ECOLOGY AND GEOLOGY

MODELING WILDFIRE HAZARD WITH A GEOGRAPHIC INFORMATION SYSTEM

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I. Introduction

As wildfires are becoming larger, more severe, more costly, and more frequent, a method to more effectively protect lives and property is requisite.[1] Total wild-land acres burned have quadrupled since 1990.[2] Of the years between 2000 and 2012, 10 fire seasons exceeded one billion dollars in federal suppression costs.[3] Perhaps most importantly, firefighter deaths increased 26% in the period 1998–2006 from the preceding eight-year period.[4] Incidents like the tragic deaths of 19 firefighters battling the Yarnell Hill Fire in Arizona in June of this year occur all too often.

These harrowing statistics are likely due to a combination of factors, including fire suppression, fuel management practices, and global climate change.[5] Regardless of the cause, however, these statistics cannot continue to rise. Although adoption of new forest management strategies in response to the realities of a changing world is an important objective for the future, reducing firefighting deaths can and must be done today.

II. Research Question and Model Application

This project aims to create a method for determining whether existing fire station infrastructure is adequately located to protect areas of the highest wildfire risk. To accomplish this, a location's potential for a hazardous fire will be compared against the response time from the nearest fire stations. The entire project will be done with a geographic information system (GIS), allowing analysis of spatial information and capabilities of producing graphic outputs that can be clearly interpreted by local stakeholders, including residents of the Wildland-Urban Interface, decision

1 National Interagency Fire Center, *1997–2012 Large Fires (100,000+ Acres),* 2013.
2 National Interagency Fire Center, *Total Wildland Fires and Acres (1960–2009),* 2013.
3 National Interagency Fire Center, *Suppression Costs,* 2012.
4 National Wildfire Coordinating Group, *Wildland Firefighter Fatalities in the United States: 1990–2006,* 2007.
5 Peterson et al., *Forest Structure and Fire Hazard in Dry Forests of the Western United States,* 2005.

makers, and fire management officials.

This paper will focus primarily on the creation of a decision support system to determine areas of a landscape with the highest wildfire hazard. Illustrations are examples from simulations run over Southern California's Angeles National Forest during the summer of 2013. The model is capable of evaluating the expected fire behavior for a moment in time or for average conditions. The model was designed to guide a variety of questions, including:

- If I am a citizen, where do I not want to live, in relation to wildfires?
- If I am an urban planner, where do I want to restrict construction or more strictly enforce building codes?
- If I am a fire management official, where are the most dangerous areas to dispatch my men and equipment?

III. Terminology

One of the most difficult aspects of classifying a fire as one that poses a risk to life and property is determining the definition of a "dangerous fire." The following terms can help in a discussion of what makes a fire dangerous. Fire hazard is defined "for any particular forest stand or landscape… [as] the potential magnitude of fire behavior and effects as a function of fuel conditions."[6] Flame length is the distance from "the average flame tip to the base of the fire."[7] This variable is calculated in here because, as Rothermel noted, it "is an elusive parameter that exists in the eye of the beholder. It is a poor quantity to use in a scientific or engineering sense, but it is so readily apparent to fire line personnel and so readily conveys a sense of fire intensity that it is worth featuring as a primary fire variable."[8] Fire line intensity, another measure of fire danger, is a more technical measurement that relates rate of spread and heat release per unit area.

