Simulations and Analysis of a 2012 Kansas Wildland Fire Using FARSITE

Geoff Wehmeyer

ME 374F: Fire Science

December 14, 2012

Prof. Ofodike Ezekoye

The University of Texas at Austin

Table of Contents

Simulations and Analysis of a 2012 Kansas Wildland Fire Using FARSITE

Introduction: Wildland fires are a serious concern for communities in the Western United States. Catastrophic forest fires, such as the 2008 California wildfires or the 2011 Bastrop conflagrations, can destroy hundreds of thousands of acres of land, causing serious damage to environments and ecosystems (1). At best, these outbreaks can cause families to be temporarily or permanently displaced from their homes, and at worst, human and domestic animal lives are severely endangered. Immediate economic costs associated with wildfire suppression are estimated to be around $2 billion/year, and long-term wildland fire results such as lost resources and crops, demolished infrastructures, and reduced air and water quality continue to devastate regions long after the embers are quenched (2).

Of course, not every wildfire will have such deleterious effects. Foresters working with national, state, or local services need to be able to predict how a wildfire will spread to effectively allocate resources and decide whether or not to order a potentially costly and dangerous evacuation of communities in the wildlife-urban interface. In addition to drawing on the years of experience in fire management and detailed knowledge of the local area, foresters use predictive tools such as the software FARSITE to analyze existing fires, develop controlled burns, and gauge the risk of catastrophic wildland fire (3).

In the author's home state of Kansas, the summer of 2012 was one of the driest and hottest seasons on record in the region. Many counties were in extreme drought conditions for months, and the total number of acres lost to wildland fires increased by a factor of six when compared to 2011 (4). One such fire occurred outside the town of Oberlin, KS, on June 26th, when local temperatures reached above 110^{o} F and winds gusted up to 20 mph. Over 7000 acres were burned in the rural northwestern Kansas town before firefighters and citizens were able to contain the fire that was initially ignited by an overheated car on the side of the highway. A picture of the fire damage to a cornfield is shown on the title page (5).

The purpose of this report is to explore the capabilities and limitations of FARSITE associated with uncertainties in wind predictions. Information from the June 2012 Oberlin fire will be used as the template for these simulations. This motivating fire was chosen because of its personal interest to the author, its well-documented spread, and the ability to validate aspects of the simulation using simplified models. A brief background on the history and application of wildfire modeling is discussed, and the program FARSITE is described and compared with other fire modeling tools. The inputs to the FARSITE model are defined, and parameters are perturbed to understand how input uncertainties could affect the predicted flame spread and the decisions made by foresters that can impact life safety. The simple study of a Kansas wildfire will show how accurate data and an experienced user are both necessary to maximize the utility of fire modeling tools such as FARSITE.

Background: A fundamental basis for wildfire modeling is the Rothermal Surface Flame Spread Model, developed in 1972 by Richard Rothermal from experiments performed in the National Forest Fire Laboratory in Missoula, Montana (6). Rothermal knew that for surface fires, defined as fires on vegetation contiguous with the ground, the radiative heat transfer from the flame preheated the virgin fuel ahead of the fire until the fuel reached an "ignition temperature" at which the mass flux of pyrolyzed volatiles supports ignition and the pyrolysis front advances. Rothermal also saw that wind-aided, opposed, and no-wind pyrolysis fronts had different mechanisms of heat transfer, and that a model describing flame spread would also need to take convective cooling or heating into account. He extended a previously derived relationship indicating that the rate of flame spread could be thought of as the ratio of heat flux received by the fuel to the total energy required to bring the fuel to the ignition temperature.

The heat flux received by the fuel depends on the slope, the prevailing wind speed and direction, and the temperature of the fire radiating to the fuel. The total energy required to bring the fuel to the ignition temperature depends on the thermal properties of the dry fuel and the moisture content that is vaporized in the material. The intensity of the fire, and the heat emitted from radiation, is dependent on the total energy content of the fuel, which Rothermal experimentally characterized. A wind tunnel was used to measure experimental coefficients relating wind speed to the fire propagation rate, and data was gathered at different sloped inclines. To account for the heterogeneous mixture of fuels in real burning situations, Rothermal derived mean values for fuel properties of 11 different types of fuel, ranging from short grass and brush to open timber. Future researchers would refine these fuel categories. Using experimental correlations to support heat and mass transfer analysis, Rothermal derived a series of equations and curve fits that would predict the rate of spread of a surface wildland fire.

Researchers have expanded on Rothermal's surface spread model, but it remains the basic foundation of practical semi-empirical wildfire modeling. Rothermal helped to develop the computer program BEHAVE, a point model using flame spread correlations to produce graphs and tables of fire behavior (7). A program called FARSITE is a deterministic fire area simulator that requires spatial and temporal data inputs to calculate a two-directional, time-dependent spread perimeter (8). FARSITE models fire growth using Huygen's principles of wave growth applied to nonuniform spatial grids. A wind-slope vector is assigned to the X-Y coordinates at the perimeter of the fire, and the perimeter propagation from that point is calculated by multiplying the rate of spread by a variable time step in the simulation.

An elliptical fire shape within a finite element is assumed such that two-dimensional spread can be experimentally correlated with current one-dimensional models of wind-aided leading fire spread (9). Other modeling tools that have been developed include physics-based computational fluid dynamic programs such as Wildlife-Urban Fire Dynamics Simulator (WFDS) that use large-eddy simulations to characterize fire spread and combustion product transfer (10).

FARSITE can be a very useful tool to supplement detailed knowledge of fire behavior in a specific region. If foresters have developed detailed and accurate spatial models, maintain access to accurate fuel and weather information, and perform verifications and checks on their simulations, they can use FARSITE to estimate how an existing fire will spread or help manage fuel distribution in wild areas. FARSITE simulations can be ran on a personal computer faster than real-time and are less computationally intensive than CFD programs such as WFDS. Spotting models and crownfire models can be implemented to increase the applicability and complexity of the simulation. The disadvantages of tools such as FARSITE can be seen when compounded errors in the accuracy of the input data, mistakes on the part of the user, and assumptions made in the modeling software can misrepresent the physical situation. For example, modeling crownfires - where flames spread to tree canopies and the transfer mechanisms for flame spread are significantly altered - is a continued challenge in empirically based models (8). This report studies surface fires only, but even for these conditions uncertainties in the data input - such as weather, wind, fuel moisture, and fuel content - could also affect the model's flame spread predictions.

