Understanding stochastic wildfire simulation results

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Executive summary

Stochastic simulations of wildfire occurrence and growth have become an integral part of both wildfire incident management and land management planning applications. The FSPro simulation system, implemented in the online Wildland Fire Decision Support System (WFDSS), acknowledges that weather inputs to wildfire growth modeling systems—wind and fuel moisture—are uncertain beyond just a few days, and therefore simulates the range of potential growth possible given the distribution of wind and fuel moisture inputs. The FSim wildfire occurrence and growth simulation system, like FSPro, acknowledges uncertainty in weather inputs, but also accounts for uncertainty regarding the likelihood of wildfire starts, where they are likely to occur on the landscape, and their duration. The MTT function of FlamMap5 relies on a single problem-fire weather and duration scenario, but acknowledges uncertainty in where a problem-fire may ignite on the landscape.

This document and companion set of PowerPoint slides (pending) is designed to provide awareness-level information about these stochastic wildfire simulation systems by describing their inputs and outputs, along with a simplified description of how they work. The document focuses heavily on FSim, the most complex of the three systems identified above. FSim is being used in an increasing array of land and fire management planning applications. Although only a relatively small set of wildfire modelers currently has access to FSim, a wide range of practitioners—fuel specialists, fire ecologists, non-wildfire resource specialists, fire management officers, researchers, *etc*.—have access to analyses based on its results. This document is designed to help those practitioners correctly interpret the results of FSim and its related stochastic wildfire simulation systems.

1. Introduction

1.1 What is stochastic wildfire simulation?

Wildfire simulation systems can be classified into two types: deterministic and stochastic. In a deterministic simulation system, there is no accounting for uncertainty or variability in model inputs, so you get the same result every time the simulation is run. FARSITE and the basic use of FlamMap are deterministic wildfire simulation systems (Table 1). Stochastic simulation is the numerical simulation of a phenomenon in a way that incorporates uncertainty in the simulation inputs. In a stochastic simulation system, uncertainty and variability in model inputs are inherently incorporated into the simulation. Many thousands of iterations are conducted and then summarized into an overall result. Commonly used stochastic wildfire simulation systems include FSPro, FSim, and the Minimum Travel Time (MTT) function of FlamMap5 when used with random ignitions.

Table 1—Matrix showing the primary wildfire modeling systems used for simulating one or many wildfires and one or many weather scenarios. FARSITE is a deterministic simulation system used for one wildfire and one weather scenario; the others are stochastic, incorporating variability in weather and/or wildfire occurrence.

	One weather scenario	Many weather scenarios
One fire	FARSITE[a]	FSPro[b]
Many fires	FlamMap5[c]	FSim[d]

[a]FARSITE is desktop software available at www.firelab.org; its functionality is replicated in the Wildland Fire Decision Support System (WFDSS) as "Near-term fire behavior" analysis.

[b]FSPro is currently available only within WFDSS.

[c]FlamMap5 is desktop software available at www.firelab.org. Some of its functionality is replicated in WFDSS; however, the stochastic simulation feature of FlamMap5 described in this paper is not available within WFDSS.

[d]FSim is custom software developed at the Missoula Fire Sciences Laboratory.

Sources of uncertainty in stochastic wildfire simulation systems include 1) fire weather, 2) fire occurrence, and 3) fire containment (the likelihood of fire containment on each day of a simulation). Fuel and topography—well known to affect wildfire behavior—are considered constant in these stochastic simulation systems. The variable inputs related to fire-weather include wind speed, wind direction and fuel moisture contents. The variable inputs related to wildfire occurrence are the frequency (number of starts per unit time), timing (in relation to seasonal drying) and location (spatial pattern) of possible wildfire starts.

1.2 Types of stochastic wildfire simulation systems

Stochastic simulation systems inherently incorporate variability in their inputs. Three stochastic simulation systems have been developed for operational or research use in a variety of contexts (Table 2).

Table 2. Review of the characteristics of three widely-used wildfire modeling systems that model natural variability with probabilities. From Scott and others (2013).

Characteristic	FSPro	FlamMap5	FSim
Planning context & decisions supported	Suppression strategy development	Fuel treatment planning, "problem fire" analysis	Fire management plan development, preparedness and response planning, fuel treatment planning
Duration	Days to weeks	One to a few burning periods	Entire wildfire season
Fires considered	Individual escaped wildfire	Problem-fire ignitions	All large-fire ignitions
Simulation type	One wildfire, many weather scenarios	Problem fires, extreme weather scenarios	Large wildfires, all weather scenarios
Type of burn probability	Conditional on current wildfire location and specified time period	Conditional on specified weather scenario and duration	Annual (full wildfire season)
Source of Variation	Wind speed, wind direction, fuel moisture content, fuelscape	Ignition locations, fuelscape	Wind speed, wind direction, fuel moisture content, fuelscape, ignition location, ignition probability, containment probability, wildfire duration

FSPro is a stochastic simulation system that simulates many weather scenarios for one wildfire of a specified duration. Like FARSITE, FSpro simulates wildfire growth from a known point or polygon for a pre-determined time period of time (typically one to several weeks). Unlike FARSITE, FSPro inherently accounts for uncertainty in weather over the course of the simulation.

The FlamMap5 MTT function simulates wildfire growth from many wildfire start locations for a single "problem fire" weather scenario. The problem-fire weather scenario is a combination of fuel moisture contents, wind speed and wind direction that tends to produce challenging short-duration (1- to 2-day) wildfire events on the landscape under study. The same problem-fire weather scenario is used to simulate wildfire growth for thousands of randomly selected wildfire-start locations. Randig is a command-line version of FlamMap5 used in research and development applications; it has the ability to simulate more complex weather and wildfire-duration scenarios.

FSim is a stochastic simulation system that simulates the occurrence, growth, suppression and intensity of wildfires across a large landscape. The wildfire occurrence sub-model of FSim is based on annual ignition likelihood, so FSim's results are on an annual basis. Section 2 (below) describes FSim in detail.

1.3 How stochastic systems estimate pixel burn probability

A basic output of all three stochastic wildfire simulation systems is a raster (grid) of burn probability (*BP*), expressed as a decimal fraction (for example, 0.01 for a 1-in-100 chance of burning). All three systems estimate burn probability in much the same way. First, each system conducts many thousands of iterations; each iteration contains random elements of wildfire occurrence and/or fire weather, and therefore each iteration produces a different result; the results can be expressed as a final wildfire perimeter (or set of perimeters). Next, at each pixel across the landscape, the number of times a wildfire perimeter overlaps the pixel is counted. That count, divided by the number of iterations, is the burn probability for the pixel.

We will illustrate how stochastic wildfire simulation systems estimate pixel burn probability using a portion of an FSim run for the Sierra Nevada mountains that spans the Sierra National Forest and Yosemite National Park (Figure 1). This portion of the landscape covers roughly 1 million acres. The 32,000-ac lower South Fork Merced River sub-watershed (6th-level HUC) is shown in Figure 1 in crosshatch, and a selected pixel within the sub-watershed is shown as a black square. This sub-watershed and selected pixel will be used to illustrate how to summarize FSim results for a pixel and an area in this and later sections.