IV. Angeles National Forest

Located in the San Gabriel Mountains surrounding metropolitan Los Angeles, the Angeles National Forest proves an excellent study site for developing and testing a wildfire risk model. This study focuses on a selection of forest directly north of the City of Los Angeles totaling 1952 square kilometers. It is an extremely rugged area with many slopes approaching 90 degrees. The forest's Mediterranean-type climate causes its landscape to be dominated by the drought-tolerant shrubby vegetation known in the western United States as chaparral.[9] However, the wide variety of elevation and aspect combinations yield a diverse array of grasslands, shrub oaks, and pine forests intermixed with the chaparral.[10] Fire is an integral part of the ecosystems in southern California and is important to forest health.[11] The Angeles National Forest has experienced more

6 *Ibid*.
7 Jimenez, *Firefighter Math—Flame Length*.
8 Stratton, *Guidance on Spatial Wildland Fire Analysis: Models, Tools, and Techniques,* 2006.
9 California Chaparral Institute, *Chaparral Facts,* 2005.
10 Landfire.gov, *Fuel Model Gridded Dataset,* 2010.
11 Philpot, *Fire Dynamics in Chaparral,* 1979.

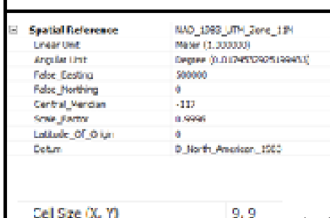
than 4,800 fires since recorded history began in 1900, ranging in size from several square meters to tens of thousands of acres.[12]

V. Methodology

Layer Name	Format	Source
Wind Speed	Interpolated (IDW) Points	Western Regional Climate Center
Wind Direction	Interpolated (IDW) Points	Western Regional Climate Center
Precipitation	Raster	Worldclim.org
Minimum Temperature	Raster	Worldclim.org
Maximum Temperature	Raster	Worldclim.org
Mean Temperature	Raster	Worldclim.org
Fuel Model	Raster	Landfire.gov
Vegetation Rights	Raster	Landfire.gov
Vegetation Cover Percentage	Polygon	National Forest Service/Cal-Veg
Canopy Base Height	Raster	Landfire.gov
Canopy Bulk Density	Raster	Landfire.gov
Elevation	Raster	USGS
Slope	Derived Raster	USGS
Aspect	Derived Raster	USGS

Figure 1. Spatial datasets and their sources.

Data were obtained from a variety of sources, in a wide array of spatial extens, projections, datums, and cell sizes. All data was first entered into the GIS for manipulation.



(*)

Data were converted from their native projection and datum to North American Datum of 1983, with a UTM Zone 11 Projection. Cell Size was set at 9m by 9m.

Datasets were clipped from their original spatial extent to the boundary of the study area.

Ready to Model

Figure 2. Manipulations to spatial datasets.
(*)Please see following page for table blow-up.

12 Kansas City Fire Access Software, *Fires in the Angeles National Forest,* 2013.

Spatial Reference	NAD_1983_UTM_Zone_11N
Linear Unit	Meter (1.000000)
Angular Unit	Degree (0.0174532925199433)
False_Easting	500000
False_Northing	0
Central_Meridian	-117
Scale_Factor	0.9996
Latitude_Of_Origin	0
Datum	D_North_American_1983
Cell (X, Y)	9, 9

Figure 2 Cont'd

The methodological process for determining hotspots of fire hazard was as follows:

1. Spatial datasets were downloaded from freely available and nationally consistent data distribution sources. Using these sources allowed similar simulations to be completed on any study site in the contiguous United States.
2. The data was manipulated so that it was limited to the study site in a common projection and datum with a standard cell size.
3. Using the ArcFuels toolbar,[13] which joins GIS software with third-party fire modeling packages, the data was converted to a format suited for further analysis.
4. FlamMap, which will be discussed later, analyzed the landscape for potential fire behavior.
5. The data was imported back into the GIS.
6. The data was spatially joined so that each point on the landscape had several fire behavior variables associated with it.
7. The landscape was queried and points that met a user's conditions were extracted and defined as hotspots.

