fire spread. In: Northern Forest Fire Laboratory, Problem Analysis. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Rage Experiment Station, Missoula MT. Unpublished paper on

file with: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT. 24 p.

- Rothermel, Richard C. 1969. A fire behavior model for field applications. In: Northern Forest Fire Laboratory, Study Plan. Unpublished paper on file with: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT. 25 p.
- Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.
- Rothermel, Richard C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.
- Rothermel, Richard C.; Anderson, Hal E. 1966. Fire spread characteristics determined in the laboratory. Res. Pap. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 34 p.
- Rothermel, Richard C.; Philpot, Charles W. 1973. Predicting changes in chaparral flammability. Journal of Forestry. 71(10): 640–643.
- Schroeder, Mark J.; Fosberg, Michael A.; Lancaster, James W.; [et al.]. 1972. Technical development of the National Fire Danger Rating System. Review Draft. Unpublished paper on file with: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT. 151 p.
- Scott, Joe H. 1999. NEXUS: A system for assessing crown fire hazard. Fire Management Notes. 59: 20–24.
- Scott, Joe H. 2007. Nomographs for estimating surface fire behavior characteristics. Gen. Tech. Rep. RMRS-GTR-192. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 119 p.
- Scott, Joe H.; Burgan, Robert E. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.
- Smith, Diane M. 2012. The Missoula Fire Sciences Laboratory: A 50-year dedication to understanding wildlands and fire. Gen. Tech. Rep. RMRSGTR-270. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 62 p.
- Sullivan, Andrew L. 2009a. Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. International Journal of Wildland Fire. 18(4): 349–368.

- Sullivan, Andrew L. 2009b. Wildland surface fire spread modelling, 1990-2007. 2: Empirical and quasi-empirical models. International Journal of Wildland Fire. 18(4): 369–386.
- Sullivan, Andrew L. 2009c. Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models. International Journal of Wildland Fire. 18(4): 387–403.
- Van Wagner, Charles E. 1978. Metric units and conversion factors for forest fire quantities. Information Report PS-X-71. Chalk River, ON: Canadian Forestry Service, Petawawa Forest Experiment Station. 15 p.
- Wells, G. 2008. The Rothermel fire-spread model: Still running like a champ. Fire Science Digest. 2: 1–12. http://www.firescience.gov/Digest/FSdigest2.pdf. (Accessed May 18, 2017).
- Wilson, Ralph. 1980. Reformulation of forest fire spread equations in S.I. units. Res. Note. INT-292. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 5 p.
- Ziel, Robert; Jolly, W. Matt 2009. Performance of fire behavior fuel models developed for the Rothermel surface fire spread model. In: Hutchinson, Todd F., ed. Proceedings of the 3rd fire in eastern oak forests conference; 2008 May 20–22; Carbondale, IL. Gen. Tech. Rep. NRS-P-46. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 78–87.

3.2 Scientific Publications By The Technosylva Team On The Models And Methods Used In The Wildfire Analyst™ Modeling Framework

- Cardil A, Monedero, A, Schag, G S de-Miguel, M Tapia, Ramirez, J. 2021 - Current Opinion in Environmental Science & Health, 2021 Fire behavior modeling for operational decision-making
- Cardil A, de-Miguel S, Silva CA, Reich PB, Calkin D, Brancalion PHS, Vibrans AC, Gamarra JGP, Zhou M, Pijanowski BC, Hui C, Crowther TW, Hérault B, Piotto D, Salas-Eljatib C, Broadbent EN, Almeyda Zambrano AM, Picard N, Aragão LEOC, Bastin JF, Routh D, van den Hoogen J, Peri PL, Liang J. 2020. Recent deforestation drove the spike in Amazonian fires. Environmental Research Letters 15, 121003
- Cardil A, Rodrigues M, Ramirez J, de-Miguel S, Silva CA, Mariani M, Ascoli D. 2020. Coupled effects of climate teleconnections on drought, Santa Ana winds and wildfires in southern California. Science of the Total Environment 142788. https://doi.org/10.1016/j.scitotenv.2020.142788