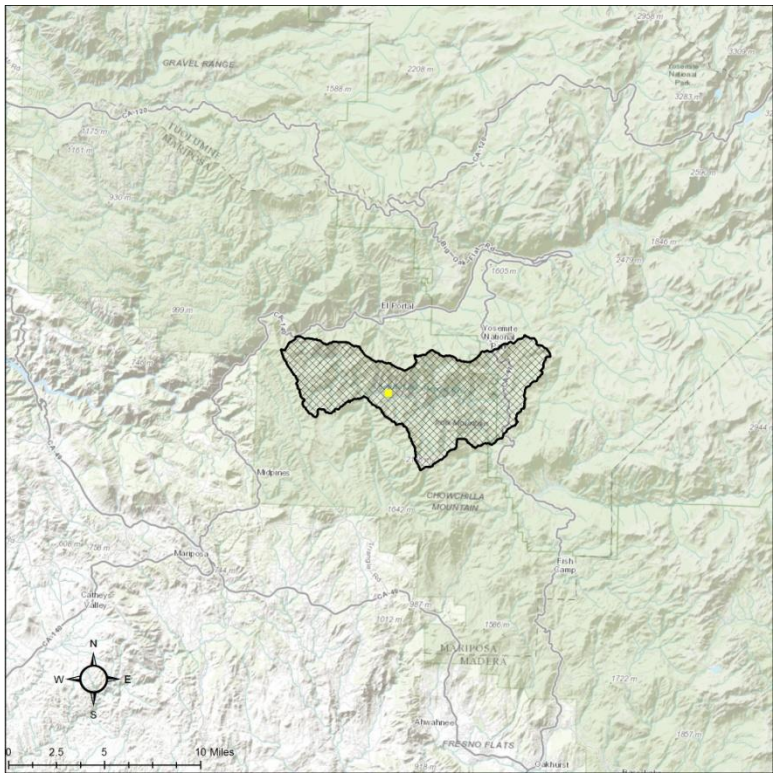

Figure 1. A 1 million acre portion of the 26 million acre landscape used for an FSim run for the Sierra Nevada mountains. The lower South Fork of the Merced River sub-watershed (6th-level HUC) is shown in crosshatch, and a selected pixel near the center of the sub-watershed is shown as a yellow square.

The 20,000-iteration FSim run produced a complete set of simulated wildfire perimeters (Figure 2). Thousands of wildfire perimeters overlap each other; so only the top-most perimeters are visible. The lower South Fork of the Merced River sub-watershed (6th-level HUC) is shown in crosshatch; a selected pixel within the sub-watershed is shown as a black square.

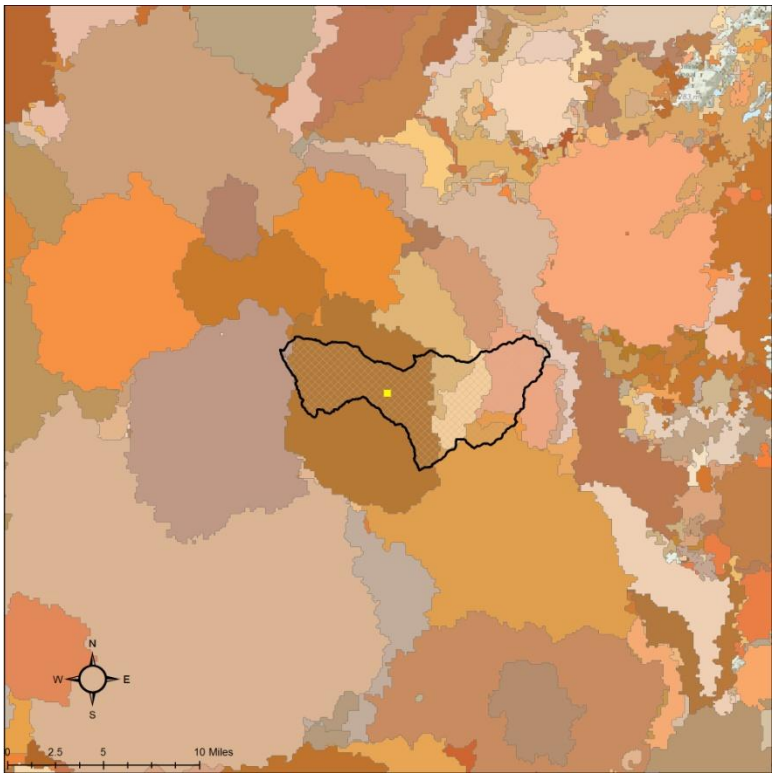

Figure 2. A complete set of simulated final wildfire perimeters (earthtones) for a 1 million-acre portion of a 20,000-iteration FSim run. The yellow square represents selected pixel within the lower South Fork Merced River sub-watershed (6th level HUC) outlined in black.

Now, imagine placing a pin through the selected pixel and highlighting all of the perimeters the pin goes through. For example, Figure 3 shows one wildfire perimeter that burned across the selected pixel. Much is known about each individual wildfire from FSim's outputs. This one started on Julian day 187 (July 6) at the 100th percentile ERC(G) value of 119, and actively burned for 45 days, eventually burning 57,000 acres. The start location, shown as a blue dot in Figure 3, is more than 5 miles from the selected pixel.

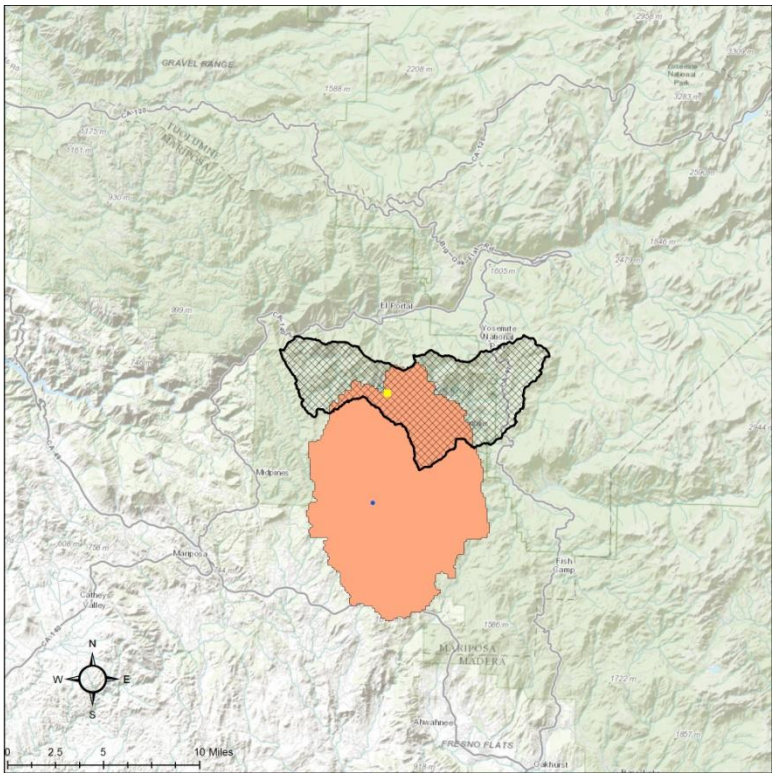

Figure 3. A simulated wildfire perimeter (orange) that burned the selected pixel (shown as a yellow square). The start location of the simulated wildfire is shown as a blue dot, and the lower South Fork of the Merced River sub-watershed is shown in crosshatch.

