PYROLOGIX
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Methods and outputs of the Wildfire Exposure Simulation Tool (WildEST)

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1 Overview of WildEST

1.1 What is WildEST

WildEST—the Wildfire Exposure Simulation Tool—is a cloud-based software system that uses a command-line application of the FlamMap fire behavior modeling system[1] to produce continuously variable landscape-scale spatial data representing fire weather, flame-front, and ember characteristics as well as integrated measures of risk to buildings, wildfire hazard, and suppression difficulty.

WildEST incorporates simulations made with the USDA Forest Service WindNinja model[2] to adapt the general wind speed and wind direction to reflect the influence of local topography. The WildEST fire behavior calculations use conditioned dead fuel moisture content, so sheltered fuel complexes—higher canopy cover or more northerly aspect, for example—have higher dead fuel moisture contents than exposed fuel complexes.

Weather inputs for WildEST do not follow the historical standard of relying on a single weather condition (often a selected percentile). Instead, WildEST calculates fire characteristics for a full range of historical weather conditions. The weather conditions from gridded historical weather data are classified into 216 Weather Types based on wind speed (nine classes), wind direction (eight classes) and fuel moisture content (three classes). A relative likelihood that a given grid cell will be burned under each of these Weather Types is then derived and termed the Weather Type Probabilities (*WTP*s). WildEST calculates potential fire behavior for these Weather Types, and then uses the *WTP*s to weight each Weather Type's result. The *WTP* weights are a combination of Weather Type frequency and potential area burned, which gives higher weight to high-spread conditions. Fires burning in high-spread conditions cover more land area in a burning period leading to a higher probability of a given location experiencing that condition while burning. The development of the *WTP* rasters is described in Section 1.4.

For some WildEST outputs, the *WTP*s are used to estimate the probability of occurrence (or exceedance) of certain fire behavior characteristics, like the probability that headfire flame length will equal or exceed a given threshold, or the probability that the type of fire will be passive or active crown fire. For other outputs, such as the characteristic flame length, the *WTP*s are used as weighting factors to calculate the mean (expected value) from the fire behavior results for each Weather Type.

Nearly all WildEST results are "conditional", meaning they assume a fire occurs, regardless of its probability of occurrence. These results are calculated without the need for an annualized Burn Probability (*BP*) raster. Some WildEST results are "expected annual", meaning that they incorporate the annual likelihood that a fire will occur. Producing those results requires that an annualized *BP* raster be provided as input.

WildEST includes an ember module that simulates ember production, transport, and load (accumulation). WildEST also tracks the sources of embers that land on a specified "target"—such as buildings—which allows a fuel management planner to target these ember sources for treatment to mitigate hazard and risk.

WildEST uses simulated elliptical dimensions to take the simulated headfire intensity and translate it into the likelihood that flame length (calculated from fire intensity) will fall within each of the six Fire Intensity Levels after accounting for non-heading fire intensity (see Section 1.2).

WildEST is deterministic, which means it does not suffer from a sample-size problem for individual pixels and will produce the same result for a given set of inputs. That makes WildEST ideal for judging the effects of

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[1] Command line application developed by the Missoula Fire Sciences Laboratory, Missoula, Montana; https://www.firelab.org/project/flammap.

[2] https://www.firelab.org/project/windninja

various scenarios on potential fire behavior characteristics, such as a treated-condition landscape, a future-year landscape (e.g., ten years out), or a worst-case scenario. A small portion of WildEST's results could be produced by a stochastic wildfire simulation system, but results of those systems are challenged by a relatively small sample size at each individual pixel (see section 1.3 for more information). For example, two stochastic simulations with the same inputs could produce different results at individual pixels, which presents a challenge for an analysis designed to look for differences between simulations—due to planned fuel treatments, for example.

1.2   Non-heading Fire Intensity[3]

Fire intensity depends in part on the direction of flame-front spread relative to the heading direction (Catchpole et al. 1982; Catchpole et al. 1992). Rothermel-based fire modeling systems inherently simulate fire spread and intensity in the heading direction only, so an adjustment is needed to account for spread in non-heading directions (backing, flanking, etc.).

By assuming that a wildfire grows as an ellipse with the ignition at the rear focus (Alexander 1985), the geometric properties of an ellipse can be used to find the relative fire-area burned at or above a given fireline intensity (*FLI*) based on just two factors—the FLI at the head of the fire and the length-to-breadth ratio (*LB*) of the ellipse (Alexander 1982; Catchpole et al. 1992). Following Finney (1998), *LB* can be estimated as

$$LB = 0.936e^{0.1147U_m} + 0.461e^{-0.0692U_m} - 0.397$$

where

U_m is the effective midflame wind speed (mi/h) after combining (vectoring) midflame wind speed, slope steepness, and wind direction (Finney 1998).

For surface fires, midflame wind speed is a function of fuelbed depth for unsheltered fuelbeds or a function of canopy cover and canopy height for fuelbeds sheltered by a forest canopy (Albini and Baughman 1979). For passive and active crown fires' midflame wind speed (for the purposes of estimating *LB*) is taken to be half of the 20-ft wind speed (Albini and Baughman 1979; Finney 1998). The backing ratio (*BR*), the ratio of backing spread rate to heading spread rate, can be calculated from *LB* as

$$BR = \frac{LB - \sqrt{LB^2 - 1}}{LB + \sqrt{LB^2 - 1}}$$

Certain elliptical dimensions (Figure 1) can be calculated from the headfire rate of spread (*ROS*head), *LB* and *BR* following equations taken directly or modified from Catchpole, Alexander and Gill (1992) and Finney (1998). The labeling of the elliptical dimensions *a* and *b* are reversed in Finney (1998) compared to Catchpole, Alexander and Gill (1992); this documentation uses the labeling of Catchpole, Alexander and Gill (1992), for which the parameter *a* is the half-length of the ellipse length and *b* is the half-width.

$$a = \frac{ROS_{head}(1 + BR)}{2}$$

$$b = \frac{a}{LB}$$

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[3] This section is taken verbatim from the corresponding section of Scott (2020).
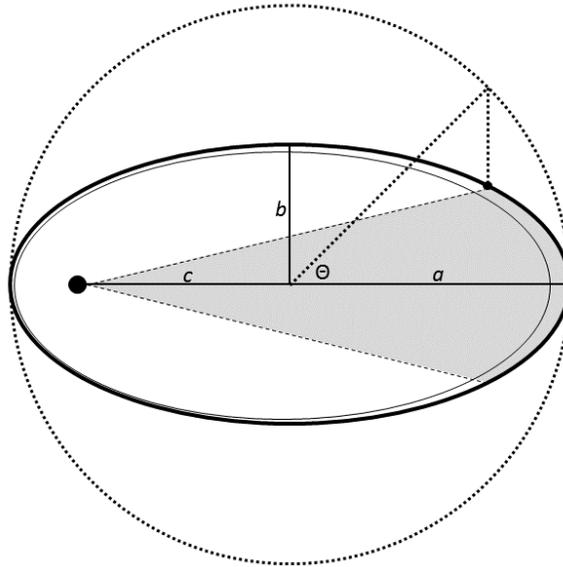
$$c = a\sqrt{1 - LB^{-2}}$$

Figure 1. Elliptical dimensions a, b and c as defined by Catchpole et al. (1992), where the angle Θ identifies a point on the ellipse based on the subtending circle, shown as the dotted circle. The shaded area represents the proportional fire-area burned at or above the proportional fireline intensity for a given Θ.

Following Catchpole, Alexander and Gill (1992), the proportional *FLI* (or *ROS*) can be determined for a given angle θ as a function of elliptical dimensions defined above

$$PropFLI_\emptyset = \frac{\dfrac{b(a + c\cos\cos\emptyset)}{\sqrt{a^2\emptyset + b^2\emptyset}}}{a + c}$$

where θ is the angle of the subtending circle of the ellipse (Catchpole et al. 1992). The proportional fire-area burned at or above that proportional FLI can be determined for the same angle θ as

$$PropArea_\emptyset = \frac{(a\emptyset + c\sin\sin\emptyset)}{\pi a}$$

The proportional area burned above any proportional intensity can then be plotted for a range of θ, and for a range of *LB* values (Figure 2). This permits one to find the proportional fire-area burned at or above a given proportional fireline intensity value.
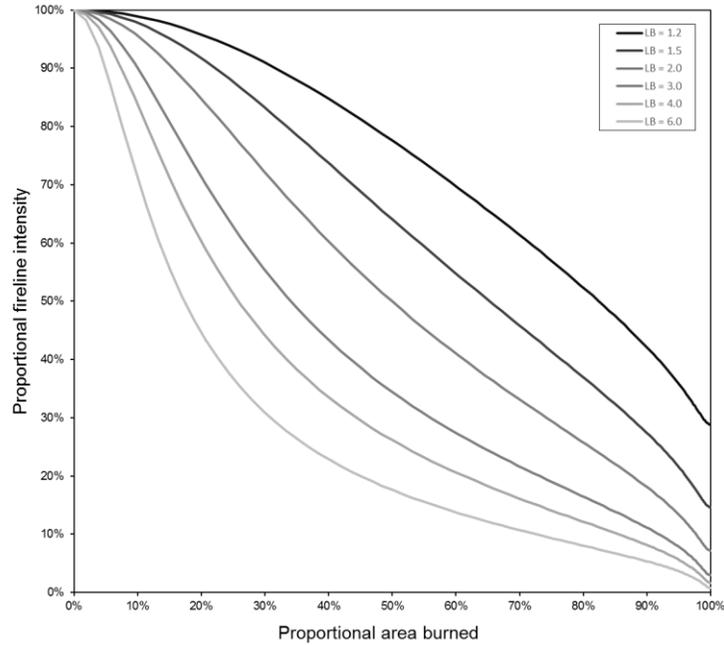
Figure 2. Plot of proportional fireline intensity against proportional fire-area burned for a range of length-to-breadth ratios. This figure is analogous to Figure 4 of Catchpole et al. (1992).