- Cardil A, de-Miguel S. 2020. COVID-19 jeopardizes the response to coming natural disasters. Safety Science 130, 104861. https://doi.org/10.1016/j.ssci.2020.104861
- Garcia M, Riaño D, Yebra M, Salas FJ, Cardil A, Monedero S, Ramirez J, Martín MP, Vilar L, Gajardo J, Ustin S. 2020. A Live Fuel Moisture Content product from medium spatial resolution Landsat TM satellite time series ready for implementation in fire behavior models. Remote Sensing, 12(11), 1714; https://doi.org/10.3390/rs12111714
- Cardil A, Mola-Yudego B, Blázquez-Casado A, González-Olabarria JR (2019) Fire and burn severity assessment: calibration of Relative Differenced Normalized Burn Ratio (RdNBR) with field data. Journal of environmental management 235:342-349.
- Ramirez J, Monedero S, Silva CA Cardil A. 2019.Stochastic decision trigger modelling to assess the probability of wildland fire impact. 2019. *Science of the Total Environment*
- Ramírez J, Monedero S, Buckley D. 2011. New approaches in fire simulations analysis with Wildfire Analyst. The 5th International Wildland Fire Conference, Sun City, South Africa. https://doi.org/10.13140/2.1.2045.7766
- Ramirez, J., Mendes, M., & Monedero, S. (2015). Enhanced forest fire risk assessment through the use of fire simulation models. In *ISCRAM 2015 Conference Proceedings - 12th International Conference on Information Systems for Crisis Response and Management* (Vol. 2015–Jan).
- Cardil, A., Monedero, S., Silva, C. A., & Ramirez, J. (2019). Adjusting the rate of spread of fire simulations in real-time. *Ecological Modelling*, *395*, 39–44. https://doi.org/10.1016/j.ecolmodel.2019.01.017
- Cardil A, Ramirez J, Monedero S, Silva CA (2019) Assessing and reinitializing wildland fire simulations through satellite active fire data. *Journal Of Environmental Management* 231, 996-1003
- Artès, T., Cardil, A., Cortés, A., Margalef, T., Molina, D., Pelegrín, L., & Ramirez, J. (2015). Forest fire propagation prediction based on overlapping DDDAS forecasts. In *Procedia Computer Science* (Vol. 51). https://doi.org/10.1016/j.procs.2015.05.294
- Ferragut, M.L. Asensio, S. Monedero, J. Ramirez (2008) Scientific Advances in fire modelling and its integration in a Forest Fire Decision System. Modelling,

Monitoring and Management on Forest Fire I. WIT *Transactions on Ecology and the Environment.* .Clave: CL, 119, pp. 31-38, WIT Press

- Monedero S, Ramirez J, Cardil A (2019) Predicting fire spread and behaviour on the fireline. Wildfire Analyst Pocket: a mobile App for wildland fire prediction. *Ecological modelling* 392, 103-107. https://doi.org/10.1016/j.ecolmodel.2018.11.016
- Monedero, S.; Ramirez, J.; Molina-Terrén, Domingo M.; Cardil, Adrián. (2017. Simulating wildfires backwards in time from the final fire perimeter in point-functional fire models. *Environmental Modelling & Software* 92:163-168.
- Ferragut, L., Asensio, M. I., Cascón, J. M., Prieto, D., & Ramirez, J. (2013). An efficient algorithm for solving a multi-layer convection-diffusion problem applied to air pollution problems. *Advances in Engineering Software*, *65*. https://doi.org/10.1016/j.advengsoft.2013.06.010
- Valcarce, F., Gonzalo, J., Ramirez, J., Montes, A. C., & Chuvieco, E. (2006). The new generation of remote sensing services for operational forest fire-fighting within GMES. In *AIAA 57th International Astronautical Congress, IAC 2006* (Vol. 3).