There are 330 additional wildfire perimeters that burned the selected pixel during the 20,000-iteration FSim run, for a total of 331 (Figure 4). The start locations of these wildfires that burned the selected pixel originate in an area encompassing roughly 175,000 acres (Figure 4).

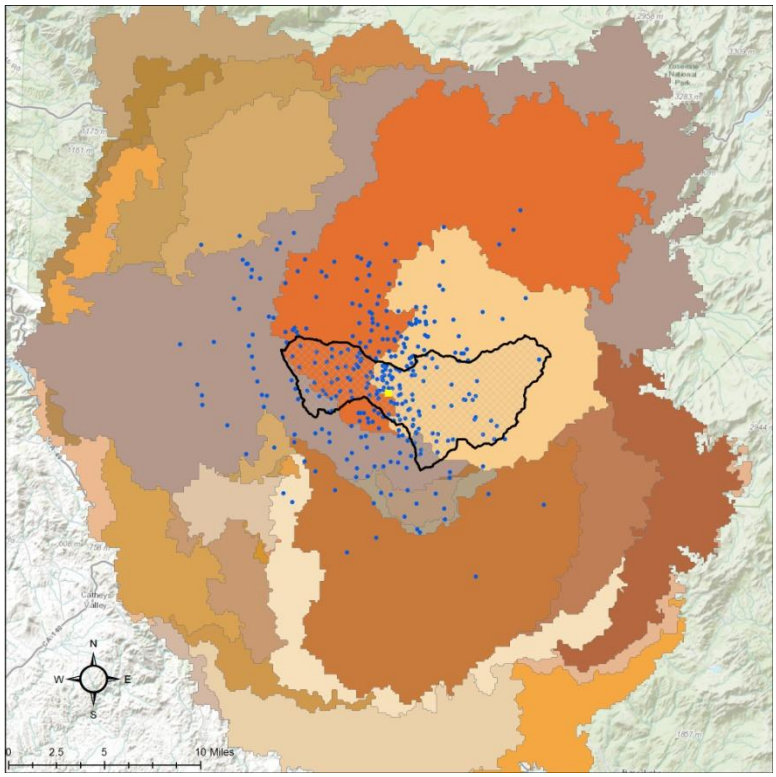

Figure 4. The 331 perimeters (earthtones) that burned the selected pixel (black square) within the lower South Fork of the Merced River sub-watershed (crosshatch). The start locations of these 331 wildfires are shown as blue dots.

The burn probability at the selected pixel is calculated as the number of times it burned divided by the number of iterations in the simulation

$$BP = \frac{Number\ of\ times\ burned}{Number\ of\ iterations} = \frac{331}{20{,}000} = 0.01655$$

A burn probability of 0.01655 means that there is a 1 in 60 chance (1/0.01655) that this particular pixel will burn in a large wildfire in one year. The odds are 59:1 against burning. Figure 5 illustrates FSim's *BP* produced for the example landscape described above.

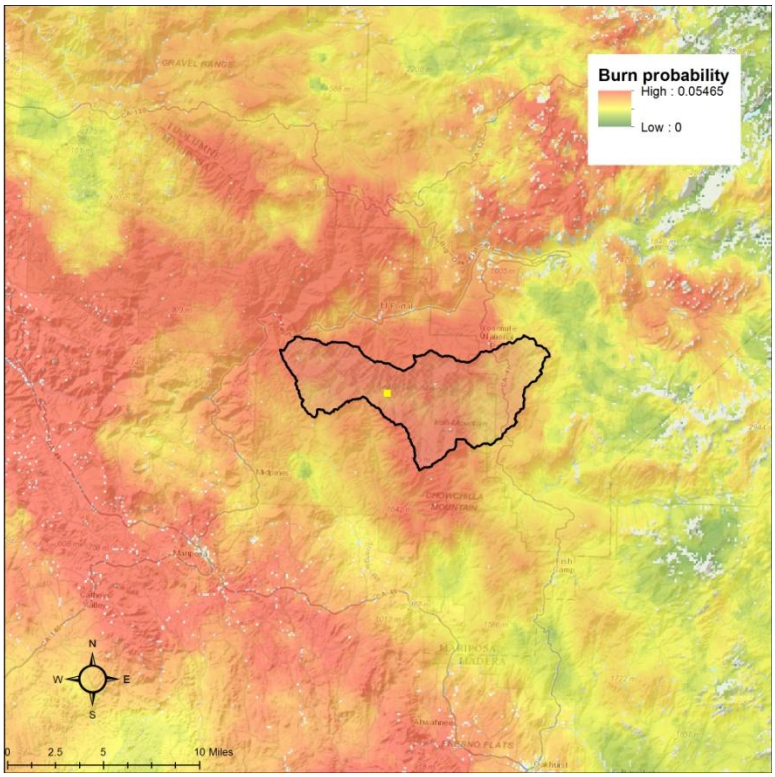

Figure 5. Burn probability across the landscape surrounding the lower South Fork of the Merced River sub-watershed (outlined in black).

Although the same basic approach is used to calculate *BP* in all three systems, the interpretation of the *BP* results differs considerably among the systems.

FSim

FSim produces and annual large-fire *BP* result, meaning that it represents that annual probability that a large wildfire will burn the pixel in question. Because large wildfires are responsible for burning the overwhelming majority of all acres burned (more on that later), FSim's large-fire *BP* is also a good representation of the likelihood of burning in a wildfire of any size.

FlamMap5

FlamMap5 produces a conditional *BP*, meaning the *BP* given the condition that a problem-fire occurs somewhere in the study area landscape. The absolute problem-fire *BP* at a pixel has little inherent meaning and cannot be compared across different assessment landscapes. All other things equal, a larger landscape will result in a smaller problem-fire *BP* at any pixel, because the assumed problem wildfire could occur anywhere on the landscape. Nonetheless, the relative problem-fire *BP* across a landscape provides a landscape-scale view of what parts of the landscape are most and least likely to burn in a problem fire.

FSPro

The *BP* estimated by FSPro has similarities to both FSim and FlamMap5. Like FSim, it pertains to a defined period of time. However, whereas FSim *BP* refers to a whole year (annual), FSPro *BP* refers

to whatever period of time was specified for the simulation, usually one to several weeks. Knowing the FSpro simulation duration is critical to correct interpretation of its results. FSpro results are also conditional in that certain pre-conditions may exist for a particular simulation. For one, the FSpro result is conditioned on the current wildfire location. More importantly, FSpro permits the user to specify a period of deterministic fire weather, overriding any stochastic variability in weather during that period.