VI. Assumptions and Limitations

This model has a variety of important assumptions and limitations that may cause erroneous calculations of fire behavior. Perhaps most importantly, the model relies on a host of previously published models to complete calculations of potential fire behavior. Each model has its own set of assumptions, which are in turn factored into the model presented here. Secondly, using

13 Ager et al., *ArcFuels,* 2013.

remotely sensed spatial vegetation data is far better than interpolating sparsely spaced point data sources. However, remotely sensed data is available only at coarse spatial resolutions and is not updated regularly, causing misinterpretation or underrepresentation of various vegetation characteristics. Third, wind is an important variable in fire behavior. The wind data used in this model was interpolated from 11 point sources in the region and may not incorporate topographic discontinuities, such as ridges, that can impact fire behavior.[14] Finally, the input that perhaps most completely dictates fire behavior is fuel moistures.[15] It is defined as the "moisture content of dead organic fuels, expressed as a percentage of the oven dry weight of the sample."[16] There are several different classes of fuel moisture depending on fuel particle size and whether the fuel is alive or dead. The use of FlamMap requires that fuel moistures be input for the entire landscape rather than in a grid that gives each point a unique value, causing possible variations between the "true" value and the valued used in the experimental simulations.

VII. Raster Modeling

To simplify reality, this model uses a technique called raster modeling. A raster is a data storage format that "consists of a matrix of cells organized into a grid where each cell contains a value representing information."[17] In this model, a landscape is represented by 14 separate rasters, giving each cell a value for themes such as wind speed,[18] wind direction,[19] precipitation,[20] minimum,[21] maximum,[22] mean temperature,[23] vegetation height,[24] fuel model,[25] slope,[26] aspect,[27] elevation,[28] vegetation cover,[29] canopy base height,[30] and canopy bulk density.[31] These inputs were used by FlamMap to calculate fire behavior for each cell.

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14 Stratton, *Guidance on Spatial Wildland Fire Analysis: Models, Tools, and Techniques,* 2006.

15 Rothermel et al., *Modeling Moisture Content of Fine Dead Wildland Fuels: Input to the BEHAVE Prediction System,* 1986; Barrows, *Forest Fires in the Northern Rocky Mountains,* 1951.

16 Southern California Geographic Area Coordination Center, *Fuels/Fire Danger*, 2013

17 Environmental Research Systems Institute, *What is Raster Data?,* 2008.

18 Western Regional Climate Center, *Raw Climate Data in Electronic Format (Hourly Records),* 2013.

19 *Ibid*.

20 WorldClim.org, *Global Mean Monthly Precipitation Grids,* 2013.

21 WorldClim.org, *Global Mean Monthly Miniumum Temperature Grids,* 2013.

22 WorldClim.org, *Global Mean Monthly Maximum Temperature Grids,* 2013.

23 WorldClim.org, *Global Mean Monthly Mean Temperature Grids,* 2013.

24 Landfire.gov, *Vegetation Height Gridded Datasets,* 2010.

25 Landfire.gov, *Fuel Model Gridded Datasets,* 2010.

26 United States Geological Survey, *Digital Elevation Model,* 2013.

27 *Ibid*.

28 *Ibid*.

29 United States Department of Agriculture, Forest Service, *Vegetation Classification and Mapping Project,* 2013.

30 Landfire.gov, *Canopy Base Height Gridded Datasets,* 2010.

31 Landfire.gov, *Canopy Bulk Density Gridded Datasets,* 2010.

VIII. FlamMap

FlamMap is a fire behavior mapping and analysis program that computes potential fire behavior characteristics over a landscape.[32] The software computes the expected fire behavior for a specified and constant set of weather and fuel conditions. Each cell is calculated independently—cells do not impact one another. FlamMap cannot map fire spread. Instead, its "output lends its well to…identifying hazardous fuel and topographic combinations…aiding in prioritization and assessment."[33] In this model, FlamMap was used to calculate flame length, fire line intensity, rate of spread, and heat release per unit area.