Wind speeds are generally measured 20 feet above the ground at weather stations across the United States. Wind adjustment factors have been developed to account for the discrepancies between the free stream winds and the speeds seen at midflame of the surface fire (11). FARSITE adjusts the user input wind speed to a midflame speed for a given element based upon the characteristics of the fuel depth and amount of sheltering that can impact the wind flow. Obtaining accurate measurements and predictions of input wind speeds, however, can be difficult. Recorded values of the 20 foot wind speed are generally only averages of conditions that can drastically change even by the minute. Spatial changes for 20 foot wind speed and direction over the landscape of the fire can be modeled in FARSITE, but wind gusts and lulls can significantly impact the dynamics of fire spread, and foresters attempting to predict future fire spreads need to rely on their experience and meteorological forecasts to decide what wind values accurately represent realistic conditions. This report will analyze three different variations in wind speed calculations for the Oberlin, KS June 2012 fire. A baseline case using wind data from a nearby weather station over the course of four days will be compared to a scenario where the forester replicates the wind speed from June 25th to predict future spread, and a situation where the forester estimates a constant average wind speed for each day and night of the simulation. Though in actuality the Oberlin fire was contained within one day, this simulation aims to explore how variations in input wind information could affect long-term modeling performance and accuracy.

Hypothesis: Three variations in wind speed predictions in a FARSITE model of a Kansas surface fire will have a substantial impact on the rate of fire spread, and the forester's decision whether or not to evacuate inhabitants near the town of Traer, KS northwest of the fire would depend on the accuracy of the wind direction prediction.

Statement of Conditions: As with any model, the predictions of FARSITE simulations rely upon the accuracy of the data input. FARSITE simulations generally require spatial inputs of the landscape, adjustments to the fuel models, temporal inputs of the weather and wind, modeling parameters, and information regarding the ignition site and time. This section details the specific input values chosen for this report's June 2012 Oberlin, KS fire simulations.

Spatial Inputs: The five basic spatial inputs that form a FARSITE landscape file are elevation, slope, aspect, fuel type, and canopy cover. Freely available mappings of this geospatial information for the United States are provided by the LANDFIRE program, an interagency program that provides data for fire management and resource allocation (12). The latest geographic data available from the program dates from 2008, and Figure 1 below shows the region of interest shaded in black. The resolution of each pixel or element is 30 meters by 30 meters. The area of study was roughly chosen based on the newspaper accounts of the ignition location just north of Interstate 36 and the resulting flame spread to the north. If the fire was not suppressed, foresters would be interested in seeing how far north the flame spreads, and if residents near the town of Traer would need to be evacuated.

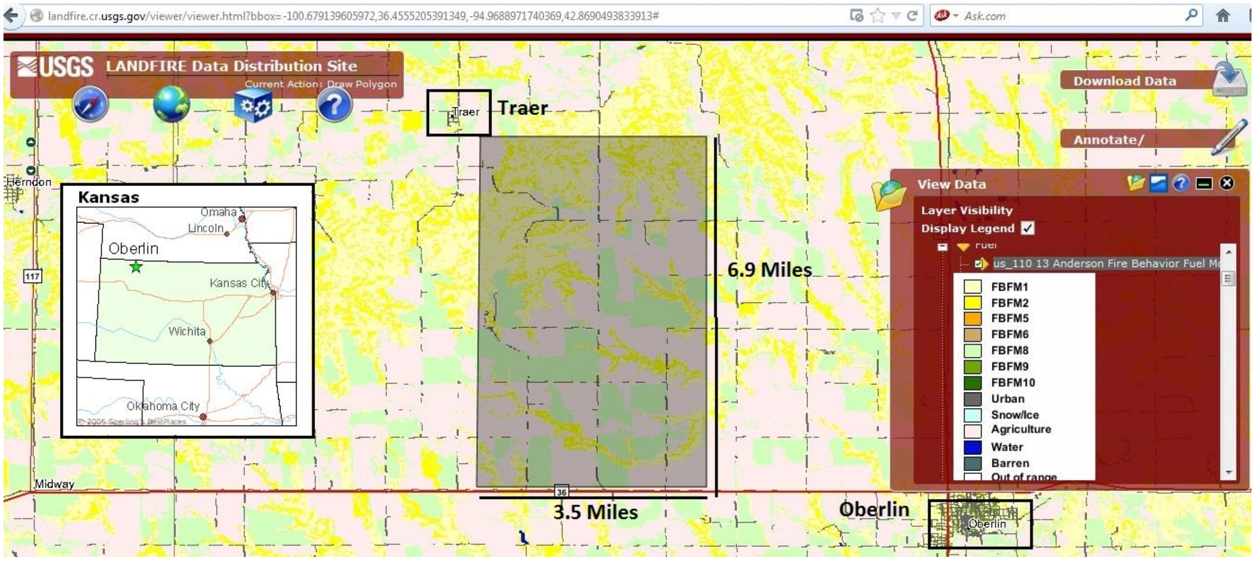

Figure 1: LANDFIRE selection of Oberlin fire area with superimposed image of Oberlin's location in Kansas. The color legend shows fuel categories, and relevant distances and locations are labeled.

The slope, or rate of change of elevation, and the aspect, or the horizontal direction of a vector perpendicular to the slope, both impact the mechanisms and rates of fire spread. This Kansas agricultural region has little to no canopy cover, so the underbrush and grass are exposed to direct sunlight and experience reduced fuel moisture content.

The fuels in LANDFIRE are categorized into standard fuel behavior models developed for surface fire spread modeling, and the following paragraph details distinctions assembled by Scott and Burgan (13). Fuel behavior models group common fuelbed materials into divisions with common fuel loads, fuelbed depths, and extinction moisture percentages. For instance, the fuel label "GR1" indicates that the fuel is modeled as "short, sparse, dry climate grass," and the label "GS2" would correlate with a mixture of 1-3 ft. tall shrubs and fine grass. The fuel load, or total volatile mass, for live and dead fuels is provided for different size categories of fuel particles. Size distinctions are described in terms of the time it takes for the fuel particle to respond to changes in moisture. 1 hour dead fuels such as grass, leaves, or mulch have small characteristic diameters (< ¼") and are more sensitive to environmental changes that affect moisture, whereas 100 hour fuel particles with diameters larger than one inch do not respond as quickly to the environment and have different dynamic burning characteristics. Fuel loads of live herbaceous and woody fuels are also characterized. For example, in the fuel category "GR1," the model estimates the amount of 1 hour fuel load for grass to be 0.45 kg/m^2 of surface area, whereas a category of shrubs and grass such as "GS2" has a thicker bed depth, a 1 hour fuel load of 2.2 kg/m^2, and a 100 hour fuel load of 2.2 kg/m^2. All fuels are assumed to have a constant heat release rate of 8000 Btu/lb (18.6 kJ/g), which would not be accurate for all varieties of fuel. For example, Quintiere lists measured values of the heat of combustion of red oak to be 12 kJ/kg and of Douglas fir to be 13 kJ/kg (14).