To use these equations operationally, the required proportional *FLI* is calculated as the ratio of threshold *FLI* for a given fire intensity level (FIL) class break (Table 1) to the headfire *FLI*. Knowledge of the elliptical dimensions permits brute-force estimation (by iteration) of the subtending angle θ that produces the required proportional *FLI*; from θ, one can then calculate the proportional fire-area burned at or above the threshold *FLI*. This proportional fire-area burned is taken to be the probability of exceeding the threshold flame-length value, also called the flame-length exceedance probability (FLEP) for each *FIL* class break. The probability that a given flame length is within a given FIL—called flame-length probability (*FLP*)—is calculated from the *FLEP*s by subtraction. For example, the probability that flame length will be in FIL2 (flame lengths between 2 and 4 feet) is the probability of *FL* exceeding 2 feet minus the probability of *FL* exceeding 4 feet.
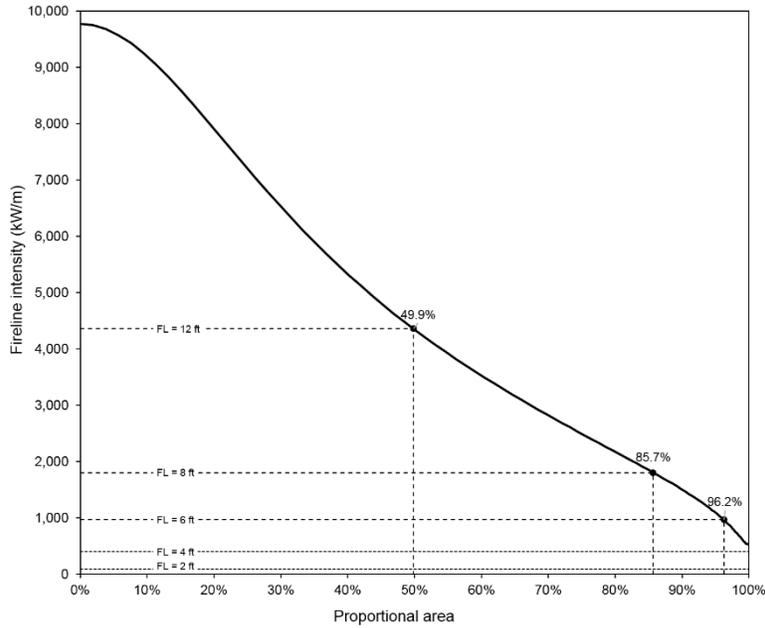
Figure 3. For a surface headfire intensity of 9,770 kW/m at a 20-ft wind speed of 15 mi/h (LB = 2.275), one can find the proportional fire-area burned at the fireline intensities that correspond to class breaks in the FIL classification. Those proportional areas determine the flame-length exceedance probability for each FIL. Flame-length probability for a class is found by subtraction. For example, the probability of FIL5 (flame lengths between 8 and 12 feet) is 35.8% (85.7% - 49.9%).

Table 1. Proportional intensity and proportional area burned for FIL class breaks, for a headfire fireline intensity = 9,770 kW/m and LB ratio = 2.275.

Fire Intensity Level	Proportional intensity	Proportional Area (FLEP)
2' (FIL1/2)	0.00907	1.0000
4' (FIL2/3)	0.04091	1.0000
6' (FIL3/4)	0.09876	0.9622
8' (FIL4/5)	0.18459	0.8568
12' (FIL5/6)	0.44566	0.4987

The estimation of *FLP*s using this process can be illustrated for a simple fire environment of heavy shrub fuel (fuel model SH5; Scott and Burgan 2005) on flat ground under a 15 mi/h wind speed at the 6.1-m (20-ft) height. The example assumes dead fuel moisture contents of 4% for the 1-h timelag class, 5% for 10-h and 6% for 100-h, and 110% for the moisture content of live the woody component. Using Rothermel's (1972) surface fire spread model as implemented in Nexus (Scott and Reinhardt 2001), the headfire intensity is 9,770 kW/m (*FL* = 17.4 ft). For that headfire intensity one can estimate the required proportional intensity values that correspond to the flame-length breakpoints, and then the proportional areas that correspond to those proportional intensities (Table 1, Figure 3).

These proportional areas represent the relative proportion of burned area that exceeds the upper end of the flame-length range for each FIL. In this example, 49.87% of the elliptical fire area is burned at or above the 12-ft flame length threshold (4,354 kW/m), 85.68% of the area is burned above an 8-ft flame length threshold,

96.22% above a flame length of 6 feet, and 100% above 4 feet (Table 1). The minimum fireline intensity, corresponding to the rear of the fire, is greater than the threshold for a 4-ft flame length, so 100% of the fire area would burn above this threshold. By subtraction, 0% of the fire area is burned in FIL1 and FIL2, 3.78% in FIL3, 10.54% in FIL4, 35.81% in FIL5 and 49.87% in FIL6. Note that the sum of these flame-length probabilities is 100%.

1.3 WildEST Versus a Stochastic Wildfire Simulator

Wildfire hazard assessments conducted by the USDA Forest Service typically rely on FSim[4]—a stochastic Monte Carlo Simulator (MCS) of fire occurrence and spread—for both the wildfire likelihood (quantified as *BP*) and wildfire intensity (quantified as flame length probabilities, or *FLPs*) components of the assessment. Pyrologix developed the WildEST system in part to address shortcomings that arise when using an MCS for fire intensity results and to provide additional fire behavior characteristics not produced by an MCS. For example, MCSs typically produce only FLPs, whereas WildEST additionally includes type of fire and headfire-only intensity measures). WildEST augments but does not replace an MCS because WildEST requires an annualized *BP* raster as input for producing certain outputs, and an MCS is the preferred modeling system for producing an annualized *BP* raster.

WildEST and an MCS should produce similar outputs assuming similar input data and a high number of stochastic iterations. An MCS represents variability in the fire environment with random draws from their distributions; WildEST models an exhaustive classification of weather types and calculates expected measures based on the estimated likelihood of a fire burning in each fire environment.

The following subsections highlight a few additional important differences between WildEST and an MCS like FSim.

1.3.1 Spatial Resolution

The spatial resolution (grid cell size) of MCS intensity estimates is typically limited to the resolution of the fire growth modeling. For national-scale projects with FSim, the resolution has typically been 270 m; smaller domains have been run at 90- to 120-m resolutions. Currently, FSim cannot use finer resolutions due to excessive computational run time. WildEST is not impacted in this way and can produce fine-resolution results even on large landscapes.

1.3.2 Model Type

The MCS FSim model produces intensity results that are limited to 1) the mean fireline intensity (*MFI*) of simulated fires that burned each grid cell, and 2) the conditional probabilities that flame length will be in each of the six FILs (FLPs). The flame-length range for each FIL is defined in Table 2. In FSim, flame length always accounts for the effect of relative spread direction (heading, flanking, backing). Because the *FLP*s are determined by tallying the relative fraction of times a grid cell burned in each FIL, they suffer from a problem of low sample size, especially in places where *BP* is low. For example, where *BP* is 1-in-500 (0.002), a pixel would burn 20 times over 10,000 iterations. The flame length of those 20 fires is tallied into the six flame-length bins, which is too small of a sample size to provide a stable estimate of flame-length probabilities. Running FSim a second time could generate vastly different *FLP*s for the same pixel, though patterns are largely consistent at a landscape scale.

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[4] https://www.firelab.org/project/fsim-wildfire-risk-simulation-software; see also Finney et al. (2011)

WildEST is deterministic, so it does not suffer from an MCS's sample-size problem. Additionally, WildEST can be used to generate both head-fire and non-heading fire intensity results.

Table 2. Fire Intensity Levels (FILs) are defined by flame length.

Fire Intensity Level	Flame length (ft)
1	0<FL<2
2	2<FL<4
3	4<FL<6
4	6<FL<8
5	8<FL<12
6	12<FL

1.3.3 Fire Characteristics Produced

WildEST is used to generate a broader array of fire characteristics than *MFI* and *FLPs*, including the characteristic rate of spread and heat per unit area, type of fire, crown fraction burned, ember production, and maximum ember travel distance. These additional fire characteristics allow the calculation of additional measures of wildfire hazard, including ember load.

1.3.4 Spatial Precision of Weather Data

FSim is currently limited to using just one stream of weather for a large area (several million acres). FSim does not support dead fuel moisture conditioning, which accounts for the effects of elevation, canopy cover, slope steepness, and aspect on dead fuel moisture content.