IX. Extracting Important Areas by Attribute Combinations

Once the data from FlamMap calculations were successfully imported back into the GIS, analysis of hotspots could begin. The rasters were spatially joined so that each cell had several fire behavior variables associated with it. Several climatic variables, including average monthly precipitation and temperature, were also added to extend the versatility of the analysis. The model user can query any combination of these variables to assess dangerous hotspots. For example, one could

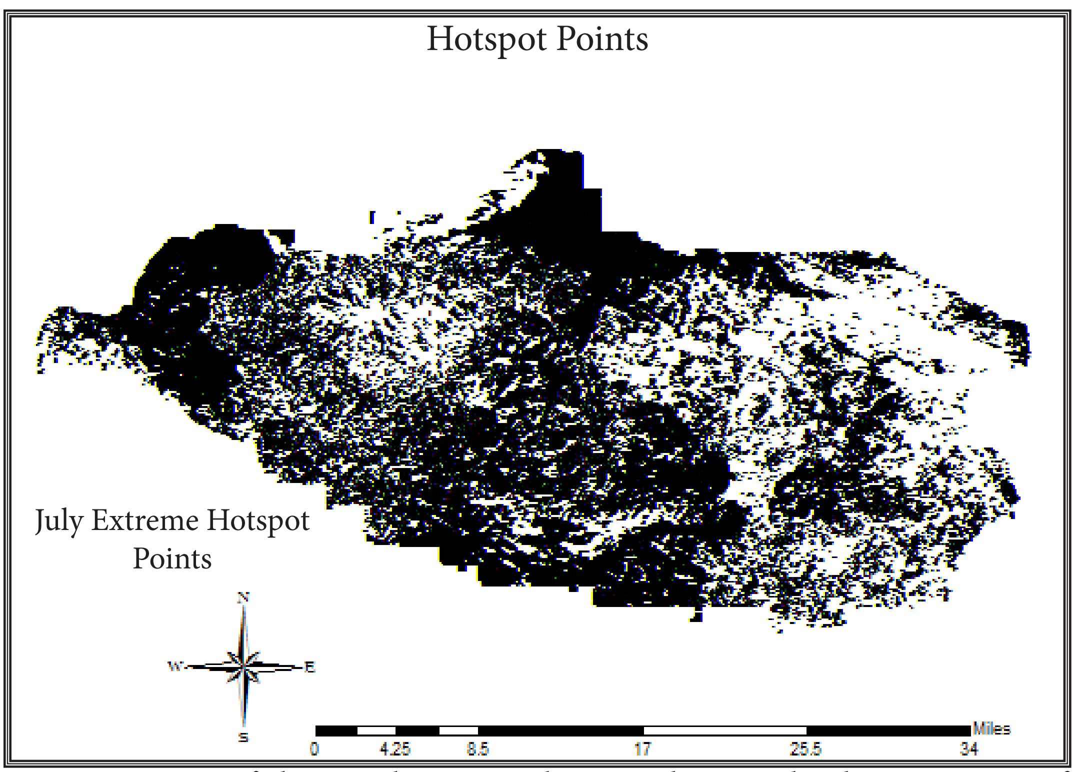

Figure 3. Map of the Angeles National Forest showing the decomposition of extreme fire behavior into points.

32 Finney et al., *FlamMap,* 2012.

33 Stratton, *Guidance on Spatial Wildland Fire Analysis: Models, Tools, and Techniques,* 2006.

determine areas with high flame length and high rate of spread or find areas with low average precipitation currently experiencing high winds. The possibilities are quite wide, allowing the model user to determine the combination he or she believes to be most pertinent. Each cell on the landscape either meets the conditions set forth by the user or it does not.

X. Density of Selected Points

The cells that do meet the user's query are decomposed into a set of points, which in turn serve as the basis of a point density calculation. Each point is given a circular neighborhood with a radius of 100 meters. The more points inside of this neighborhood, the higher the coverage. The result is a determination of the density of cells per hectare that meet the user's query.