The standard fuel behavior model also includes categories for areas with no flame spread, such as roads, urban areas, or well-plowed agricultural regions such as cornfields. The areas shown in white in Figure 1 are agricultural regions and the fuel behavior model labeled them as “NB3,” a non-burning area. The manual describing the fuel types, however, indicates that this delineation is only applicable if the spaces between crop rows are mowed and kept free of grass and other fuels (13). According to a newspaper article describing the event, the crop fields did slow down the blaze, but stubble and grass between the rows still allowed the field to burn (5). This example shows how FARSITE users need to carefully assess the input data and update the fuel models based upon actual conditions. If users input the data directly from LANDSCAPE, fires would almost immediately be stifled in the agricultural region.

Separate spatial ArcGIS files for the elevation, slope, aspect, fuel types, and canopy cover were downloaded from the LANDFIRE site and converted to ASCII files using the program ArcMAP 10.1. As seen in ArcMAP and shown in Figure 2, the selected area is fairly flat on the southern side but slopes downwards in the northwest. The ASCII files were then loaded into FARSITE to create a landscape file.

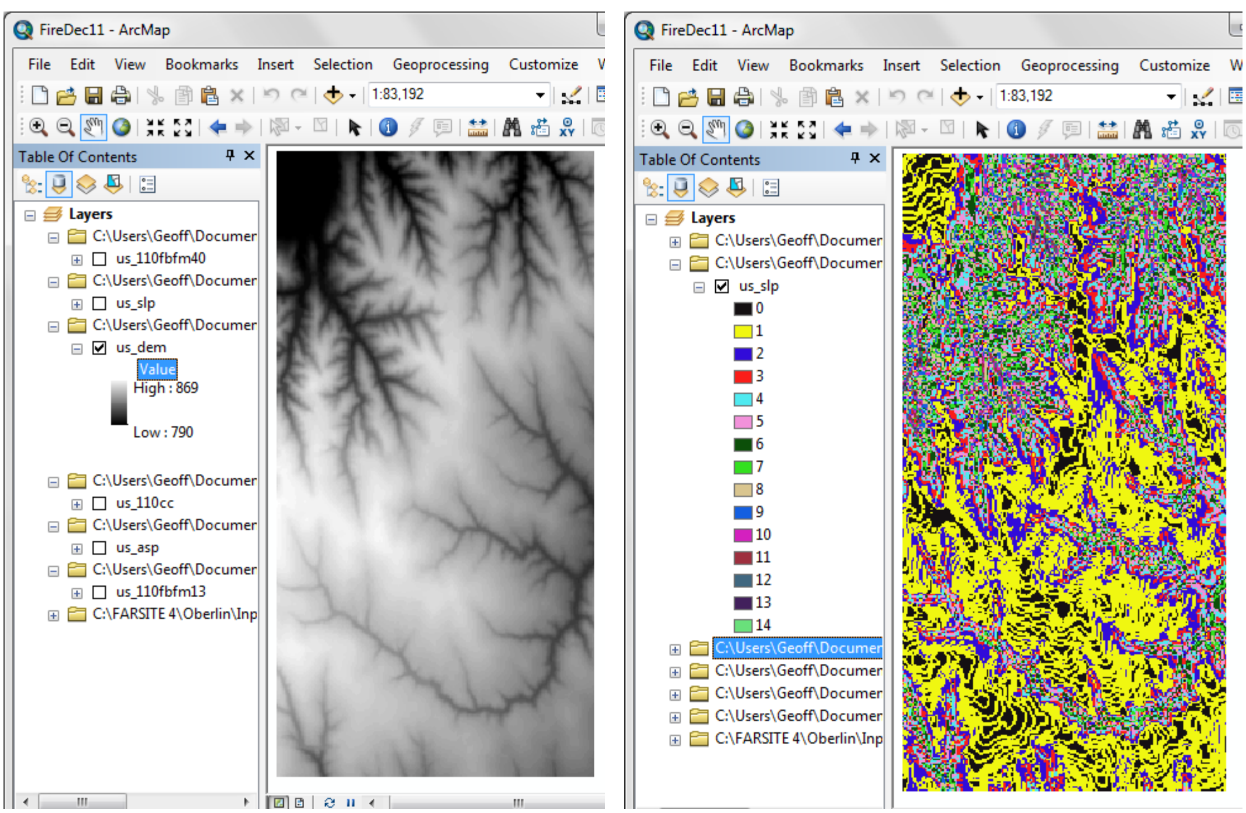

Figure 2: ArcMAP images. (Left) Elevation (meters). (Right) Slope (degrees)

Adjustments and Conversions: Experienced users can adjust the rate of flame spread for certain fuel behaviors. For instance, if a forester knows that a fire in the prairie grass in her specific area spreads much more slowly than is predicted by FARSITE, she could create an adjustments file to modify the propagation rate for that fuel classification. Or, the user could change the fuel model associated with a certain set of particles using a Conversions file. This project did not employ any adjustments to the standard fuel model, but did convert the agricultural "NB3" region to a "G1" short grass region as previously discussed.

Fuel Moistures: The initial fuel moisture percentage for dead 1 hour, 10 hour, and 100 hour fuels can significant impact the rate of flame spread. Fuels with greater moisture percentages require more input energy to pyrolyze the same amount of fuel, since the input heat flux also vaporizes the water in the fuel. In hot, arid climates such as Kansas in the summer of 2012, low fuel moisture contents significantly contribute to the danger of fire spread. The US Forest Service maintains a database of historically recorded fuel moistures through the Wildland Fire Assistance Center (15). As seen in Figure 3, the 100 hour fuel moisture content in Oberlin was estimated to be between 6-10%. Note that there are no black triangles (weather stations measuring and reporting moisture information) in Kansas, so these values are estimated and should be treated with caution. Since nearby regions in northwestern Kansas and Colorado have <5% moisture contents, the 100 hour moisture was estimated to be 6%. From Table 3 in the Standard Fire Behavior Models reference by Scott and Burgan, this moisture content is between 'Low' to 'Very Low,' and the 10 hour and 1 hour moisture contents are estimated as 5% and 4%, respectively (13). From Table 4 in the same reference, the live herbaceous content was estimated as 40% and the live woody fuel moisture content was chosen to be 70% based upon the 'Low' to 'Very Low' range of dead fuel moistures.