WildEST uses gridded historical weather data[5] at a native spatial resolution of 2 to 10 km. It uses both fuel moisture conditioning at the native resolution of the fuel inputs (typically 30 m but can be finer) and WindNinja data at 120-m resolution to produce continuously variable fire characteristics results that are free of seamlines due to coarse-scale weather inputs.

1.3.5 Topology Effects

One notable advantage of FSim — or any other fire spread MCS — is that it inherently accounts for any effects of fire spread topology[6] on fire intensity. For example, the land on the lee side of a large nonburnable feature (such as a lake) is less likely to experience a head-fire. Instead, a fire must flank around this location, resulting in lower fire intensity. This topology effect is pronounced for short-duration fires or when there is a dominant fire-carrying wind direction.

WildEST does not address such topological effects. Each location is evaluated using only the fuel, weather, and topography at the location, with no consideration for adjacent nonburnable features that could potentially reduce intensity by reducing the potential for heading spread.

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[5] Potential sources of gridded historical weather datasets to derive Weather Type Probabilities include gridMET, NREL (wind speed), RTMA, ERA5, and WRF reanalysis data.
[6] Fire spread topology is the network of possible fire spread pathways given the fire environment.

1.4 Weather Type Probabilities

Gridded historical weather datasets are used to derive the Weather Type Probability (*WTP*) rasters that give weight to the Weather Type results in the WildEST process. The *WTP*s are calculated from an Area-Burned Index (*ABI*), which is calculated for each weather observation in the historical dataset:

$$ABI = f(SPI, WS, LFP, BurnMinutes)$$

where *SPI* is the Schroeder Probability of Ignition (Schroeder 1969), a function of dry-bulb temperature and fine dead fuel moisture content; *WS* is the open (20-ft) wind speed in mi/h; *LFP* is the daily large-fire probability as a function of *ERC*; and *BurnMinutes* is a tabular function of wind speed and Energy Release Component (*ERC*) percentile.

The *LFP* is a prediction from spatially-explicit logistic regressions derived from observed large fires within the Short (2022) Fire Occurrence Database (FOD) and their corresponding *ERC* values. A 150-km moving window was used to select fire observations, creating a unique logistic regression for each 4-km pixel in the gridded *ERC* dataset. We also account for burnable area in the same 150-km window by dividing the probability by the fraction of ignitable area within the window, which prevents bias in areas with a low proportion of ignitable area, particularly coastlines.

As stated above, we define 216 unique Weather Types based on wind speed, wind direction, and moisture content. The weather parameters associated with each *ABI* value are binned according to the reported weather conditions for a given day or hour in the record.

There are nine wind speed bins (Table 3), eight wind direction bins (Table 4), and three fine dead fuel moisture content bins (Table 5). Note that if fine dead fuel moisture content was above 12 percent, then the *ABI* values for those conditions are not included in the sums.

The *ABI* values are summed within a Weather Type bin and normalized by the total *ABI* for all Weather Types for a given historical-weather pixel. This process collapses the individual *ABI* values across many years of the historical record into a smaller set of *WTP* rasters as fractions of the total *ABI*. The *WTP*s integrate the potential relative area burned for that weather type (*ABI*) and the relative frequency of weather scenarios by summing the daily *ABI* values each time a weather scenario occurred in the observation record. A weather type with higher wind speed, higher *ERC* values, and higher *SPI* will receive a weighting according to the larger *ABI* value, but weather types with lower *ABI* values occurring at high enough frequencies may ultimately receive a larger weighting. These *WTP* fractional rasters weight the subsequent fire behavior outputs.

The *WTP*s are pre-calculated at the native resolution of the historical weather data (2 to 10 km cell size). These native-resolution *WTP*s are upsampled to the final fuelscape resolution using cubic convolution before application so that the weather inputs vary continuously and seamlessly across the landscape. The *WTP*s are renormalized to ensure the fractional values still sum to 1 after the upsampling.

The *WTP* rasters themselves also permit the production of several rasters representing wind speed and fine dead fuel moisture characteristics across the fuelscape. For example, the conditional likelihood of having a wildfire burn with a nominal wind speed of 15 mi/h (13-18 mi/h) is calculated by summing the *WTP*s for all Weather Types for that wind speed (any wind direction and moisture content). These metrics are called characteristic because they are ABI-weighted, representing characteristic fire weather conditions.

Table 3. Wind speed bins used to define Weather Types and the associated nominal wind speed used in WildEST simulations.

20-ft Wind Speed (mi/h)	Nominal 20-ft Wind Speed (mi/h)
0 - 3	1
3 - 8	5
8 - 13	10
13 - 18	15
18 - 23	20
23 - 28	25
28 - 33	30
33 - 38	35
>= 38	40

Table 4. Wind direction bins used to define Weather Types and the nominal wind direction used in WildEST simulations.

Wind Direction (degrees)	Nominal Wind Direction (degrees)
337.5 - 22.5	0
22.5 - 67.5	45
67.5 - 112.5	90
112.5 - 157.5	135
157.5 - 202.5	180
202.5 - 247.5	225
245.5 - 292.5	270
292.5 - 337.5	315

Table 5. One-hour timelag moisture content bins used to define Weather Types and the nominal moisture content used in WildEST simulations. Fine dead fuel moisture content above 12 percent is assumed to be a no-spread condition.

1-hr Timelag moisture content (%)	Nominal 1-hr Timelag moisture content Bin (%)
< 4	3
4 - 6	5
6 - 12	8

1.5   Downscaling Weather Inputs

WildEST relies upon gridded historical weather data typically available at a spatial resolution of roughly 2-10 km, depending on the source. These data represent a coarse-scale grid for which the weather data corresponds to each grid cell center. At run time, WildEST downscales weather inputs to the final fuelscape resolution (30-m resolution or finer). Details on the downscaling of wind speed, wind direction, and moisture content are provided in the following sub-sections.

1.5.1 Wind Speed and Direction

We use a multi-step process to downscale the coarse-scale gridded wind data to the final resolution. The downscaling is done with pre-calculated grids produced using the mass-conservation model in WindNinja using the domain-average wind as input. With the mass-conservation approach in WindNinja, spatially variable terrain-adapted wind speed is a linear function of the domain-average wind speed, and terrain-adapted wind direction is insensitive to wind speed. These modeling features permit us to run the WindNinja model only eight times—once for each cardinal and intercardinal wind direction. From those eight simulations we can produce terrain-adapted wind direction and wind speed rasters for any domain-average speed.

We run WindNinja across CONUS at 120-m resolution using an overlapping tile set (60 km x 60 km) using a constant vegetation type (grass) for all simulations to avoid any potential discontinuities at tile boundaries. The overlap between tiles eliminates edge effects that can otherwise be present at edges of WindNinja runs.

The wind direction input to WindNinja is first adjusted for convergence angle at the tile centroid in LANDFIRE's CONUS Albers spatial reference (WKID:5070) so that the nominal wind direction is always correctly modeled relative to the terrain. Each tile has its own convergence angle adjustment. The values in the resulting wind direction rasters represent the wind direction that would result in the correct wind direction across the terrain when using a fuelscape in WKID:5070.

1.5.2 Fine Dead Fuel Moisture Content

We use gridded historical weather data to produce coarse-scale Weather Type Probabilities (*WTP*s) as described in Section 1.4. These data represent how often a fire would occur when the fine dead fuel moisture content fell within each of three classes (Table 5). The moisture content values in the gridded historical weather data, which are calculated from temperature and relative humidity, are assumed to apply to a location on flat ground with no forest cover within each coarse pixel.

To enable dead fuel moisture conditioning, we develop three sets of stylized temperature and relative humidity inputs that produce the three nominal moisture content values on flat ground with no canopy cover. The end of the conditioning period is set at September 1 at 1500 hours, which makes southwest aspects the driest. We set the elevation raster in the fuelscape to 0 and set the elevation of the weather station to 0 so there are no adiabatic adjustments of temperature and relative humidity. This is done because elevation is already accounted for in the gridded historical weather datasets. The simulated 1-hr moisture content in the WildEST runs therefore account for aspect and canopy characteristics (cover and height); elevation is accounted for in the gridded historical weather data.

1.6 Ember Modeling

The ember modeling in WildEST consists of ember production, ember transport, and ember load. In addition, the ember modeling tracks the source locations of embers that are transported to buildings.

1.6.1 Ember Production

In WildEST, conditional ember production—measured by the conditional Ember Production Index (*cEPI*)—is the weighted-mean relative number of embers lofted (*NEL*) per unit area across all Weather Types, given that a fire occurs. *NEL* is a function of the type of fire, fire intensity, and, for crown fires, the number of trees torching together. For each Weather Type, every burnable pixel is assigned to one of 12 Ember Production Classes (EPCs) based on the calculated flame length, type of fire, and number of trees torching together (Table 6). For surface fires, *NEL* is assumed to be a function of flame length. For passive and active crown fires, *NEL* is assumed to be proportional to the number of trees torching together, which itself is a function of Crown

Fraction Burned (*CFB*) and Canopy Fuel Load (Table 7). The table of number of trees torching together was patterned after Finney (1998).

Maximum Spotting Distance (*MSD*) is a function of EPC and 20-ft wind speed. A lookup table of *MSD* is generated by applying the Albini surface fire (Albini 1983) and crown fire (Albini 1979) spotting models as they are implemented in BehavePlus 6[7]. For each Weather Type, *MSD* is determined from the lookup table.