1.4 How stochastic systems estimate flame-length probability

In addition to estimating pixel *BP*, some stochastic wildfire simulation systems also estimate the conditional flame-length probability (*FLP*)—the probability distribution of flame length at a pixel, given the condition that a wildfire burns the pixel. With a deterministic simulation system like FARSITE, a simulated wildfire burns a pixel only once, and an estimate of the flame length at that pixel can be made deterministically. For example, when a pixel burns in FARSITE, the set of live and dead fuel moistures, wind speed and direction, fuel characteristics, and orientation of the flame front with respect to the heading direction at the pixel are known for the time of burning, so flame length can be calculated without variation or uncertainty. With a stochastic simulation system, a given pixel can burn many times, each time in a potentially different fire environment or with a different relative spread direction (heading, flanking, backing). In other words, each iteration can result in a different flame length at a given pixel.

Stochastic simulation systems address this variability in two ways. First, and available only in FSim, the mean fireline intensity value of each iteration that burns a pixel can be calculated. FSim makes this calculation for fireline intensity (kW/m) and produces a grid representing the mean fireline intensity (*MFI*) of the iterations that burned the pixel. FSim does not generate a similar grid of mean flame length; instead, FSim tallies the number of times a pixel burns in a flame-length class and divides that by the number of times the pixel burned in total. This result is the conditional flame-length probability for each flame-length class. FSim currently uses the standard Fire Intensity Levels (FILs) for the flame-length classification (Table 3).

Table 3. Classification of flame length by Fire Intensity Level.

Fire Intensity Level	Flame length (ft)
FIL1	0-2
FIL2	2-4
FIL3	4-6
FIL4	6-8
FIL5	8-12
FIL6	12+

Let's return to the *BP* example from the previous section, where we identified 331 simulated wildfires that burned a pixel. For each of those cases, FSim knew the fire environment for the day the wildfire burned the pixel—wind speed and direction, and fuel moistures—as well as the relative spread direction where and when the wildfire burned across the pixel. This detailed information is not archived in the simulation systems, but to illustrate the calculation of *FLP* let's assume that it is

(Table 4). Coupling these fire environment and spread direction inputs with the fuel and topography characteristics at the pixel, we can also deterministically simulate flame length and classify it into an FIL (Table 4). By querying the fire modeling landscape file, it was determined that surface fuel at the pixel was represented by fuel model GR2, with no overlying forest canopy. The pixel is located on a steep southwest-facing slope.

Table 4. Fire environment variables and relative spread direction for a hypothetical sample of 10 wildfires (out of 331) that burned a selected pixel within the lower South Fork of the Merced River sub-watershed. The pixel is on a steep southwest-facing slope and is represented by fuel model GR2 (grass about 1-2 feet tall). Fine dead and live herbaceous moisture content values were associated with the 80th, 90th and 97th percentile bins.

Iteration	Moisture Contents (percentile)	Wind Speed (mi/h)	Wind Direction	Headfire Flame Length (ft)	Relative Spread Direction	Actual Flame Length (ft)	Actual Fire Intensity Level
1	97	5	SW	5.1	Head	5.1	3
2	97	5	S	5.0	Head	5.0	3
3	90	15	W	5.2	Flank	2.4	2
4	80	10	N	2.3	Back	0.8	1
5	80	5	S	2.8	Flank	1.5	1
6	90	25	SW	6.9	Flank	2.8	2
7	80	10	W	5.9	Flank	3.0	2
8	80	20	SW	8.2	Flank	3.6	2
9	90	5	S	3.7	Flank	3.2	2
10	90	15	SE	4.7	Head	4.7	3

Headfire flame length can be calculated from the fire environment variables—fuel, topography and weather (fuel moisture, wind speed, and wind direction). However, the actual flame length simulated at the pixel also requires knowledge of the relative spread direction at the time the wildfire burned the pixel—that is, whether the wildfire was a heading fire, flanking, or backing[1]. After making the adjustment for relative spread direction, FSim simply tallies the Fire Intensity Level associated with the flame length.

The conditional flame-length probability for a given fire intensity level (FLP_{FIL}) is the number of times the pixel burns at the FIL divided by the total number of times the pixel burned. *FLP* is a conditional probability, given that the pixel burned, so the sum of *FLP* across all FILs is always 1 (Table 5).

[1] For clarity, only these three nominal spread directions are shown on the table, but stochastic simulation systems work with relative spread direction as a continuous variable in degrees from the maximum spread direction.

Table 5 Flame-length probability (*FLP*) for an FIL is the number of times the pixel burns at the FIL divided by the total number of times the pixel burned. The sum of *FLP* across all FILs is always 1.

	Tally	*FLP*
FIL1	5	0.0151
FIL2	234	0.7069
FIL3	90	0.2719
FIL4	2	0.0060
FIL5	0	0.0000
FIL6	0	0.0000
sum	331	1.0000

FSim uses six flame-length classes, so there are six corresponding *FLP* grids in addition to the overall *BP* grid. FSpro currently does not produce *FLP* grids or any other measure of wildfire intensity. FlamMap5 can use either the same six-class classification used by FSim or a 20-class classification (in metric units).

1.5 Conclusion

Stochastic wildfire simulation systems incorporate inherent variability and uncertainty in their inputs into the simulation, producing probabilistic outputs. Three primary stochastic wildfire simulation systems are in common use. FSPro simulates many weather scenarios for one wildfire over the course of one to several weeks. It is used to support wildfire incident management decisions. FlamMap5 simulates many randomly-located wildfires but only one problem-fire weather scenario for a specified—and usually short—duration. It is used to assess wildfire likelihood for a common but problematic wildfire event. Finally, FSim simulates many randomly located wildfires and many weather scenarios for many thousands of simulated wildfire seasons. It is used to assess landscape scale wildfire likelihood when considering the full range of possible wildfire sizes.

All three stochastic simulation systems estimate burn probability in much the same way—by counting the number of iterations in which the pixel burned by the total number of iterations. In addition to estimating burn probability, FlamMap5 and FSim also estimate the distribution of flame length values experienced at the pixel, called the flame-length probability. These simulation systems incorporate the effects of variability in wind speed, wind direction, fuel moisture and relative spread direction—heading, flanking, and backing—on the probability distribution of flame length.

2. About FSim

FSim—the large-fire simulation system—is a comprehensive wildfire occurrence, growth and suppression simulation system that estimates wildfire likelihood and intensity across a large landscape that inherently addresses randomness and uncertainty in its inputs (Finney and others 2011). FSim is a stochastic simulation system that simulates many thousands of iterations, then integrates those iterations into a coherent result. An FSim iteration spans one entire year. For that reason, the terms "fire season" and "year" are often used synonymously with iteration. Simulations with FSim typically use ten- to fifty-thousand iterations.

2.1 FSim focuses on "large" wildfires

FSim is called the large-fire simulation system because it focuses on the relatively small fraction of wildfires that escape initial attack and become large. This focus is justified by the historical distribution of fire sizes. Nationwide, the largest 1 percent of wildfires account for between 80 and 99 percent of the area burned, depending on geographic region (Strauss and others 1989). That is, most wildfires contribute very little to total area burned, whereas the very few large wildfires account for nearly all of the total area burned.