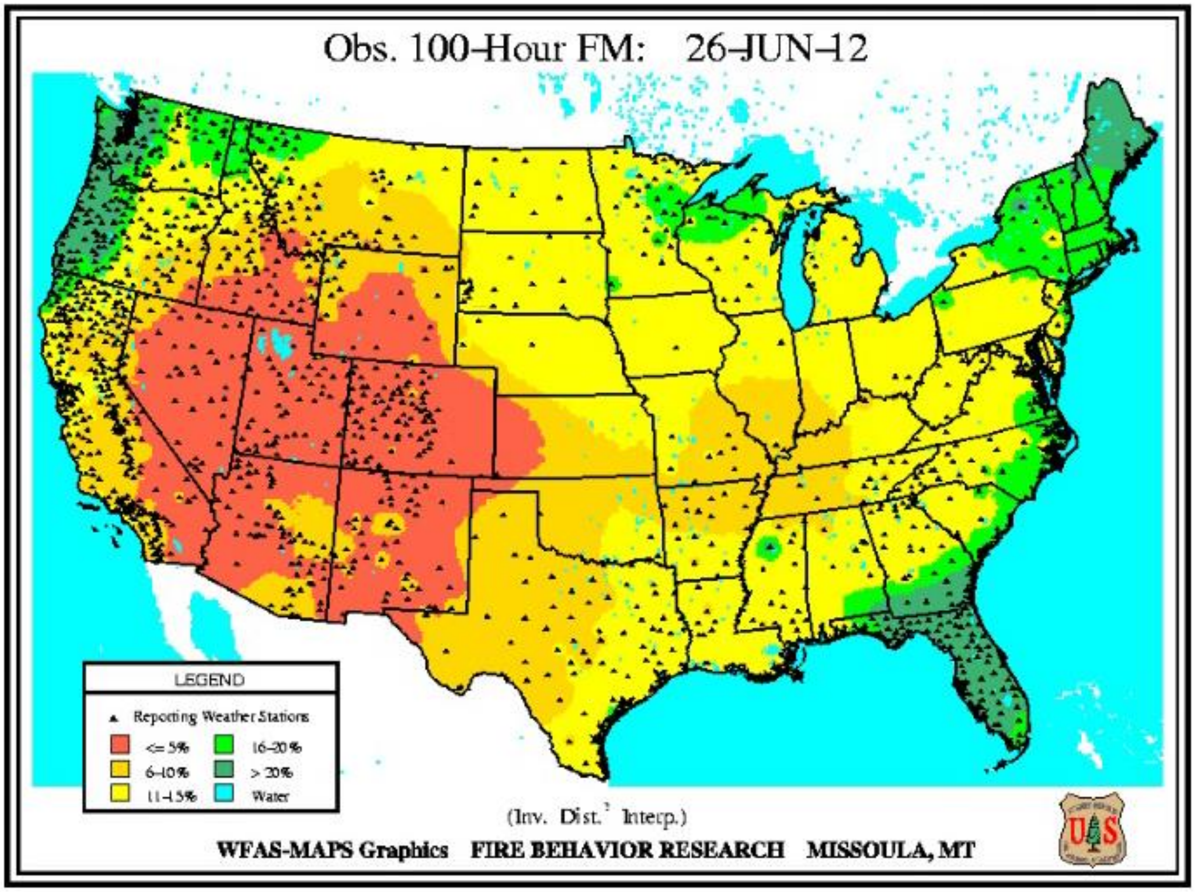

Figure 3: Fuel Moisture for 100 hour fuels (15)

Weather: FARSITE requires ambient weather information for the simulation study period of June 25th – June 31st. Temperature and humidity levels are primarily used to calculate the moisture levels in the fuel as time progresses. Rather than inputting hourly temperature data, the user enters in the minimum and maximum temperatures, the corresponding maximum and minimum relative humidity percentages, and the times at which these limiting values occur for each day. FARSITE then fits a sinusoidal distribution to the temperature and humidity fits. More advanced spatially heterogeneous temperature distributions are possible, but in this simulation more spatially detailed environmental conditions would not be accurate or insightful. The temperature and humidity distributions for the study period of interest were found using information from the Kansas City Fire Access SofTware, or KCFAST (16). This web application allows users to search compiled historical fire weather data collected at weather stations across America. The nearest station to Oberlin, KS, is located 82 miles west in Kirwin, KS. Oberlin is about 300 meters higher in elevation than Kirwin, so temperature and humidity data taken in Kirwin may differ from the conditions outside Oberlin. The peak temperature recorded on June 26th in Kirwin was 113°F, which is the same temperature reported in Oberlin on the day of the fire (5). Hourly Kirwin temperature distribution from June 26th can be seen in Figure 4, indicating that FARSITE's sinusoidal temperature approximation based on the minimum and maximum values is a reasonable assumption. Information about the output data .ftp files from KCFAST was found in a handbook on the Remote Automated Weather Station (RAWS) program that initially collected the data (17).

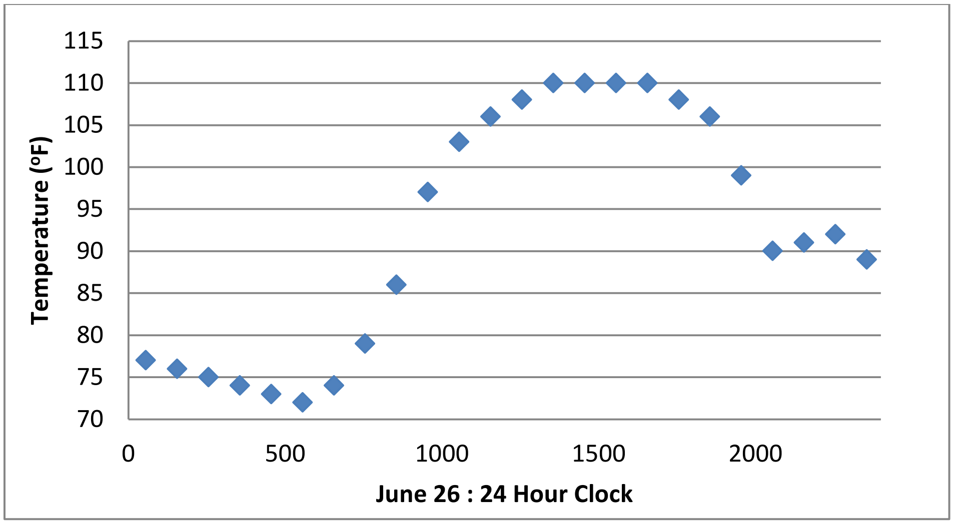

Figure 4: Kirwin hourly temperature distribution

The temperature and humidity distribution of the entire study period is derived from the Kirwin measurements. In a predictive fire setting, future environmental conditions would not be precisely known, and the forester would have to judge reasonable minimum and maximum values. The weather file for the given simulation is shown in Figure 5.