Annualized ember production—as measured by the Ember Production Index (*EPI*)—is the product of *cEPI* and annual *BP*.

Table 6. Ember Production Class (EPC) definitions. The number of trees torching together is a function of Canopy Fuel Load and Crown Fraction Burned.

Ember Production Class (EPC)	Type of Fire	Headfire Flame Length (ft)	Number of trees torching together	Relative Numbers of Embers Lofted (*NEL*) per ha
0	Nonburnable	0		0
1	Underburn (surface fire)	ALL		50
2	Passive or active crown fire	ALL	1	120
3	Passive or active crown fire	ALL	2	250
4	Passive or active crown fire	ALL	3	600
5	Passive or active crown fire	ALL	10	1000
6	Passive or active crown fire	ALL	20	2000
7	Surface fire	0-2		25
8	Surface fire	2-4		120
9	Surface fire	4-6		175
10	Surface fire	6-8		250
11	Surface fire	8-12		500
12	Surface fire	12+		1000

Table 7. Number of trees torching together as a function of Crown Fraction Burned (CFB) and Canopy Fuel Load. This table generally follows Finney (1998).

		Crown Fraction Burned (percent)			
		0-25	25-50	50-75	75-100
Canopy Fuel Load (kg/m²)	0 - 0.5	1	2	3	10
	0.5 - 1.5	2	3	10	10
	1.5 - 2.5	3	10	10	20
	2.5+	10	10	20	20

1.6.2 Ember Transport

To simulate the distribution of embers at various distances from the lofting cell to the maximum distance, WildEST can use either a negative-exponential distribution (Finney 1998) or log-normal distribution (Gannon et al. 2021). Because the wind direction represents wind directions within a 45-degree range (Table 4), the number of embers lofted are "transported" in a 45-degree fan downwind of the lofting cell, as illustrated in Figure 4 for the same three fuel complexes and three wind speeds outlined in Table 8.

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[7] https://www.firelab.org/project/behaveplus

Table 8. Fire behavior and ember characteristics for three fuel complexes at three wind speeds (very dry fuel conditions).

Fuel complex	20-ft wind speed		
	5 mi/h	15 mi/h	25 mi/h
GR2	Surface fire FL = 1.0 m NEL = 120 MSD = 100 m	Surface fire FL = 2.0 m NEL = 250 MSD = 400 m	Surface fire FL = 2.8 m NEL = 500 MSD = 750 m
SH5	Surface fire FL = 3.8 m NEL = 500 MSD = 300 m	Surface fire FL = 6.8 m NEL = 1,000 MSD = 750 m	Surface fire FL = 9.0 m NEL = 1,000 MSD = 1,000 m
TU5 w/canopy	Unberburn FL = 1.2 m NEL = 50 MSD = 30 m	Passive crown fire FL = 7.5 m NEL = 1,000 MSD = 750 m	Active crown fire FL = 24 m NEL = 2,000 MSD = 1,500 m

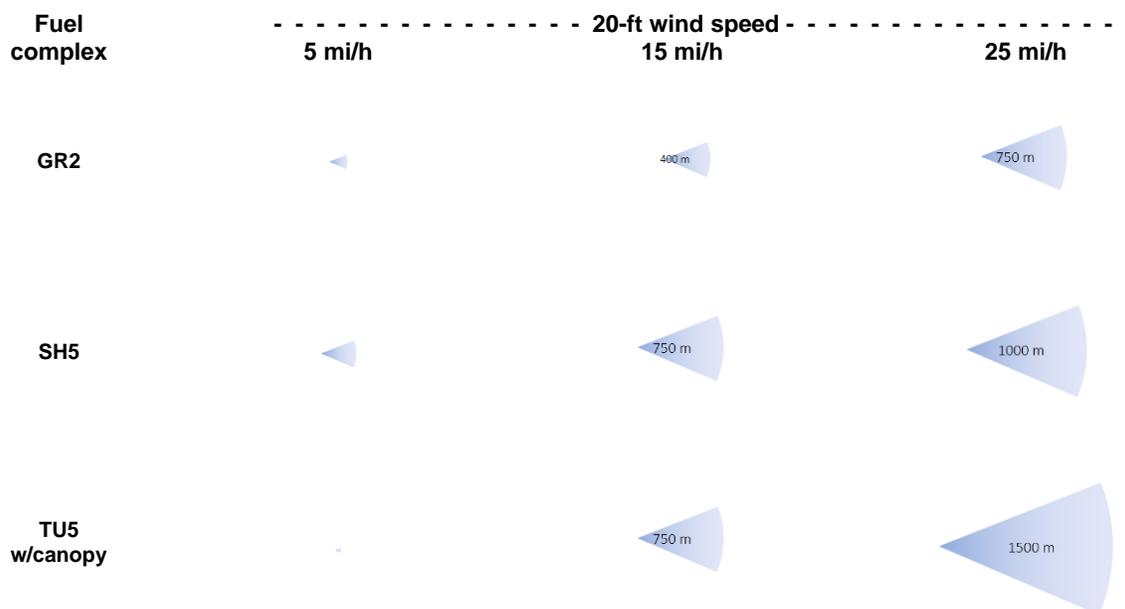| Fuel complex	20-ft wind speed		
	5 mi/h	15 mi/h	25 mi/h
GR2		400 m	750 m
SH5		750 m	1000 m
TU5 w/canopy		750 m	1500 m

Figure 4. Illustration of ember transport from a source pixel (the tip of the cone) for three fuel complexes and three wind speeds. This example assumes wind is blowing from left to right across the page.

1.6.3 Ember Load

For each Weather Type, the ember production and transport models are combined such that embers accumulate within grid cells downwind of the lofting cell. The accumulation of embers is measured as the conditional Ember Load Index (*cELI*). It integrates all characteristics of the spatially variable fire environment—wind speed, wind direction, surface fuel moisture content, surface and canopy fuel characteristics, and topography.

Annualized ember load, as measured by the Ember Load Index (*ELI*), is the product of *cELI* and annual *BP*.

2 WildEST Outputs

This section describes the full range of potential outputs produced with WildEST. Not all outputs are produced for every project.

2.1 Fire Weather Characteristics

Gridded historical weather characteristics are an important input to WildEST, but WildEST also produces downscaled weather characteristics as outputs so that an analyst can gauge how the downscaled weather inputs may affect the simulations. The weather characteristics also help to visualize how the weather inputs vary continuously across the landscape. WildEST produces fire weather characteristics outputs for wind speed, wind direction, and fine dead fuel moisture content.

Two types of weather characteristics are calculated in WildEST: a weighted-mean—or characteristic—result, and weather probabilities. Neither type is calculated directly from the input *WTPs*. They are instead calculated only after they have been downscaled in WildEST using WindNinja (for winds) and dead fuel moisture conditioning (for dead fuel moisture content).

The weighted-average result is calculated as the sum-product of the *WTPs*, and the weather rasters produced by WildEST as part of the fire behavior simulation. For wind speed, the weather rasters are the 20-ft wind speed rasters that have been modified to reflect the effect of terrain on wind speed. For moisture content, the weather rasters are the conditioned dead fuel moisture content for the 1-hr timelag class. The "driest" fuel will be found on SW aspects and with no canopy cover. The "wettest" aspects will be found on NE aspects under heavy canopy cover.

The weather probability result is calculated as the sum of the *WTPs* for the weather characteristic of interest. For wind speed, WildEST calculates nine Wind Speed Probabilities (*WSPs*), one for each wind speed class (Table 3). There are up to 24 Weather Types to sum within each wind speed class (eight directions and three moisture contents). For moisture content, WildEST calculates three Moisture Content Probabilities (*MCPs*), one for each moisture content class (Table 5). There are up to 72 Weather Types to sum within each moisture content class (nine wind speeds and eight wind directions).

2.1.1 Wind Speed Probabilities (*WSPs*)

WildEST can produce a set of rasters representing the historical conditional likelihood that 20-ft wind speed will be in each of the nine wind speed bins (Table 3) during a wildfire event. For an any given grid cell, the sum of these probabilities is 1 (100 percent). These wind-speed probabilities are a companion to the characteristic wind speed raster described in the next section. They can be used to examine the range of variability in wind speeds around the characteristic wind speed. They can also be used to determine how often a wildfire might burn under wind speeds at or above a speed considered problematic for the area.

2.1.2 Characteristic Wind Speed (*wWS*)

WildEST produces a raster representing the historical conditional weighted-mean—or "characteristic"—20-ft wind speed across the landscape. This raster is produced by downscaling gridded historical weather data using WindNinja for each Weather Type, then applying the Weather Type Probabilities for each downscaled wind speed raster. Characteristic Wind Speed is the sum-product of the downscaled 20-ft wind speed and

WTP across all Weather Types and is best used for visualizing the spatial variation in fire-carrying windiness across any geography.

2.1.3 Wind Direction Probabilities (*WDPs*)

Wind Direction Probabilities (*WDPs*) indicate the likelihood that a fire will be carried by winds from each of the eight cardinal and intercardinal directions (Table 4) regardless of wind speed or moisture content. For any given grid cell, the sum of these probabilities is 1 (100 percent). These wind-direction probabilities are a companion to the characteristic wind direction raster described in the next section. They can be used to examine the range of variability in wind direction around the characteristic wind direction. They can also be used to determine how often a wildfire might burn under wind directions considered problematic for the area (for example, a wind direction that would carry fire into a developed area).