This is not to say that small wildfires are trivial to fire management in general. Fire management activities—prevention and preparedness in particular—are a significant reason for this unequal distribution. Successful initial attack, a direct result of preparedness, is a significant factor in keeping most wildfires small. All wildfire ignitions, whether they are become large or stay small, are important for planning prevention and preparedness activities. But once we move to the realm of simulating the potential for wildfire effects (such as annual area burned) the disproportionately large amount of area burned by the largest fires suggests that we focus on simulating the relatively few large wildfires that burn nearly all of the area.

No initial attack modeling

FSim does not simulate wildfire prevention activities or initial attack success. Instead, FSim assumes that the recent wildfire history on the landscape, which includes the effects of prevention and initial attack success, is a guide to future large-fire occurrence. That is, FSim does not, in its current form, simulate the effects of changes in prevention or preparedness on large-fire occurrence and subsequent changes in burn probability. A fire management unit with many ignitions—justifying significant preparedness funding—may also have low burn probability. In this case, the low burn probability does not necessarily mean that preparedness funding is unjustified. In fact, lower burn probability is, in part, a result of preparedness expenditure, which serves to keep more wildfires trivially small. FSim assumes that prevention, preparedness and initial attack success is reflected in the recent historic wildfire occurrence record and continues at that level.

Basic FSim operation

Several terms used in this section are specifically defined for use in FSim. A single use of FSim is called a simulation, or simply a 'run'. A simulation consists of many thousands of iterations. An

iteration is the simulation of an entire year, ending with the last day of the calendar year. Each iteration can result in any number of wildfires, including zero.

FSim consists of three wildfire simulation modules (occurrence, growth, and suppression), which are built on the foundation of a fourth module—weather generation. The weather generation module simulates daily values of the Energy Release Component (ERC) of the National Fire Danger Rating System (NFDRS; citation). The occurrence module simulates the likelihood that a wildfire will escape initial attack and become a large wildfire. This likelihood is calculated as a function of ERC-G for each day of a simulation. The growth module simulates the daily growth of a newly ignited or ongoing wildfire, through both flame front spread and spotting (new fires ignited by embers ahead of the flaming front), as a function of fuel, weather and topography. The suppression module simulates the likelihood that, on any given day of a simulation, the simulated wildfire will be contained and therefore no longer grow on subsequent days.

As a stochastic simulator, FSim simulates wildfire occurrence, growth and suppression for thousands of iterations, then compiles those results to produce raster datasets which indicate: 1) the annual probability that wildfire will burn each discrete part of the landscape (pixel), and 2) the mean fireline intensity given that it does. It is important to note that there is no temporal component to FSim beyond a single wildfire season. FSim performs repeated iterations of one wildfire season, defined by the fuel, weather, topography and wildfire occurrence inputs provided. FSim does not simulate how its simulated wildfires might influence the likelihood or intensity of future wildfires. Each year represents an iteration of how fires might burn given the current landscape and historic weather conditions from the past few decades.

2.2 FSim outputs

Raster

FSim's ASCII-format raster outputs include annual burn probability *(BP*) and mean fireline intensity (MFI). FSim's remaining raster outputs are stored a text file (often referred to as the "FLP text" file). After post-processing this FLP text file in a GIS, FSim also produces six flame-length probability (*FLP*) rasters corresponding to the six FILs (Table 3). These rasters are described in sections 1.3 and 1.4 above.

Vector

In addition to the raster outputs, FSim can also save as output the final perimeters of each simulated wildfire during the entire simulation. These perimeters are saved as polygons in one or more ESRI Shapefiles. The attribute table provided with each shapefile indicates several important characteristics of each wildfire, including:

- iteration identifier
- final wildfire size (ac)
- start location (X-Y)
- start date (Julian date)
- ERC(G) on start date
- Percentile ERC(G) on start date

- number of active burn days

This set of simulated final perimeters with associated attributes can be considered an "event set" for the landscape. An event set is a set of *N* elements (events) generated by a stochastic simulator as possible future outcomes of wildfire occurrence, growth and behavior. With stochastic wildfire simulations, an event is the result for one complete wildfire season, during which any number of wildfires—including zero—may have been simulated to occur. Each event has an annual probability of occurring of $1/N$, where N is the number of iterations in the simulation.

The information available for each event in the set can be extended by GIS analysis to summarize conditional fire effects within each perimeter. For example, if a raster representing the sediment volume produced if a wildfire occurs, then summing the values within a perimeter is the total volume produced by the simulated wildfire, which can then become an additional attribute of the event set.

2.3 Conclusion

FSim is a comprehensive wildfire occurrence, growth and behavior simulation system that incorporates stochasticity in wildfire start location, fuel moisture, wind speed and direction and wildfire duration. FSim focuses on "large" wildfires because a relatively small number of the largest wildfires account for the overwhelming majority of the acres burned by wildfire.

FSim produces both raster (gridded) and vector (point and polygon) outputs. Raster outputs include the annual burn probability and the conditional flame-length probabilities in six flame-length classes. FSim also produces an ESRI Shapefile with the final wildfire perimeters of all simulated wildfires. The attribute table provided with the Shapefile lists several important characteristics of each wildfire.

3. The relationship between FSim results and fire history measures

Both FSim results and fire history measures provide information about the likelihood of wildfire. When considering these two information sources, it is critical to differentiate between wildfire likelihood at a point (or quasi-point[2]) and likelihood for an area. Whereas a point might be an individual tree at which past fire occurrence can be estimated, a quasi-point is a group of trees that collectively indicate past fire occurrence for a relatively small area. Likelihood for an "area" can refer to any size, but it is important to know and report the size of the area. Some area-based measures of fire history lose their relevance for very large areas.

Because the records for relatively small fires are often incomplete, it is most useful to limit this summary to the "large" fires that account for the vast majority of area burned. What is considered a large fire may differ among study areas due to differences in fuel and climate, but typically varies from 10 to 300 acres.

3.1 Fire history

Summary measures of past fire history are available for points and areas. In some cases, the term "natural" indicates a measure of fire history for a time period that does not include the effects of European settlement, usually before the end of the 19th century. The term "contemporary" typically refers to the most recent several decades.

An important characteristic of both point and area-based measures of fire history is that they are measured over time (several decades, up to several centuries) and are therefore influenced by complex spatial and temporal fuel dynamics—the occurrence of wildfire in one year influences occurrence in later years. In other words, the likelihood of burning a given point on the landscape is not necessarily constant in time. For example, in the years immediately following a wildfire, the likelihood of having another fire may be temporarily reduced while vegetation grows and fuel accumulates[3].

Point measures

A measure of fire history at a point is the mean fire-return (fire-free) interval, which indicates the average time interval (in years) between successive fires at a particular point on the landscape. Historical fire return intervals determined by tree-ring dating of fire scars are point fire-return intervals.

Area measures

A good measure of fire history for an area is the fire rotation (also called the natural fire rotation, fire-rotation interval, and fire cycle)—the estimated time required to burn an area equivalent to the size of the study area (A), given the historical area burned (AB_t) during a specified period (t).

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[2] In the wildfire context, a quasi-point is a homogeneous land area for which a wildfire occurring in any one part of the area could reasonably be assumed to have burned the entire area—i.e., small enough to be considered a point.