XI. Results—Extreme Fire Assessment

The model was developed with the capability to analyze the climatological average conditions for a landscape or assess the fire danger in an area for a particular moment. To demonstrate this quality, an extreme fire behavior assessment was done on the Angeles National Forest for a moment in time—July 26, 2013, at 11am (Figure 4)—and the climatological average conditions for the month of July (Figure 5). The landscape was queried for cells that have flame lengths greater than 20 feet or a fire line intensity exceeding 2000 British Thermal Units (BTU) per foot per second. Fire behavior analysts describe this type of fire as extreme: "Fire spreads very rapidly presenting extreme resistance to control. Any form of attack will probably not be effective. Safety of firefighters in the area is of critical concern."[34] The maps indicate the portion of the surrounding hectare that exhibits this extreme fire behavior. The absence of color on the map indicates that while a fire may occur, it will not display extreme fire behavior given the input conditions. The climatological average is likely to aid in planning efforts, informing citizens and local decision makers on where to limit settlement. The moment in time, on the other hand, is likely to be of more use to fire fighters as it shows the most dangerous areas for a particular moment. Real-time conditions fluctuate widely over the month, and even within a day, so it is important to note the variation between the real time assessment and the climatological conditions assessment.

Testing on the model indicates that an initial result can be produced in as little as one day, and subsequent, near-real-time results can be produced in 30–60 minutes, depending on data quality, data availability, and computer hardware. Initial simulations indicate that putting this model into widespread field use can save lives. While firefighting management personnel receive weather and wind updates throughout the day, it is often difficult for them to spatially synthesize this data. An examination of two of recent Yarnell Hill Fire reveals that potential extreme fire behavior and the possibility of high winds were communicated to Division Supervisors at least 80 minutes before the fire reached the crew's location and burned them over. Had officials recognized the crew's location as a hotspot, the tragedy may have been avoided.