2.1.4 Characteristic Wind Direction (*CWD*)

Characteristic Wind Direction (*CWD*) is the most dominant fire-carrying direction from which wind will carry fire at each location across the landscape. Unlike Characteristic Wind Speed, the Characteristic Wind Direction is not a WTP-weighted mean. Instead, it is the direction of maximum *WDP*. Caution is needed when interpreting *CWD* because wind directions other than the dominant direction could also have relatively high occurrence rates that require consideration.

2.1.5 Moisture Content Probabilities (*MCPs*)

Moisture Content Probabilities (*MCPs*) indicate the likelihood that 1-hr timelag moisture content will be within each of three bins (Table 5) after performing dead fuel moisture conditioning. For any given grid cell, the sum of these probabilities is 1 (100 percent). The *MCPs* vary spatially across the landscape with the gridded historical weather data, which captures the effects of elevation on temperature and relative humidity. Dead fuel moisture conditioning is used so that the effects of aspect, slope steepness, and forest canopy cover are incorporated into the results.

2.1.6 Characteristic Moisture Content (*wMC*)

Characteristic (or "weighted") moisture content (*wMC*) is the weighted-mean 1-hr timelag dead fuel moisture content, which is calculated as the sum-product of Weather Type Probability and conditioned 1-hr *MC*. Characteristic Moisture Content varies spatially across the landscape with the gridded historical weather data, which captures the effects of elevation on temperature and relative humidity. Dead fuel moisture conditioning is used so that the effects of aspect, slope steepness, and forest canopy cover are incorporated into the results.

2.2 Flame Front Characteristics

The WildEST flame front characteristics include season-long headfire characteristics (rate of spread, heat per unit area, fireline intensity and flame length), average-worst headfire characteristics (95th percentile flame length and Fire Intensity Scale), and conditional probabilities for fire type, and operational control exceedance probabilities. These characteristics are described below in the following sections. WildEST also produces "fire-effects" flame-length probabilities, which are calculated in a way that incorporates non-heading spread directions (section 2.2.2).

Table 9. Example of flame-front characteristics calculations for a hypothetical location with the following characteristics: flat ground; moderately dry conditions; heavy timber-understory fuel (TU5); canopy base height = 2.0 m; canopy height = 20 m; canopy bulk density = 0.15 kg/m^3; canopy cover = 40 percent. After accounting for the effect of canopy cover on dead fuel moisture, the 1-hour dead fuel moisture content was 6.3% for this simulation.

Wind Speed (mi/hr)	WTP (fraction)	ROS (ch/h)	HPA (kJ/m^2)	FLI (kW/m)	FL (ft)	Fire Type (class)	Non-heading Flame-length Probabilities (fraction)					
							FIL1	FIL2	FIL3	FIL4	FIL5	FIL6
1	0.0074	1.0	28,937	167	2.7	U	-	1.00				
5	0.6890	1.7	28,937	269	3.3	U	-	1.00	-	-	-	-
10	0.2572	2.6	28,937	422	4.1	U	-	0.79	0.21	-	-	-
15	0.0287	15.7	45,921	4,031	22.1	P2	-	0.01	0.05	0.09	0.24	0.60
20	0.0118	51.2	72,766	20,808	66.1	A	-	-	-	0.01	0.03	0.97
25	0.0059	76.4	77,583	33,122	90.1	A	-	-	-	0.00	0.01	0.98
6.3	**1.0000**	**3.3**	**30,228**	**852**	**5.3**	See Table 11	**-**	**0.90**	**0.06**	**0.00**	**0.01**	**0.03**

2.2.1 Season-long Flame-front Characteristics

Characteristic Rate of Spread (*wROS*)

Characteristic (or "weighted") Rate of Spread (*wROS*) is the weighted-average rate of spread (m/min) for a given pixel in the fuelscape, including any contributions of crown fire spread. Characteristic *ROS* is calculated as the sum-product of 216 *ROS* rasters and their corresponding *WTP* rasters. It represents the season-long tendency for rate of spread at a pixel given the fuel, weather, and topography at that pixel. It is best used as a relative measure for comparison with other pixels on the landscape rather than for its nominal value.

The Characteristic Rate of Spread for the simplified example fire environment is 3.3 ch/hr, calculated as the sum-product of the *WTP* and *ROS* columns in Table 9.

Characteristic Heat Per unit Area (*wHPA*)

Characteristic (or "weighted") Heat Per unit Area (*wHPA*) is the weighted-average heat load (kJ/m^2) for a given pixel in the fuelscape, including any contributions of crown fire spread. Weighted *HPA* is calculated as the sum-product of 216 *HPA* rasters and their corresponding *WTP*s. It represents the season-long tendency for heat load at a pixel given the fuel, weather, and topography at that pixel. It is best used as a relative measure for comparison with other pixels rather than for its nominal value.

The Characteristic Heat Per Unit Area for the simplified example fire environment is 30,228 kJ/m^2, calculated as the sum-product of the *WTP* and *HPA* columns in Table 9.

Characteristic Fireline Intensity (*wFLI*)

Characteristic (or "weighted") Fireline Intensity (*wFLI*) is the weighted-average (or "characteristic") fireline intensity in kW/m for a given pixel in the fuelscape, including any contributions of crown fire spread. Weighted *FLI* is calculated as the sum-product of 216 *FLI* rasters and their corresponding *WTP*s. It represents the season-long tendency for fireline intensity at a pixel given the fuel, weather, and topography at that pixel. It is best used as a relative measure for comparison with other pixels rather than for its nominal value.

The Characteristic Fireline Intensity for the simplified example fire environment is 852 kW/m, calculated as the sum-product of the *WTP* and *FLI* columns in Table 9.

Characteristic Flame Length (*wFL*)

Characteristic (or "weighted") Flame Length (*wFL*) is the weighted-average (or "characteristic") flame length in feet for a given pixel in the fuelscape, including any contribution of crown fire spread. Weighted *FL* is calculated as the sum-product of 216 FL rasters and their corresponding *WTP*s. It represents the season-long tendency for flame length at a pixel given the fuel, weather, and topography at that pixel. It is best used as a relative measure for comparison with other pixels rather than for its nominal value.

The Characteristic Flame Length for the simplified example fire environment is 5.3 ft, calculated as the sum-product of the *WTP* and *FL* columns in Table 9.

2.2.2 Fire-Type Probabilities (*FTP*)

Fire-type probability (*FTP*) rasters indicate the conditional probability that a given pixel will experience a certain type of fire (Table 10). At a given pixel, the sum of fire-type probabilities equals 1 (100 percent). The *FTP*s indicate the range of fire types that can be produced by the fire environment at the location, and their relative prevalence. *FTP*s are useful for identifying areas likely to burn with undesirable fire types — which often correspond to undesirable fire severity.

Table 10. The WildEST Type of Fire classification.

Raster value	Code	Type of fire	Burnable land cover?	Forest canopy present?	Crown Fraction Burned (%)
1	N	Non-fuel	No		-
2	S	Surface	Yes	No	-
3	U	Underburn	Yes	Yes	0
4	P1	Low-grade passive	Yes	Yes	$0<CFB<25$
5	P2	Mid-grade passive	Yes	Yes	$25<CFB<60$
6	P3	High-grade passive	Yes	Yes	$60<CFB<90$
7	A	Active	Yes	Yes	$90<CFB$

The non-fuel "fire type" (N) is assigned to pixels that do not have burnable fuel in the fuelscape and therefore do not experience any type of fire. The only possible raster values for non-fuel probability are 1 (100%), meaning the pixel is nonburnable, or 0 (0%), meaning the pixel is burnable (that is, *not* non-fuel). Similarly, the surface fire type (S) is assigned to pixels with burnable fuel but without forest canopy present. In such cases, surface fire is the only possibility, so the only possible raster values are 0 and 1. We distinguish surface fire (S) from an underburn (U) because the latter indicates that crowning was possible but not achieved.

The remaining five fire types require a pixel to have both a burnable surface fuel model and a tree canopy present, representing the possibility of a crown fire under some conditions. Raster values for these crown-fire-capable fire types range from 0 to 1, inclusive. Crown fire types are commonly classified as simply passive or active. But passive crown fire represents a large range of crowning behavior from a single tree torching up to nearly continuous large-group torching and intermittent crowning. We therefore divide passive crown fire into three sub-classes based on the crown fraction burned (*CFB*) estimated for the fire environment. Crown fraction burned represents the fraction of the canopy fuel contributing to the overall rate of spread and intensity.

The *FTP* rasters are additive for a given pixel, with the sum of all seven *FTP* rasters for a given pixel equaling 1. By including a class for non-fuel pixels, every pixel on a landscape should sum to 1.

The *FTP*s for the simplified example fire environment are the sums of the *WTP* values for each fire type in Table 9. U = 95.4%; P1 = 0.0; P2 = 2.9%; P3 = 0.0; A = 1.8%.

Table 11. Fire Type Probability is the sum of *WTP* values for all wind speeds that produce each fire type.