[3] This dependence from one year to the next differs from many other natural hazards like tornadoes and hurricanes, which are usually considered independent of one another from year to year.

$$fire\ rotation = \frac{t}{AB_t/A}$$

For example, if 10% (1000 ac) of a 10,000-ac study area burned during a ten-year period, then the fire rotation would be 100 years, or 1% per year. Note that there is no accounting for multiple burns at one location, so fire rotation does not indicate the time required to burn *every part* of the study area, just the equivalent land area. The inverse of fire-rotation interval is a rough estimate of the mean point burn probability in the study area.

Two useful summaries of contemporary fire history in a study area are the 1) mean annual number of wildfires per million acres of study area

$$\frac{N_t}{t} * \frac{1{,}000{,}000}{A}$$

where N_t is the number of fires during time period t, and 2) mean annual number of acres burned per million acres of study area

$$\frac{AB_t}{t} * \frac{1{,}000{,}000}{A}$$

These two measures are useful for parameterizing and calibrating FSim. Dividing the mean annual area burned by the burnable area of the landscape produces an estimate of the landscape-wide burn probability, which can be used for calibration in place of the mean annual area burned itself.

It may also be useful to note the mean size of large fires during the historical period as well.

$$\frac{AB_t}{N_t}$$

3.2 FSim results

FSim produces both raster (point/gridded) and polygon-based (area) results. A raster is a grid of cells across the landscape. The grid cell size of these rasters is typically small enough that it can be assumed that the *BP* applies to the whole cell, so a cell can be considered equivalent to a point. An important characteristic of FSim results is that they apply to one point in time, whereas fire history measures apply to a period of time that can span several decades up to several centuries. For example, as mentioned earlier, FSim burn probabilities may thus be lower in recently burned areas.

Point results

The raster result is a grid of annual burn probability *(BP*) expressed as a decimal fraction. If *BP* were constant through time, inverting the *BP* value would give the average wait time, in years, for a wildfire to visit the pixel, which would be analogous to a point fire-return interval. That calculated time interval implicitly assumes that *BP* is constant through time, not only at the pixel in question but also in the surrounding pixels. However, we know that *BP* is <u>not</u> constant in time, so *BP* values cannot be used to reliably infer the average wait time or fire-return interval. For example, let's say the *BP* for a grid cell is currently 0.01, and let's further say that the grid cell burns this year in a large

wildfire, significantly affecting fuel conditions in a large area around the pixel. If FSim were run again using a fuelscape updated to reflect conditions after this fire, we would see that *BP* likely went way down in the year after it burned, then perhaps slowly increase as fuel accumulated. Did the mean fire-return interval increase suddenly after the wildfire? No, it didn't. The temporal trend in *BP* over time contributes to overall fire-return interval. FSim estimates only the likelihood of wildfire in one year, not its recurrence through time, which would require simulation of post-fire fuel dynamics as well as simulation of other fuel disturbances such as windthrow and insect and disease outbreaks.

So, if FSim's *BP* results can't be compared to a fire-return interval, how can they be interpreted? Only as a measure of likelihood in the current year. There are several ways to present that likelihood in addition to expressing *BP* as a decimal fraction. One way is to express the likelihood as "odds", as is done in some gambling applications. If the annual *BP* at a pixel is 0.01, then 1 in 100 iterations is expected to result in burning. Odds are the ratio of burning to not-burning, so in this case we would say the odds are 99:1 (say 99-to-1) against burning. Another way to express this is to say the likelihood is 1-in-100 iterations. Unfortunately, we cannot say the fire-return interval is 100 years, because that would require assuming that *BP* is constant over time.

Area results

FSim produces a polygon representation of each simulated wildfire, and each polygon is attributed with the wildfire season iteration during which it was simulated. By overlaying those perimeters on a "study area", the annual likelihood that a wildfire reaches any part of the study area can be estimated. However, the same caveats about the lack of temporal simulation apply here as well. The inverse of this probability is not necessarily an area-based fire-return interval.

Section 4.2 below describes a relatively new summary of area-based FSim results that can be used to identify the likelihood of exceeding certain thresholds of fire effects, or to identify the fire effects associated with certain likelihoods of occurrence—e.g., the 100-year wildfire event.

3.3 Conclusion

FSim produces estimates of contemporary burn probability for a single landscape condition that exists at a snapshot in time, whereas fire history measures like fire-return interval and fire rotation integrate complex spatial and temporal interactions among successive wildfires through time. Although it is convenient to think of FSim results in terms of a fire rotation or return interval, that interpretation is technically incorrect.

Instead, it is best to think of burn probability in terms of its native decimal fraction, or in terms of odds. In other words, an annual *BP* of 0.01655 does not necessarily represent a fire-return interval or fire rotation of 60 years, but it does represent a 1-in-60 chance of burning in the current year, which means the odds are 59:1 against burning.

4. Summarizing FSim results

This section describes common methods for summarizing FSim's raster and vector results for any summary unit. Typical summary units may include:

- the entire landscape
- a national forest or similar unit
- an individual ranger district or similar unit
- a watershed (5th-level HUC) or sub-watershed (6th-level HUC)
- a resource or asset polygon (a municipal watershed, for example)

In the following sub-sections, methods for summarizing raster and vector results within a summary unit will be presented. The summary unit in the following examples will again be the 32,000-ac lower South Fork of the Merced River sub-watershed that was introduced earlier.

4.1 Burn probability

Mean pixel BP

The arithmetic mean *BP* is straightforward to estimate in a GIS (using ESRI's Zonal Statistics tool, for example). Even without a tool, it is easily calculated as

$$mean\ BP = \frac{\sum_j BP_j}{n}$$

where *j* refers to an individual pixel and *n* is the total number of pixels in the summary unit. The *BP* for nonburnable pixels is zero, so *n* should be the total number of pixels in the watershed, not just the burnable ones. For the lower South Fork of the Merced River sub-watershed, the arithmetic mean *BP* of the 16,034 pixels is 0.01735. The mean *BP* in a summary unit has little inherent meaning except for comparison with other units and for calculating expected area burned (see next section). Mean pixel *BP* does not represent the probability of burning any part of the watershed (which can only be calculated from the polygon results).

In addition to this simple calculation of the mean *BP*, it is also possible to use GIS to show the distribution of pixel *BP* across the sub-watershed (Figure 6).

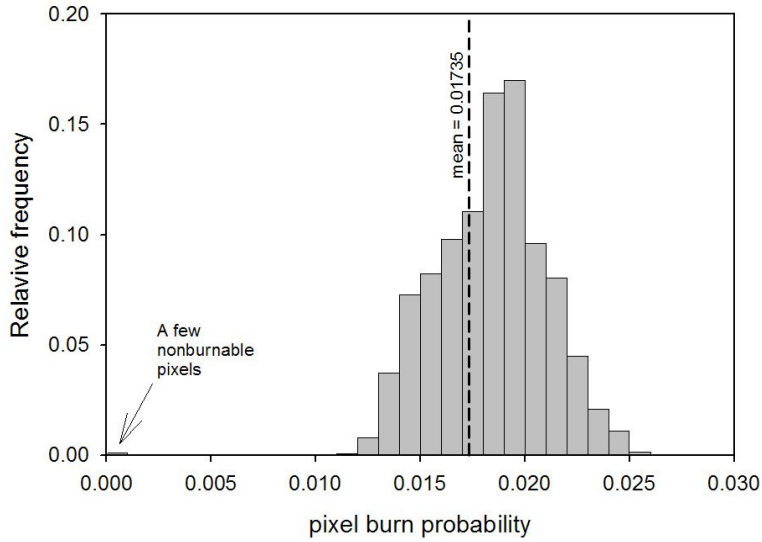

Figure 6. Histogram of pixel-level burn probability values within the lower South Fork of the Merced River sub-watershed. A very small fraction of this sub-watershed is nonburnable; those are tallied here with *BP* = 0.