34 Stubbs, *Adjective Ratings for Fire Behavior,* 2005.

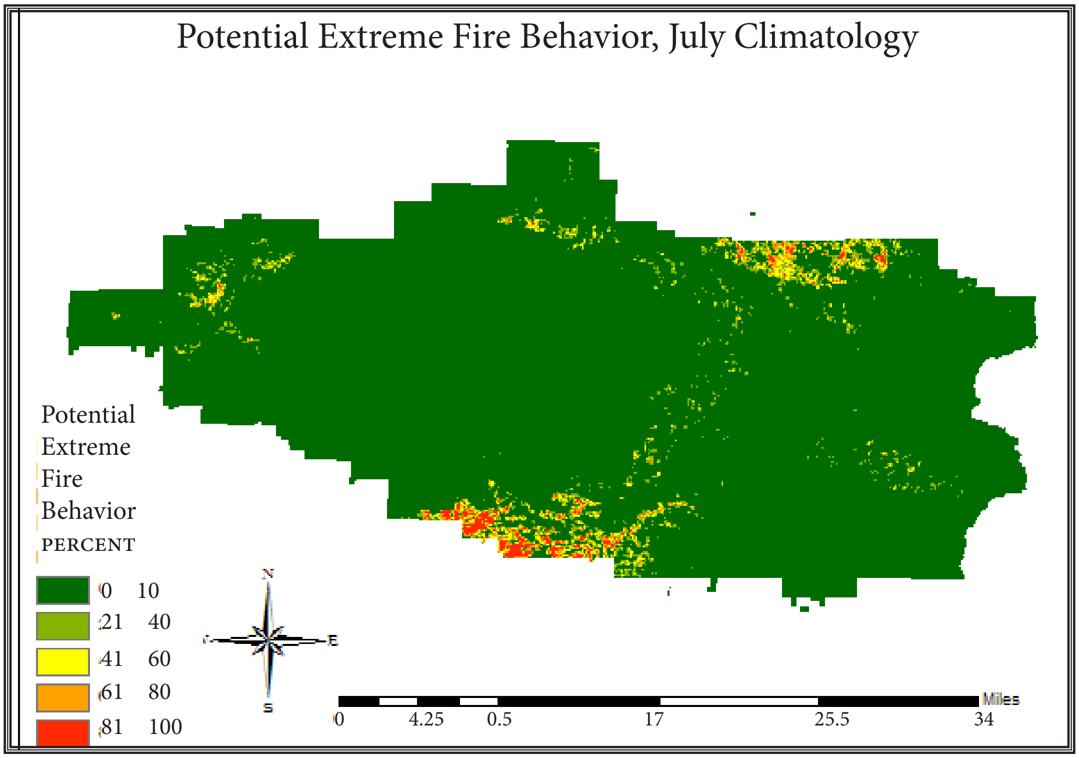

Figure 4. Map of the Angeles National Forest showing the density of extreme fire points for July climatological average conditions.

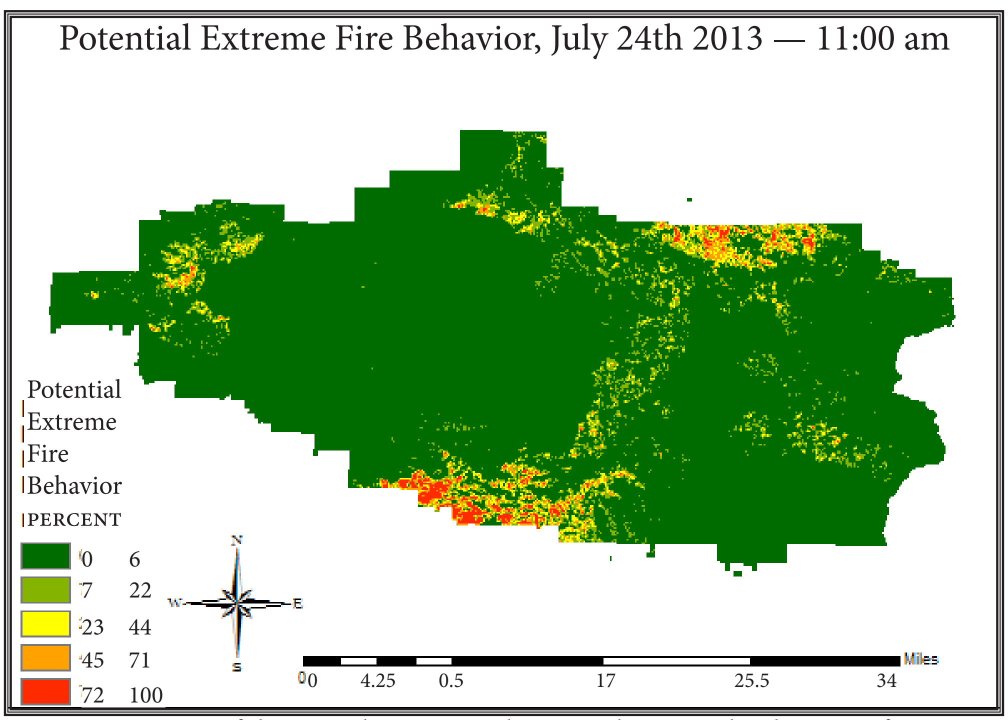

Figure 5. Map of the Angeles National Forest showing the density of extreme fire points for conditions at July 24, 2013 at 11am. Note the differences from Figure 4.

Fire experts have noted that the majority of fatalities occur when

1. The fire burns light brush, grass, or herbs.
2. When there is a shift in wind direction or wind speed.
3. When fire responds to topographic conditions and runs uphill.[35]

All three of these conditions can be explicitly modeled in the model presented here, allowing incident commanders to evaluate a unit's location in relation to a hotspot and ensure that crews are not ordered into a situation that compromises their safety.

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35 National Wildfire Coordinating Group, *Wildland Firefighter Fatailities in the Unites States: 1990–2006,* 2007.

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