Fire Type label	Fire Type	Fire Type Prob.
U	Underburn	95.4%
P1	Low-grade passive crown fire	-
P2	Mid-grade passive crown fire	2.9%
P3	High-grade passive crown fire	-
A	Active crown fire	1.8%

2.2.3 Operational Flame-Length Exceedance Probabilities (*FLEPs*)

Operational-control exceedance probability (*FLEPs*) rasters indicate the probability that the head-fire flame length in each pixel will exceed defined thresholds for certain types of operational control. The three levels of control are manual control, mechanical control, and extreme fire behavior (Andrews and Rothermel 1982). We estimate these probabilities by summing the *WTP* values for all weather types for which head-fire FL exceeds the threshold value.

Manual control is generally considered to have a threshold of 4 feet during wildfire operations. Therefore, the probability-of-exceeding-manual-control raster displays the likelihood of exceeding 4-foot heading flame lengths. Similarly, mechanical control is generally considered to have a threshold of 8 feet, and the probability raster displays the likelihood of exceeding 8-foot heading flame lengths. Extreme fire behavior is considered having a threshold exceeding an 11-foot flame length (Andrews and Rothermel 1982).

This information could be used as a supplement to the Suppression Difficulty Index (O'Connor et al. 2016) when planning wildfire suppression operations for a given area of the landscape. When summarized across a planning area, the *FLEP*s serve as a relative measure of fire suppression availability within the planning area and can be computed for the current condition fuelscape as well as a treated scenario.

The Operational Flame-length Exceedance Probabilities for the simplified example fire environment are:

- *FLEP4* – manual control: 0.3036
- *FLEP8* – mechanical control: 0.0464
- *FLEP11* – extreme behavior: 0.0464

In this example, the fact that *FLEP8* = *FLEP11* indicates that there were no cases where flame length was between 8 and 11 feet.

2.2.4 "Fire-effects" Flame-Length Probabilities (*FLPs*)

All WildEST results described thus far apply to the head of a fire, but a free-burning wildfire spreads in all directions and therefore exhibits a range of flanking and backing behavior in addition to heading behavior. Flanking and backing fires exhibit a lower spread rate and intensity than at the head of a fire (Catchpole et al. 1982; Catchpole et al. 1992). FSim and other MCS inherently capture non-heading fire spread and intensity. The deterministic approach in WildEST captures only head-fire spread and intensity, so we apply adjustments to head-fire intensity based on the geometry of an assumed fire spread ellipse (Scott 2020; Section 1.2). The *FLP* differences between heading and non-heading *FLPs* are illustrated in Figure 5.
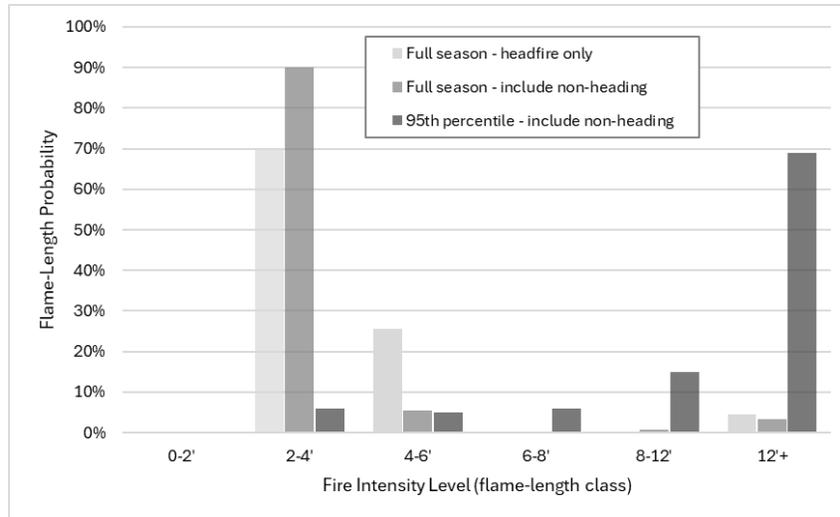
Figure 5. Flame-length probabilities for the simplified fire environment.

The WildEST non-heading characteristics include non-heading *FLPs*, which we call "fire-effects" *FLPs* because they are designed for use in an effects analysis for a landscape wildfire risk assessment as described in USDA Forest Service GTR-315 (Scott et al. 2013). These fire-effects *FLP*s are a close analog to FSim's *FLPs* and are used for the same purpose. Like the head-fire *FLPs* described above, we produce non-heading *FLPs* for the same 6 standard flame-length classes (also called Fire Intensity Levels). These fire-effects *FLP* values are shown in Table 9.

2.2.5 Average-worst Flame-front Characteristics

95th percentile Flame Length

The measures in Section 2.2 are calculated from the *WTPs* across the entire fire season. Some wildfire-safety applications require knowledge of fire behavior potential for the near-worst weather conditions. In the past, this was accomplished by separately finding the near-worst wind speed and near-worst moisture content— typically the 95th, 97th, or 98th percentiles of those measures at a weather station. However, those two variables are not necessarily independent, so the 95th percentile wind speed may not ever occur at the 95th percentile moisture content. Moreover, wind direction is not typically used in such an analysis.

To avoid those challenges of addressing wind speed, wind direction, and moisture content together in one measure of the "95th percentile", WildEST computes the 95th percentile *FL* value for a pixel as the *WTP*-weighted average of the weather types that comprise a cumulative *WTP* of 0.05 (5%) when ranked highest to lowest by *FL*. Thus, the 95th percentile FL is actually the average of the 95th percentile through the maximum, weighted by their *WTPs*.

Fire Intensity Scale

The Fire Intensity Scale (Scott 2006) is a $\log_{10}$ transformation of fireline intensity (kW/m). The 95th percentile fireline intensity is calculated using the same procedure used for *FL*. For the example presented in Table , the Fire Intensity Scale result is 4.0.

Table 12. Example of 95th percentile flame front calculations. The *WTP*s representing the worst 5% of weather types are rescaled to 1. For example, the *WTP* for wind speed of 25 mi/hr is 0.0059. As a fraction of 5%, that becomes a q*WTP* of 0.1185. Table values in gray are identical to those in Table 9.

Wind Speed	qWTP (fraction)	ROS (ch/h)	HPA (kJ/m²)	FLI (kW/m)	FL (ft)	Fire Type (class)	Non-heading Flame-length Probabilities (fraction)					
							FIL1	FIL2	FIL3	FIL4	FIL5	FIL6
1	-	1.0	28,937	167	2.7	U	-	1.00				
5	-	1.7	28,937	269	3.3	U	-	1.00	-	-	-	-
10	0.0724	2.6	28,937	422	4.1	U	-	0.79	0.21	-	-	-
15	0.5737	15.7	45,921	4,031	22.1	P2	-	0.01	0.05	0.09	0.24	0.60
20	0.2354	51.2	72,766	20,808	66.1	A	-	-	-	0.01	0.03	0.97
25	0.1185	76.4	77,583	33,122	90.1	A	-	-	-	0.00	0.01	0.98
14.0	**1.0000**	**30.3**	**54,765**	**11,168**	**39.2**		**-**	**0.06**	**0.05**	**0.06**	**0.15**	**0.69**

Table 13. Fire Type Probability for the "worst" 5% of Weather Type Probabilities.

Fire Type label	Fire Type	Fire Type Prob.
U	Underburn	7.2%
P1	Low-grade passive crown fire	-
P2	Mid-grade passive crown fire	57.4%
P3	High-grade passive crown fire	-
A	Active crown fire	35.4%

2.3   Ember Characteristics

WildEST produces indices of conditional and expected (annual) ember production and ember load. The conditional ember indices rate the potential for ember production if a fire were to occur; the expected annual ember indices include the annual *BP*. Ember characteristics are useful for proactive fuels management, response planning, and structural hardening.

2.3.1 Conditional Ember Production Index (*cEPI*)

The Conditional Ember Production Index (*cEPI*) is an index of the relative number of embers lofted at a given landscape pixel if a fire were to occur. The *cEPI* represents the relative number of embers produced at a pixel as a function of the fire environment. Being "conditional", *cEPI* does not account for variation in burn probability across the landscape.

2.3.2 Ember Production Index (*EPI*)

Ember Production Index (*EPI*) is the expected annual relative number of embers lofted from a given landscape pixel. The expected ember production index (*EPI*) is calculated by multiplying *cEPI* and burn probability (*BP*):

$$EPI = cEPI * BP$$

Given that *EPI* does incorporate burn probability, this index can help identify both the likelihood of areas being visited by fire and their potential for producing embers—information that is useful for fuel treatment prioritization to reduce ember production.

2.3.3 Conditional Ember Load Index (*cELI*)

The Conditional Ember Load Index (*cELI*) is an index of the relative number of embers that land at a given landscape location, including embers that land on nonburnable pixels that do not produce embers. The

conditional Ember Load Index (*cELI*) does not account for burn probability and can be used to identify where on the landscape hardening buildings to resist ember ignition may be needed.

2.3.4 Ember Load Index (*ELI*)

The ember load indices represent relative ember load at a pixel. Ember load incorporates downwind ember travel in addition to surface and canopy fuel characteristics, climate, and topography at the pixel. Ember Load Index combines *cELI* and the likelihood of that ember load occurring. All ember characteristics are based on headfire behavior.

The Ember Load Index (*ELI*) incorporates burn probability; however, *ELI* is not simply the multiplication of condition ember load (*cELI*) and burn probability (*BP*). Rather, *BP* is incorporated into calculations of the ember production before the distribution of embers across the landscape to determine ember load. Given that *ELI* incorporates burn probability, this index can be used to identify where on the landscape hardening buildings may be needed to resist ignition and the priority for doing so according to the likelihood of the area being visited by fire.