Polygon BP

FSim's polygon results can be used to estimate the annual probability that a wildfire will burn any part of the watershed. The polygon *BP* is the count of iterations that produced a perimeter that overlaps with the sub-watershed divided by the number of iterations

$$\frac{perimeters\ overlapping\ with\ unit}{number\ of\ iterations}$$

Recall from section 1.3 that 331 perimeters burned a specified point within the watershed. We can do a similar analysis to find all of the perimeters that burned any part of the sub-watershed, not just the selected point (Figure 7). All of the 331 perimeters that reached the selected point are included, and an additional 2,405 perimeters also reached the sub-watershed (but not the selected point), for a total of 2,736 perimeters. The annual probability that wildfire will reach any part of the sub-watershed is therefore

$$\frac{2{,}736}{20{,}000} = 0.1368$$

Notice that the polygon *BP* is much higher than the mean pixel *BP*. This polygon *BP* cannot be estimated from the pixel *BP*s. In fact, this polygon-*BP* is necessarily greater than or equal to the maximum pixel-*BP* in the watershed. To understand why this is the case, consider that the pixel with the maximum *BP* represents the number of iterations during which a wildfire burned that one pixel. There could be many more iterations that produced a perimeter that overlaps some other part of the watershed without overlapping that one pixel.

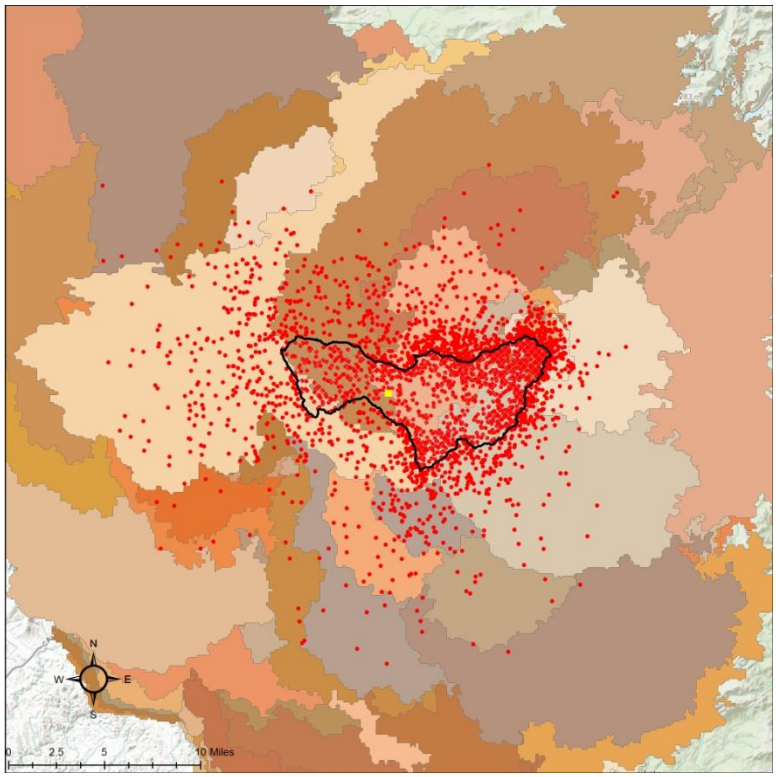

Figure 7. A total of 2,736 perimeters (blue) burned some portion of the lower South Fork of the Merced River sub-watershed (crosshatch). The start locations of these wildfires are shown as red dots.

The start locations of the 2,736 wildfires that reached some portion of the sub-watershed are shown as red dots in Figure 7. The land area that encompasses these start locations spans more than 350,000 acres; with a 5-km buffer around the points (to account for additional low-probability events not captured in the simulation) the area encompassed increases to more than 550,000 acres.

4.2 Expected annual area burned

The expected annual area burned is the average area of the summary unit burned during the simulated wildfire seasons, *including* the iterations that resulted in none of the unit burning. Both pixel and polygon methods can be used to estimate expected annual area burned.

Pixel

The pixel approach to calculating expected annual area burned for the watershed requires knowing the pixel size. The FSim results for the lower South Fork of the Merced River uses 90-m pixels, so each pixel represents 2.002 acres. Expected annual area burned is the product of pixel-mean *BP* and the area of the watershed, including nonburnable land cover. For the lower South Fork of the Merced River sub-watershed, the pixel-mean *BP* was 0.01735 and the total sub-watershed area is 32,092 acres

$$0.01735 * 32{,}092\ ac = 556.8\ ac/yr$$

Another way to estimate expected annual area burned at a single pixel (*j*) is to calculate the sum-product of *BP* times the area per pixel. The expected annual area burned in the watershed is the sum across all 16,034 pixels in the watershed

$$\sum_{j}^{n} BP_j * 2.002$$

For the lower South Fork of the Merced River, the expected annual area burned is 556.9 ac/yr.

Polygon

As identified above, 2,736 wildfire perimeters reached the sub-watershed. The area of overlap between each perimeter (*k*) and the sub-watershed can be calculated using a GIS; this is the watershed area burned by perimeter *k* (AB_k). For example, the wildfire that burned the selected pixel (Figure 3) burned a total of 10,656 acres of the sub-watershed; this is the area where the crosshatch overlaps the orange wildfire perimeter.

The expected annual area burned is the sum of area-burned across all *k* perimeters divided by the number of iterations (*N*)

$$\frac{\sum AB_k}{N} = 546.4\ ac/yr$$

This result differs from the pixel calculation by about 2 percent. The reason for the difference is simply the error associated with conversion between pixels and polygons within FSim and in a GIS, a form of round-off error.

Another way to calculate expected annual area burned from polygons is to first calculate the mean conditional area burned and then multiply that by the polygon *BP*. The mean conditional sub-watershed area burned (conditional meaning including only the 2,736 iterations in which it did burn) is 3,994 acres, and the polygon *BP* is 0.1368, so this estimate of expected annual area burned is

$$3{,}994 * 0.1368 = 546.4\ ac/yr$$

4.3 Exceedance probability and the 100-year wildfire

Exceedance probability (*EP*) is the probability of exceeding a specified level of fire effect (for example, area burned) during a specified period of time (with FSim, one wildfire season). A histogram of conditional sub-watershed area burned for the lower South Fork of the Merced River sub-watershed is shown in Figure 8. Notice that, when the watershed does burn, most of the time only a small fraction of the watershed burns. There is, however, a small chance of burning a large fraction of the sub-watershed during one wildfire season.