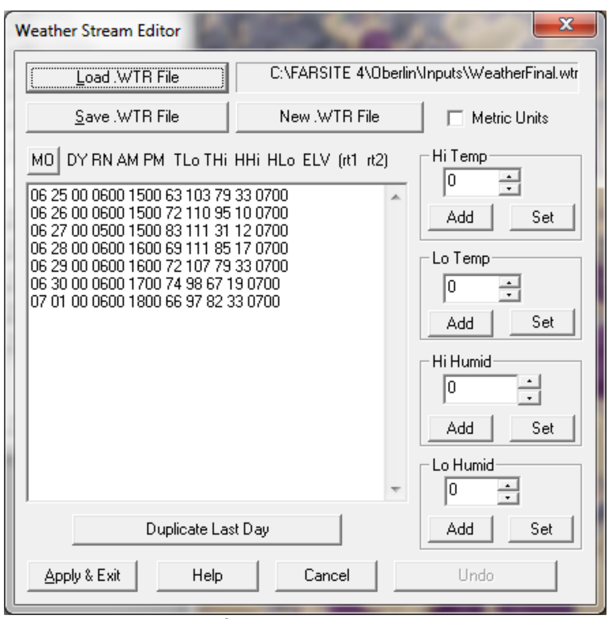

Figure 5: Temperature (^{o}F) and humidity (%) inputs to FARSITE.

Wind: Wind speed and direction are key parameters in estimating flame spread. The intermittent nature of volatile wind gusts and directional changes can make prolonged forecasting difficult. This project will cover three different scenarios for wind spread - displayed in Table 1 - to understand how perturbing wind speed inputs affect the final flame spread results. Note that the wind direction is the direction the wind is coming from; a 140^{o} direction would indicate a wind blowing from the southwest to the northeast, for example.

Table 1: Wind speed and direction variations

Scenario	A	B	C
Description	Kirwin wind reports, actual data from each day, changing by the hour.	Kirwin wind reports from June 25, exactly repeated for the next five days, changing by the hour	Kirwin wind reports, data averaged every 12 hours, constant from 0000 –1200 and 1200-2400 hours each day.
Wind Speed Range (miles per hour)	3- 28	3-15	5 – 18
Wind Direction Range (degrees from north)	47 – 267	47 – 119	145 – 221

Scenario A uses the Kirwin wind speed data that was collected from KCFAST from the dates of June 25 – July 1. Scenario B represents a situation where a rushed forester at the beginning of the June 26th fire simply repeats the hourly wind measurements from June 25th for the remainder of the simulation. Scenario C could result if a forester checks the upcoming forecast to obtain average wind speed values for the day and for the night, and uses these values in as constants in the model. All other factors in the simulation are held constant. A plot of the wind speeds used in each simulation is shown in Figure 6.

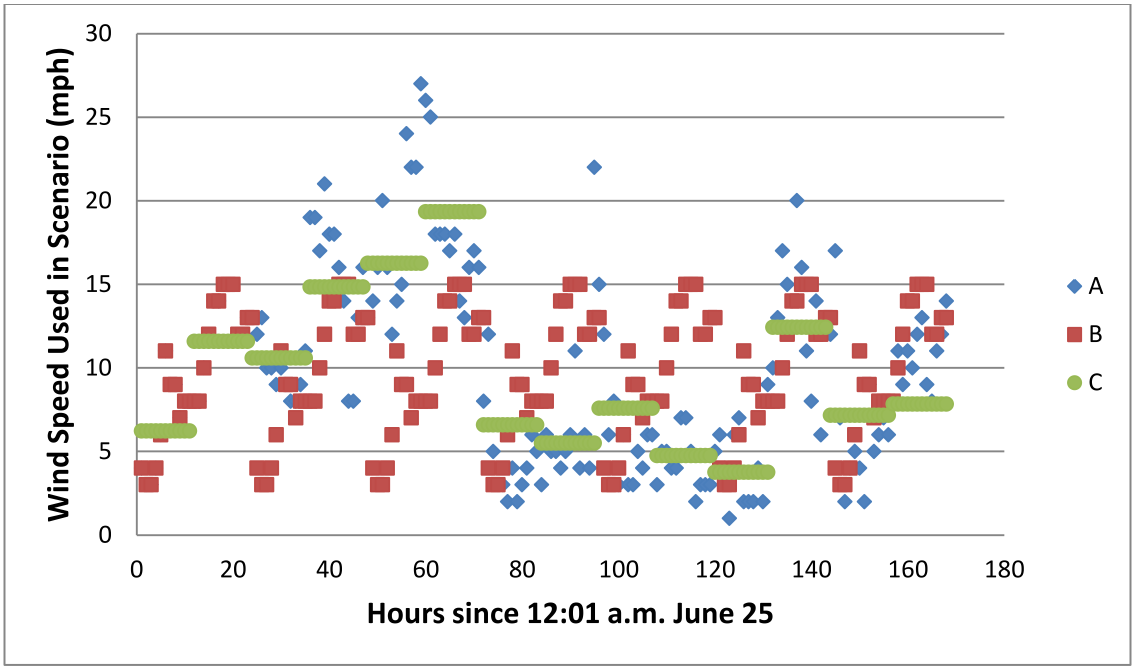

Figure 6: Wind speed values used in each simulation variation (miles per hour)

<u>Model Parameters and Fire Behavior:</u> After creating the landscape and setting the project inputs, computational details of the simulation were determined. The perimeter and the distance resolution were set to be 30 meters, which is the same distance as a pixelated landscape element. This small resolution distance resulted in a computational time that was not noticeably longer than the time required at a 60 meter resolution. As Figure 7 shows, the distribution of fuel is fairly homogenous, but elements such as roads or heterogeneous fuel elements in the northwest could be skipped over if the perimeter resolution was set significantly larger than the pixel resolution.