2.4 Integrated measures

2.4.1 Damage Potential (*DP*)

Damage Potential (*DP*) is a relative measure of the potential consequences of wildfire to a resource or asset at a given location, if a fire were to occur. *DP* incorporates both fire intensity and ember load (*cELI*). The fire intensity portion of *DP* is an extension of the conditional risk to potential structures (*cRPS*) dataset[8] produced by the Wildfire Risk to Communities (WRC) project[9]. The 2020 WRC project calculated *cRPS*[10] using coarse-resolution flame-length probabilities from FSim and a single response function applied to all vegetation types. In WildEST, the *cRPS* portion of *DP* is calculated from WildEST non-heading fire-intensity results, which are analogous to FSim's intensity results but are produced at the native fuelscape resolution and are calculated using separate response functions for different fuel type groups (lifeforms). Different response functions (RFs) for different fuel type groups (Table 14) were first proposed for the Montana Wildfire Risk Assessment[11] by state specialists whose experience was that the longer residence times of shrubland and timber fires contributed to greater likelihood of structure loss.

The response functions characterizing potential consequences to an exposed structure are applied to all burnable fuel types on the landscape regardless of whether or not a structure is actually present there. The response function does not consider building materials of structures and is meant as a measure of the relative effect of fire intensity on wildfire exposure and potential damage and can be used to inform structural inspection and hardening efforts. The *cRPS* response functions are provided below:

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[8] https://www.fs.usda.gov/rds/archive/Catalog/RDS-2020-0016
[9] https://wildfirerisk.org/
[10] The *cRPS* concept was developed by Pyrologix under the names "Hazard to Potential Structures", and "Hazard in Context". That concept was contributed to the Wildfire Risk to Communities project and became Risk to Potential Structures.
[11] https://mwra-mtdnrc.hub.arcgis.com/

Table 14. Conditional Risk to Potential Structures (*cRPS*) response function values by fire intensity level (FIL) class and fuel type group.

Fire Intensity Level	Grass	Shrub	Tree
0<FL<2	10	20	25
2<FL<4	25	35	40
4<FL<6	40	50	55
6<FL<8	55	65	70
8<FL<12	70	80	85
12<FL	85	95	100

These results are calculated using 30-m "fire-effects" flame-length probabilities from the WildEST wildfire behavior results and then smoothed into nonburnable areas to match the extent of the burn probability raster. A *cRPS* value of 0 means no exposure of a structure, and a value of 100 represents a complete loss.

Damage Potential is the simple arithmetic means of *cRPS* and *cELI* meaning that those factors have equal weight.

$$DP = \frac{cRPS + cELI}{2}$$

2.4.2 Wildfire Exposure Score

Wildfire Exposure Score[12] (W*ES*) is a relative measure of the exposure of a resource or asset—assuming one were present—to wildfire hazard. W*ES* combines the likelihood of fire (Burn Probability) with a measure of flame length in the context of its effect on likelihood and degree of damage (*cRPS*), and the relative load of embers at a location (*cELI*) after accounting for downwind ember travel from surrounding pixels. W*ES* varies considerably across the landscape. We use a standard geometric-interval classification to define the ten classes of W*ES*, where each class break is 1.5 times larger than the previous break (Table 12). So, a location in Class 7 is 1.5 times more exposed than one in Class 6, and so on.

$$WES = (ln(BP) + 12.51293) * DP$$

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[12] This integrated measure was formerly called 'Structure Exposure Score'. It was renamed to Wildfire Exposure Score in January 2025 because it has applications beyond structure exposure. When the Wildfire Exposure Score is added as an attribute to an individual structure, the attribute is called 'Structure Exposure Score'.

Table 15. Standard WES classes and the land area (acres) and number of buildings in each class in the Western U.S.

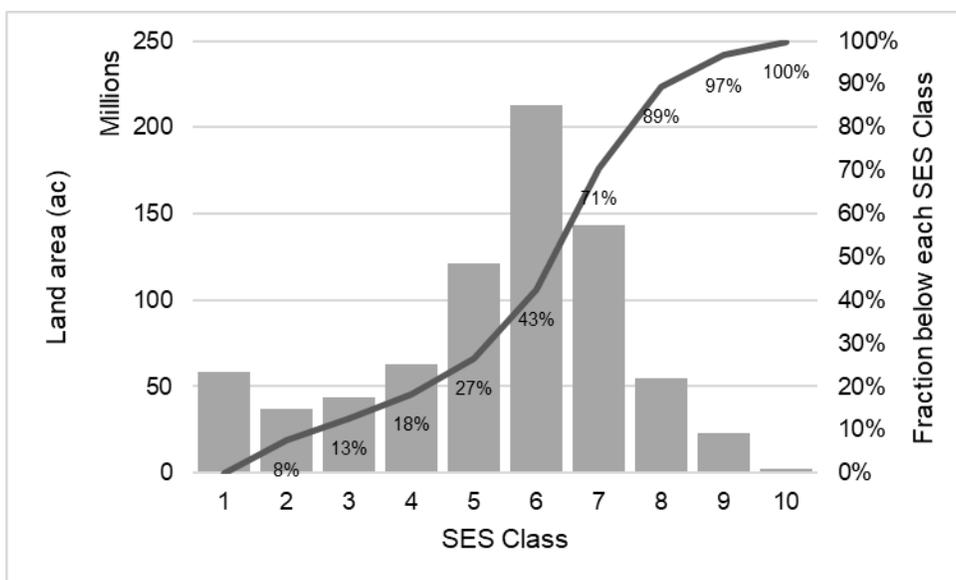| WES Class	Upper end of value range	Land Area in Western U.S. (M ac)	Fraction Land Area in Western U.S.
1/10	0	58.7	7.7%
2/10	50	37.0	4.9%
3/10	75	43.6	5.7%
4/10	113	62.7	8.3%
5/10	169	121.1	15.9%
6/10	253	213.1	28.1%
7/10	380	143.4	18.9%
8/10	570	54.4	7.2%
9/10	854	23.1	3.0%
10/10	max	2.3	0.3%
		759.4	**100%**

Figure 6. Graphical depiction of the distribution of land area across the western U.S.

2.4.3 Wildfire Hazard Potential (WHP)

Wildfire Hazard Potential (WHP) is an index developed at the Rocky Mountain Research Station that quantifies the relative potential for wildfire that may be difficult to control (Dillon et al. 2015, Dillon 2018). WHP has traditionally been calculated at 270-m resolution using nationwide outputs from the FSim large-fire simulator. WildEST calculates WHP following the methods established by Dillon et al. (2015) and Dillon (2018) but using higher-resolution inputs including 30-m vegetation inputs, upsampled 30-m burn probability results, and 30-m fire-effects flame-length probabilities from the WildEST wildfire behavior results.

2.4.4 Suppression Difficulty Index (SDI)

The Suppression Difficulty Index (SDI) is an index—first developed as a non-spatial measure by Rodriguez y Silva et al. (2014) and later as a spatially explicit measure (O'Connor et al. 2016, Rodriguez y Silva et al. 2020)—that quantifies the relative difficulty of ground-based fire suppression activities. It factors in

topography, fuels, fire behavior, firefighter line production rates in various fuel types, and accessibility (distance from roads/trails) to assess relative suppression difficulty. The SDI can be used to help inform strategic and tactical fire management decisions.

WildEST utilizes the version of the SDI methods that was adopted for general use by the USDA Forest Service for the 2020 fire season, with minor modifications. The standard SDI process calculates slope steepness from a Digital Elevation Model. We found that approach sometimes produced SDI artifacts due to the slope steepness calculation, so we use LANDFIRE's slope steepness directly.

Fire behavior inputs to the SDI model (flame length and heat per unit area) are typically calculated for a single weather condition for each pixel. Instead, we used the WildEST results for flame length and heat per unit area, which incorporate fine-scale spatial variability in the frequencies of weather types and the greater influence of high-spread conditions, as inputs to the SDI model.

2.5 Risk to Buildings

2.5.1 Sources of Ember Load to Buildings ($SELB$)

The Sources of Ember Load to Buildings ($SELB$) output is a relative index of the number of embers lofted that eventually land on a pixel with non-zero building cover (if a fire were to occur).

To produce $SELB$, WildEST must be supplied with a raster representing the locations of ember "targets" across the landscape, such as buildings. By default, WildEST uses the BuildingCover raster (Scott et al. 2020) produced by the Wildfire Risk to Communities (WRC) project[6] as ember targets. WildEST tracks all embers that land on pixels with nonzero BuildingCover and assigns to the lofting pixel their load as a source of embers to buildings. The result is a raster representing the sources of production of embers that land on or near buildings, which can be useful for fuels management and response planning.