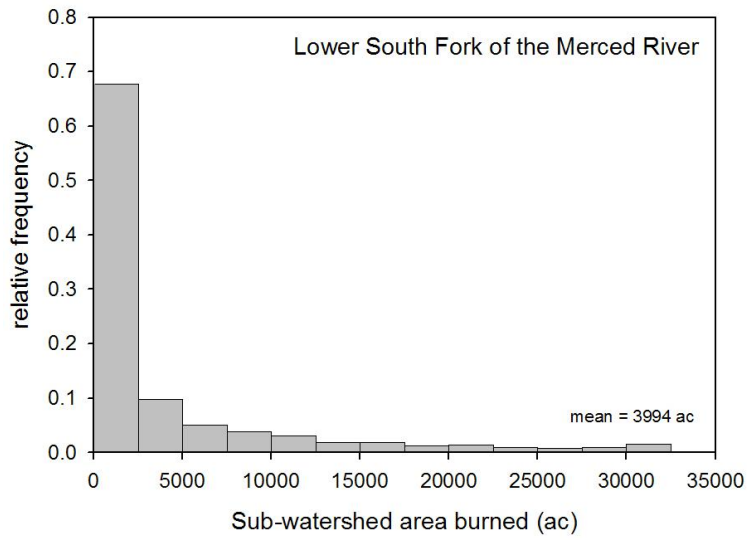

Figure 8. Distribution of conditional sub-watershed area burned (given that it does burn). The arithmetic mean sub-watershed area burned is 3,994 acres.

An *EP* curve is a continuous and cumulative form of the histogram presented in Figure 8; it also accounts for the absolute probability of wildfire reaching the sub-watershed. A complete set of exceedance probability values can be plotted on a chart for the whole range of simulated watershed area burned values (Figure 9). From the *EP* curve we see the influence of the high likelihood of burning only small amount of the watershed, and we also see the overall annual likelihood of wildfire reaching the sub-watershed. Each point on the curve represents the annual likelihood (Y-axis) of exceeding the corresponding area burned (X-axis).

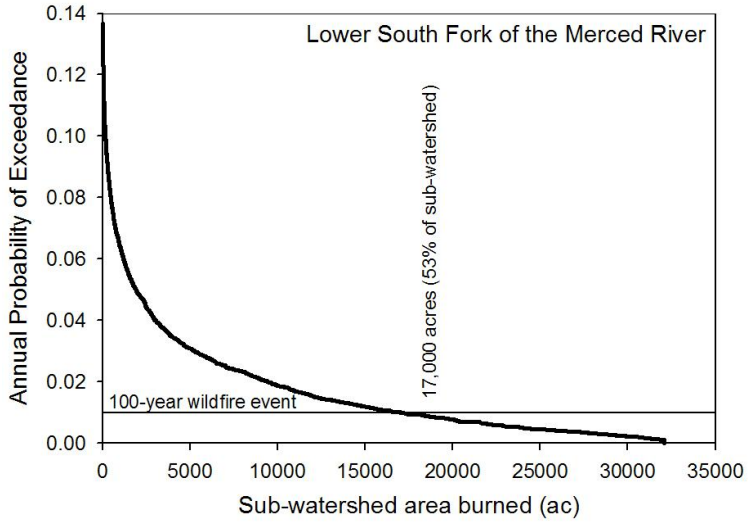

Figure 9. An exceedance probability curve for annual sub-watershed area burned in the lower South Fork of the Merced River sub-watershed. The probability of burning more than 17,000 acres of sub-watershed area (53%) in one year is 0.01, making a wildfire that burns 17,000 acres of the sub-watershed a "100-year event".

A 100-year wildfire event is one that burns the watershed area corresponding to a probability of occurrence of 1-in-100, or 0.01 on the *EP* curve. In our example, a wildfire that burns at least 17,000 ac (53%) of the sub-watershed has a 1-in-100 change of occurring annually. Thus, a 100-year event in this sub-watershed is one that burns 17,000 ac of the sub-watershed. It is possible to identify other probability-magnitude values from the *EP* curve, like the 10-year (145 ac) and 500-year (30,627 ac, or 95% of the sub-watershed) wildfire events.

5. Glossary

- **burn probability (*BP*)**
  The probability that a wildfire will burn a given point or area during a specified period of time.

- **stochastic simulation**
  a simulation that operates with variables that can change with certain probability. Stochastic means that particular factors (values) are variable or random

- **flame-length probability (*FLP*)**
  The relative likelihood of observing a defined flame-length class at a point on the landscape, given that a wildfire occurs at the point. Results from a stochastic wildfire simulation.

- **source-sink ratio (*SSR*)**
  The ratio of expected area burned in wildfires originating within a designated area to the expected area burned within the same area (adapted from Ager and others 201X). A source-sink ratio greater than 1 indicates that the area is a net source of area burned.

- **event set**
  A sample space of *N* elements generated by a stochastic simulator. With wildfire simulations, *N* is the number of simulation iterations and the result for each iteration is an element with probability of occurring of 1/*N*.

- **exceedance probability**
  The probability of exceeding a specified level of fire effect during a specified period of time (area burned during a wildfire season, for example). A series of exceedance probability values can be plotted on a chart for the whole range of simulated possible fire effects.

- **fire occurrence**
  In its original usage as a fire history term, fire occurrence is synonymous with **fire frequency**. Its contemporary usage, fire occurrence refers to the past occurrence of wildfires in a designated study area, including characteristics of the wildfires such as start date and location, final size, and cause, among other attributes.

- **fire frequency**
  In its technical sense, fire frequency is the number of wildfires per unit time per unit area in a specified area. The size of the area should be specified, or fire frequency should be normalized to a common area (e.g. wildfires per year per million acres). Fire frequency is synonymous with fire occurrence. In practice, the term fire frequency is often used in a more general sense that includes all measures of how often wildfire visits a point or area.

- **fire-return interval**
  Fire-return interval is the time in years between two wildfires at a specified point or in a specified study area of known size. Fire-return interval may refer to a point fire-return interval or to a composite fire-return interval. The fire history for the point or area is reported as the arithmetic mean fire-return interval.

- **fire-free interval**
  see **fire-return interval**

- **fire cycle**
  see **fire rotation**

- **fire rotation**
  The estimated time required to burn an area equivalent to the size of the study area (*A*), given the historical area burned (AB_t) during a specified period (*t*).

$$fire\ rotation = \frac{t}{AB_t/A}$$

  For example, of 1,000 acres of a 10,000-acre study area burned during a 10-year period, the fire rotation is 100 years. Fire rotation is analogous to, but not necessarily equal to, the mean fire-return interval. The inverse of fire rotation—the fraction of the study area burned per year—is often used as a measure of historical annual burn probability.

- **Fire environment**
  The wind speed, direction, and fuel moisture at the time of burning.

- **Fuelscape**
  A raster representation (grid of cells) of surface and canopy fuel characteristics, vegetation characteristics (canopy cover and canopy height) and topography characteristics (slope, aspect and elevation) across a landscape. A fuelscape is also called a landscape or "landscape file" (LCP) when used in FARSITE, FlamMap5 and FSim.