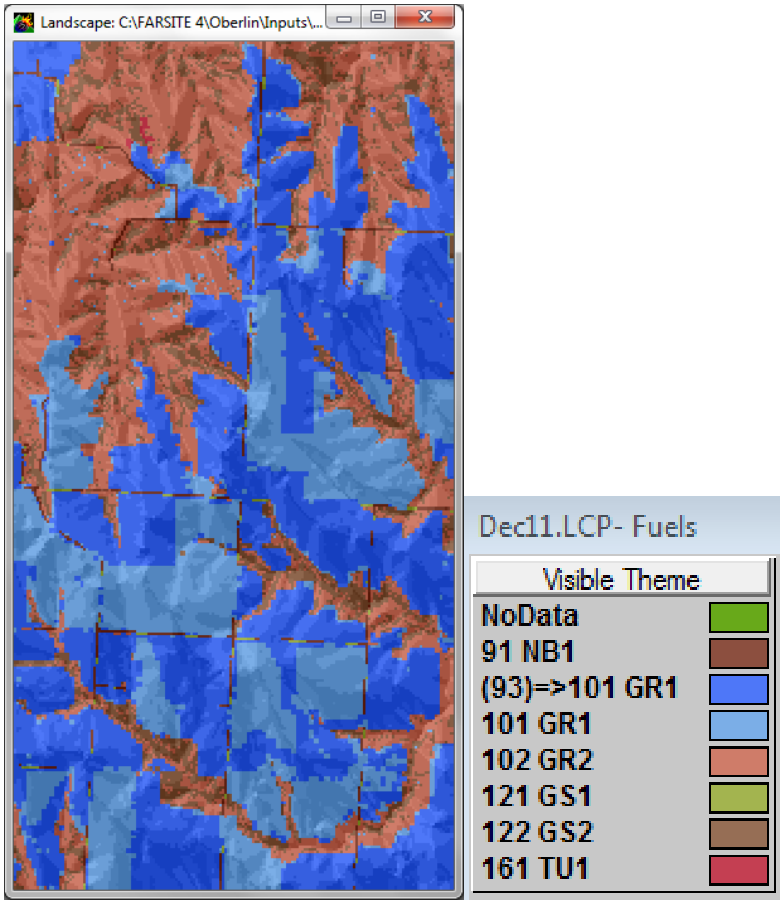

Figure 7: Fuel distribution. Note that heterogeneities in the northwest region and the roads marked as NB1 could be lost at large perimeter distance resolutions.

The maximum time step was set to be 30 minutes. The actual time step used in the fire spread simulation depends on the distance resolutions and the calculated flame spread, so having a relatively large maximum time step only means that all of the separate fires will be projected and merged every 30 minutes. The option to enable crown fire modeling was disabled since the canopy cover is almost nonexistent. Post-frontal combustion modeling of flaming and smoldering within the pyrolysis region was enabled to study the emissions and total energy released from the fire. Since the landscape was primarily grass and shrubbery, no coarse woody profile of living fuels was utilized to modify the surface fire model behavior parameters for the post-frontal combustion.

The simulation duration covered four and a half days, beginning at 10 a.m. on June 26 and ending on the evening of June 30 as shown in Figure 8. Using a conditioning period for the fuel moistures dampens out uncertainties in the initial fuel moisture inputs. In the conditioning period, FARSITE adjusts the fuel moistures according to environmental conditions, slope, aspect, and shading before the starting period.

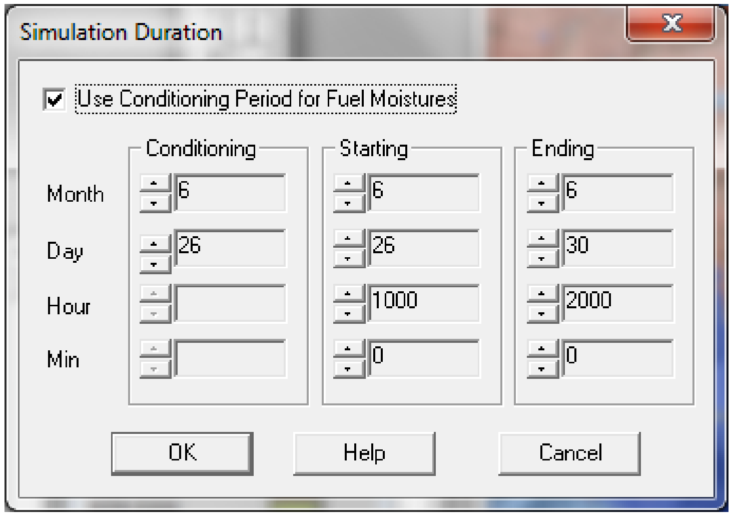

Figure 8: Simulation Duration

The ignition point was placed just north of the southern boundary at the midpoint of the studied area, representing the overheated car that initially sparked the fire. Creating a bookmark of the project at this point allowed different wind settings to be input and run with all other variables held constant.

BehavePlus Simulation: Before the complex multidimensional FARSITE flame spread program was run, reasonable estimates for the surface flame spread rate and the flame length were desired. BehavePlus is a "point" modeling system that can plot flame behavior variables for a given set of inputs at one location and one time. Figure 9 shows the input variables for a representative point near the ignition site. The fuel model, moisture, an average wind speed, direction, slope, and aspect information were taken from the previous discussions.