2.5.2 Building Impact

Building Impact is a measure of the concentration of wildfire risk to buildings if a fire were to occur. It combines Building Density, Damage Potential (which is composed of *cRPS* and *ELI*), and an exposure mask that mimics the decay of likelihood into otherwise nonburnable developed areas. It is similar to the Housing-unit Impact measure of the Wildfire Risk to Communities project (Jaffe et al. 2024) but is based on building density rather than housing-unit density, includes the effects of ember load on building exposure, and retains density as the unit of measure rather than converting to count.

$$BuildingImpact = BuildingDen * DP * ExposureMask$$

2.5.3 Building Exposure

Building Exposure is similar to Building Impact but incorporates *BP* through the use of WES instead of *DP*. The exposure mask term is not needed because it is already inherent in the WES raster. This is the most complete measure of the concentration of wildfire threat to buildings of any type—the highest values of Building Exposure have a combination of high building density, high WES (meaning high *BP*, high *cRPS*, and high *cELI*). This is similar to the Housing-Unit Risk measure of the Wildfire Risk to Communities project (Jaffe et al. 2024) but is based on building density rather than housing-unit density, includes the effects of ember load on building exposure, and retains density as the unit of measure rather than converting to count.

$$BuildingExposure = BuildingDen * WES$$

2.5.4 Housing-unit Impact

Housing-unit Impact is a measure of the concentration of wildfire risk to housing units if a fire were to occur. It combines Housing-unit Density, Damage Potential (which is composed of *cRPS* and *ELI*), and an exposure mask that mimics the decay of likelihood into otherwise nonburnable developed areas. It is similar to the Housing-unit Impact measure of the Wildfire Risk to Communities project (Jaffe et al. 2024) but includes the effects of ember load on housing-unit exposure and retains density as the unit of measure rather than converting to count.

$$HUimpact = HUDen * DP * ExposureMask$$

2.5.5 Housing-unit Exposure

Housing-unit Exposure is similar to Housing-unit Impact but incorporates *BP* through the use of WES instead of *DP*. The exposure mask term is not needed because it is already inherent in the WES raster. This is the most complete measure of the concentration of wildfire threat to housing units—the highest values of Building Exposure have a combination of high building density, high WES (meaning high *BP*, high *cRPS*, and high *cELI*). This is similar to the Housing-Unit Risk measure of the Wildfire Risk to Communities project (Jaffe et al. 2024) but includes the effects of ember load on housing-unit exposure and retains density as the unit of measure rather than converting to count.

$$HUexposure = HUDen * WES$$

2.5.6 Functional WUI

The Wildland-Urban Interface (WUI) is the area where homes and other buildings meet or intermix with wildland vegetation. To facilitate the reduction of wildfire risk to homes and businesses, we developed spatial data to allow targeting of mitigation activities in their most-needed locations within a jurisdiction. The Functional WUI dataset was generated from a comprehensive building footprint dataset, fire intensity modeling, and simulation of ember production and transport.

The **Direct Exposure** zone is burnable land cover within 75 m of a structure – the home ignition zone. Reducing fire intensity and ember production in this zone would reduce the exposure of nearby buildings to heat and embers. Buildings in this zone also require hardening of the structure to resist ignition. Residents of this zone should:

- Build or renovate to a very high standard of ignition resistance
- Maintain ornamental and natural vegetation in a way that minimizes flammability within the home ignition zone.
- Make a business or household plan for evacuating in the event of a wildfire

The **Indirect Exposure** zone is nonburnable land cover within 1500 m of burnable land cover that is within 75 m of a structure, meaning that embers and home-to-home spread could reach within this zone. Indirectly exposed structures would benefit from the hardening of the structure to resist ignition from embers and nearby structures, but defensible space is usually not required due to the heavily developed nature of the zone.

- Build or renovate to a high standard of ignition resistance
- Maintain ornamental vegetation in a way that minimizes flammability within the home ignition zone.
- Make a business or household plan for evacuating in the event of a wildfire

The **Little-to-no Exposure** zone is nonburnable land that is within 75 m of a structure but greater than 1500 m from a large (500 ha) contiguous block of burnable land cover. Flames—even from home-to-home spread—and embers are unlikely to reach the Little-to-no-exposure zone, but smoke and evacuations could still impact this area.

- Extend your support to the exposed members of the community, especially those most sensitive (vulnerable).
- Although the need for a wildfire evacuation is unlikely in this zone, it doesn't hurt to have a plan in place in case the need arises.

In addition to the above zones that contain structures, we simulated ember production and transport to identify a **Sources of Ember Load to Buildings** zone (SELB). Fuel treatment in this zone is a priority for reducing ember load to the nearby buildings.

- Implement fuel treatments in this zone to reduce ember production

Finally, the **Structure Transmission Zone** (STZ) is the unpopulated land within about 2.4 km of a group of structures. Fires that originate within or spread to the STZ have an immediate threat of reaching the nearby structures; fuel treatments that slow fire spread in this zone can reduce risk to these structures.

- Implement fuel treatments in these areas to reduce rate of spread and increase firefighter safety (e.g., remove snags)
- Plan for initial attack and evacuations
- Prioritize fire prevention activities

3 References

Albini, Frank A. 1979. Spot fire distance from burning trees- a predictive model. USDA For. Serv. Gen. Tech. Rep. INT-56.

Albini, Frank A. 1983. Potential spotting distance from wind-driven surface fi res. USDA For. Serv. Res. Pap. INT-309.

Albini F. A., Baughman, R. G. 1979. Estimating windspeeds for predicting wildland fire behavior. Res. Pap. INT 221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Alexander, Martin E. 1982. Calculating and interpreting forest fire intensities. Can. J. Botany. 60(4) 349-357.

Alexander, Martin E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. In Proceedings of the eighth conference on fire and forest meteorology (Vol. 29, pp. 85-04). Society of American Foresters, Detroit, MI, USA.

Andrews, Patricia L. and Richard C. Rothermel. 1982. Charts for interpreting wildland fire behavior characteristics. Gen. Tech. Rep. INT-GTR-131. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 21 p.

Catchpole, E.A., Alexander, M.E., Gill, A.M. 1992. Elliptical-Fire Perimeter- and Area-Intensity Distributions. Can. J. For. Res. 22, 968-972.

Catchpole, E.A., de Mestre, N.J., Gill, A.M. 1982. Intensity of Fire at Its Perimeter. Aust. For. Res. 12, 47-54.

Dillon, G. K., Menakis, J., Fay, F. 2015. Wildland fire potential: A tool for assessing wildfire risk and fuels management needs. In: Keane, R. E., Jolly, M., Parsons, R., Riley, K. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 60-76.

Dillon, G. K. 2018. Wildfire Hazard Potential (WHP) for the conterminous United States (270-m GRID), version 2018 continuous. 2nd Edition. Fort Collins, CO: Forest Service Research Data Archive.

Finney, Mark, A. 1998. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4, Revised 2004, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M.A., McHugh, C., Grenfell, I.C., Riley, K.L., Short, K.C., 2011. A Simulation of Probabilistic Wildfire Risk Components for the Continental United States. Stochastic Environmental Research and Risk Assessment 25.7, 973-1000.

Gannon, Benjamin M.; Thompson, Matthew P.; Wei, Yu. 2021. An operationally relevant framework for mapping spot fire transmission potential. Environmental Sciences Proceedings, 3, 13. https://doi.org/10.3390/10.3390/IECF2020-08001

Jaffe, Melissa R.; Scott, Joe H.; Callahan, Michael N.; Dillon, Gregory K.; Karau, Eva C.; Lazarz, Mitchell T. 2024. Wildfire Risk to Communities: Spatial datasets of wildfire risk for populated areas in the United States. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2020-0060-2

O'Connor, C.D., Thompson, M.P., Rodriguez y Silva, F. 2016. Getting ahead of the wildfire problem: quantifying and mapping management challenges and opportunities. Geosciences, 6(3), 35.

Rodriguez y Silva, F.; O'Connor, C.D.; Thompson, M.P.; Molina, J.R.; Calkin, D.E. (2020). Modeling Suppression Difficulty: Current and Future Applications. International Journal of Wildland Fire, 29(8), 739-751.

Rodríguez y Silva, F., Martínez, J.R.M., González-Cabán, A. (2014) A methodology for determining operational priorities for prevention and suppression of wildland fires. International Journal of Wildland Fire 23, 544-554.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels (Vol. 115). Intermountain Forest & Range Experiment Station, Forest Service, US Department of Agriculture.

Schroeder, M.J. 1969. Ignition probability. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. Unpublished report.

Scott, Joe H.; Reinhardt, Elizabeth D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 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.

Scott, Joe H. 2006. Off the Richter: magnitude and intensity scales for wildland fire. In Proceedings of the 3rd International Fire Ecology and Management Congress: Changing Fire Regimes: Context and Consequences, San Diego, CA, USA (pp. 13-17).

Scott, Joe, Thompson, M., Calkin, D., 2013. A Wildfire Risk Assessment Framework for Land and Resource Management. In, Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, p. 92.

Scott, Joe H. 2020. A Deterministic Method for Generating Flame-Length Probabilities. Proceedings of the Fire Continuum-Preparing for the future of wildland fire; 2018 May 21-24; Missoula, MT. U.S. Forest Service RMRS P-78.

Scott, Joe H.; Brough, April M.; Gilbertson-Day, Julie W.; Dillon, Gregory K.; Moran, Christopher. 2020. Wildfire Risk to Communities: Spatial datasets of wildfire risk for populated areas in the United States. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2020-0060

Short, Karen C. 2022. Spatial wildfire occurrence data for the United States, 1992-2020 [FPA_FOD_20221014]. 6th Edition. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2013-0009.6.

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