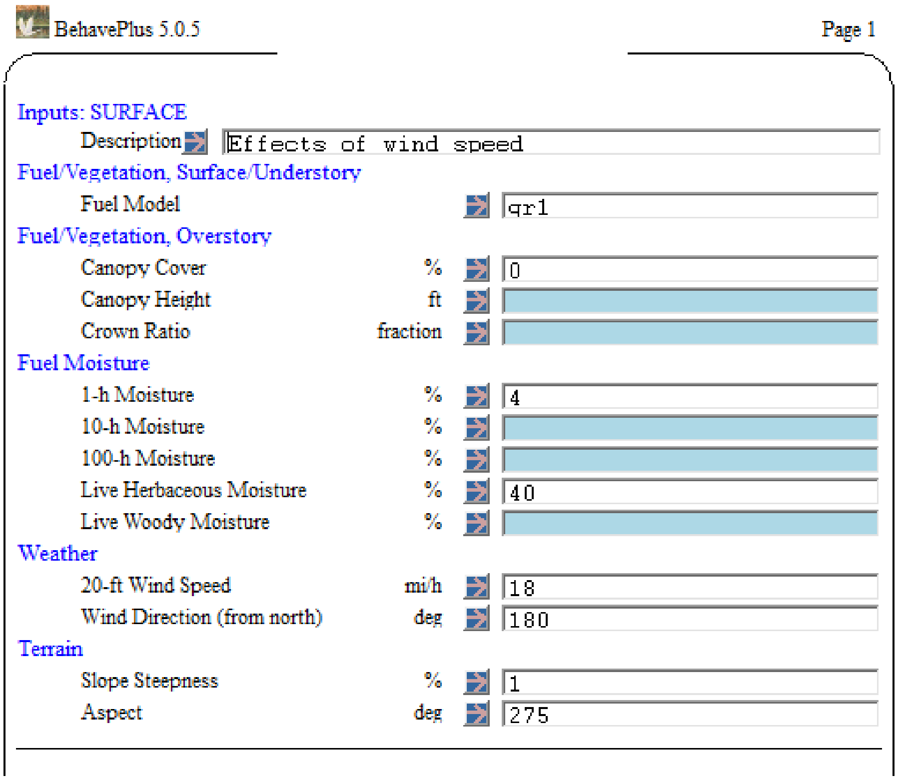

Figure 9: BehavePlus representative flame behavior input with single wind speed

The goal of running BehavePlus simulations is to get an idea of how the FARSITE simulation should act under similar conditions. BehavePlus can predict flame spread rates for different wind speed inputs, as shown in Figure 10. Another common fire description tool is the Fire Characteristics Chart shown below in Figure 11. Any point on the Fuel Characteristics Chart shows four values of interest: the energy generated by the fire per unit area (kJ/s), the surface rate of spread (meters/minute), the flame length(meters), and the fireline intensity (kW/m), which is defined as the energy release per unit time per unit length of the fire front (18).The flame length is an estimated distance from the flame tip to the "center" of the combustion zone, and the fireline intensity has been experimentally correlated with the flame length. The heat emission of the fire can be found by dividing the fireline intensity by the experimentally measured rate of spread. From an engineer's perspective, these processes are a result of the radiative and convective heat transfer interactions between the flame and the surroundings, and could be modeled using diffusive flame spread techniques. In the field, however, these charts are useful because foresters can estimate the flame length and surface spread for given fuel and wind conditions and then calculate the energy produced by the flame. The fire will be fought or managed differently depending on the rate of spread, the energy emitted by the flaming front, and the flame length (18).

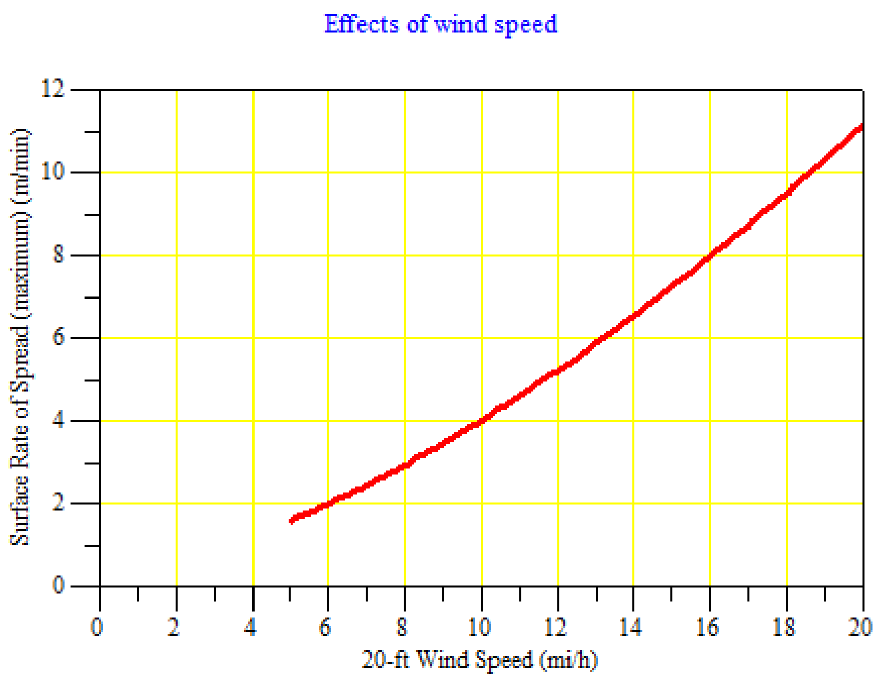

Figure 10: BehavePlus expected spread rate for representative fuel and slope inputs

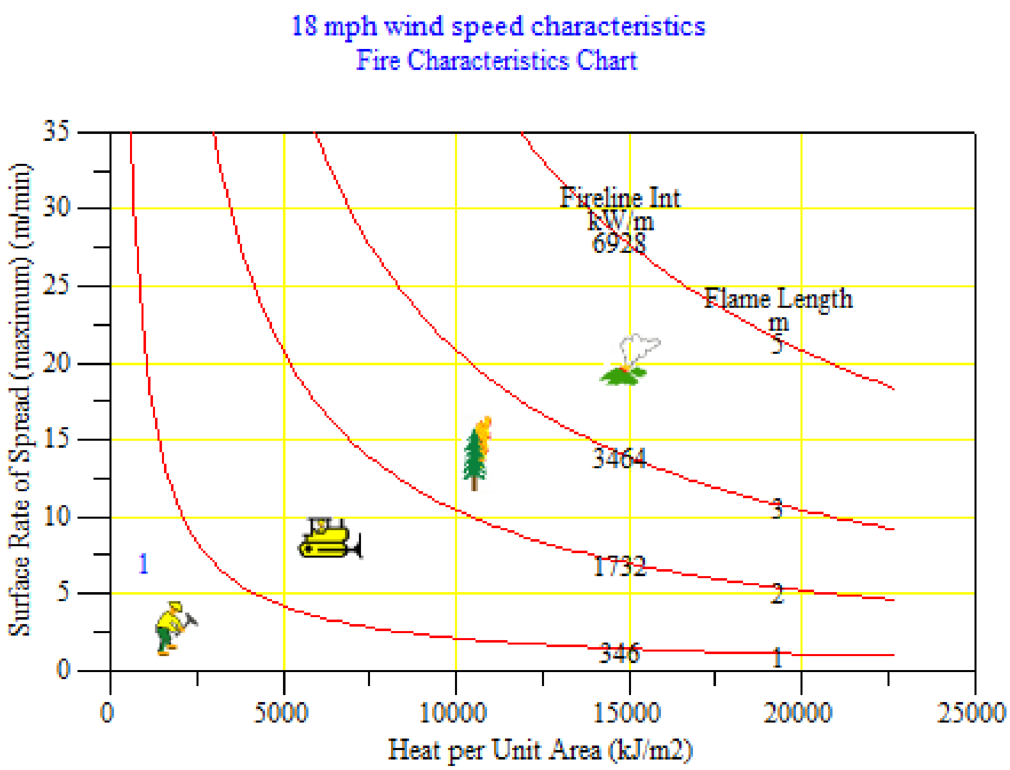

Figure 11: Fire Characteristic Chart from BehavePlus simulation

Results of FARSITE simulation: With the given inputs, FARSITE is used to gauge the effects of wind speed and direction on the flame spread behavior and to estimate fire characteristics and emissions.

Wind Effects: As seen in Figure 12 below, Scenario A (hourly Kirwin wind data) spread to the northeast, while Scenario B (June 25 data repeated each day) spread to the northwest and Scenario C (averaged Kirwin wind data constant for 12 hour intervals) spread almost entirely to the north. These spread patterns generally make sense when viewed with the ranges of wind direction provided in Table 1.

None of the simulations predicted that the fires would spread as far north as was described in a newspaper article of the event (5). If the simulation matched the report's estimates, fire would have spread two-thirds of the way towards the top of the control area on June 26th alone. Error may lie in the modeling of fuel type, fuel moisture, or the no-burn road areas that acted as intermittent borders to halt the fire's northwards progression. It is also possible that multiple fires ignited in different locations on the 26th and merged, which was not modeled in the simulations. Though these FARSITE simulations were not able to capture the observed fire behavior, comparing the simulations can still yield insight.

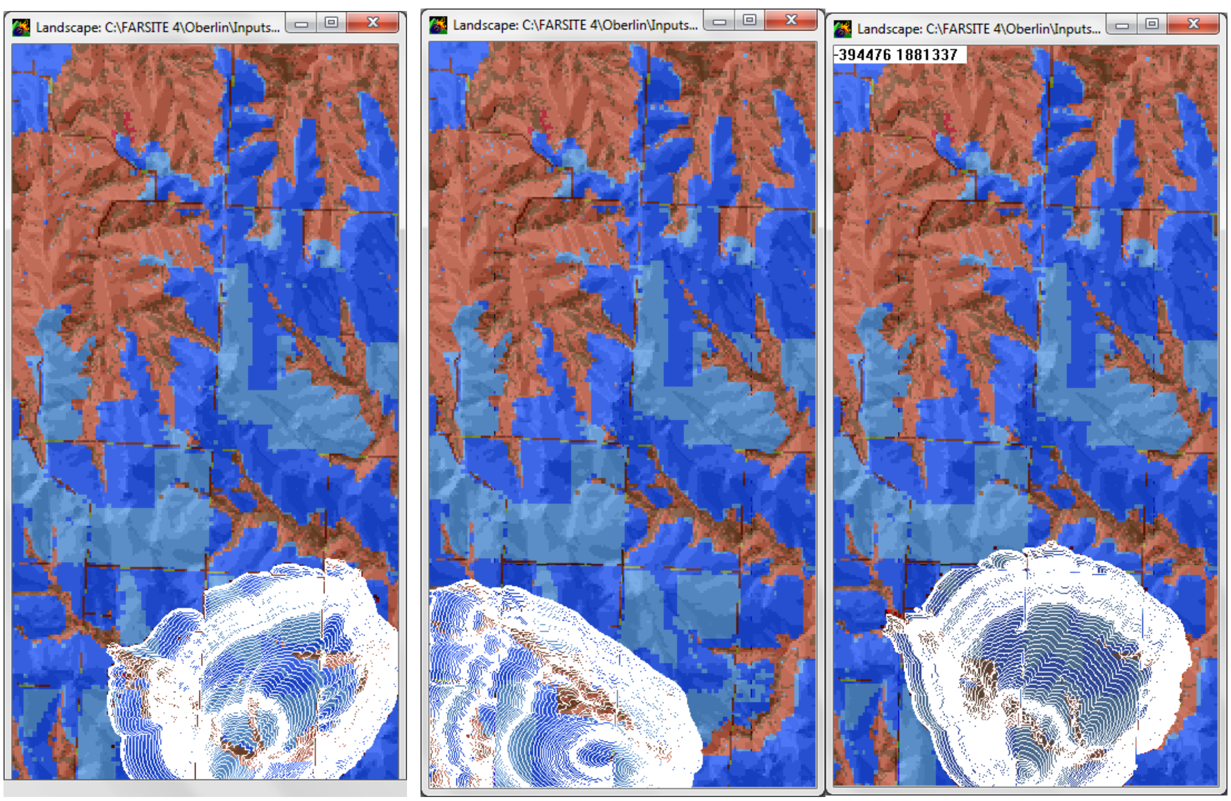

Figure 12: Fire spread for Scenarios A (Left), B (Middle), and C (Right).

The magnitudes of the wind inputs are important in determining fire behavior. Each white elliptical ring represents the fire front perimeter at the visual time step of 30 minutes. It is noted that the general spread behavior in Scenarios A and C is similar, since in both cases wind-aided propagation is initially strong at high wind speeds before slowing at the end of the simulation. This would be expected since the wind speed and directions in Scenario C are averaged versions of Scenario A, and a user would also expect that the periodic wind speeds of Scenario B in a fairly homogenous fuel region would result in the observed alternating fast and slow spread rates. In Figure 13 below, the three simulations have comparable final areas and perimeters of spread, with Scenario C being slightly larger than the other simulations. However, since the fire expanded over different terrain in each simulation, the total energy release of the fires were also calculated and found to be very similar. Though the shifting wind directions had a large impact on the fire spread direction, the changes and the averaging of the wind speed values did not have as large of an impact on the total area, perimeter, or energy released from the fire. It is worth noting that the energy released by the fires was on the order of $1.6*10^{14}$ Joules over four and a half days, which is a result of the flaming and smoldering reactions occurring behind the advancing front.

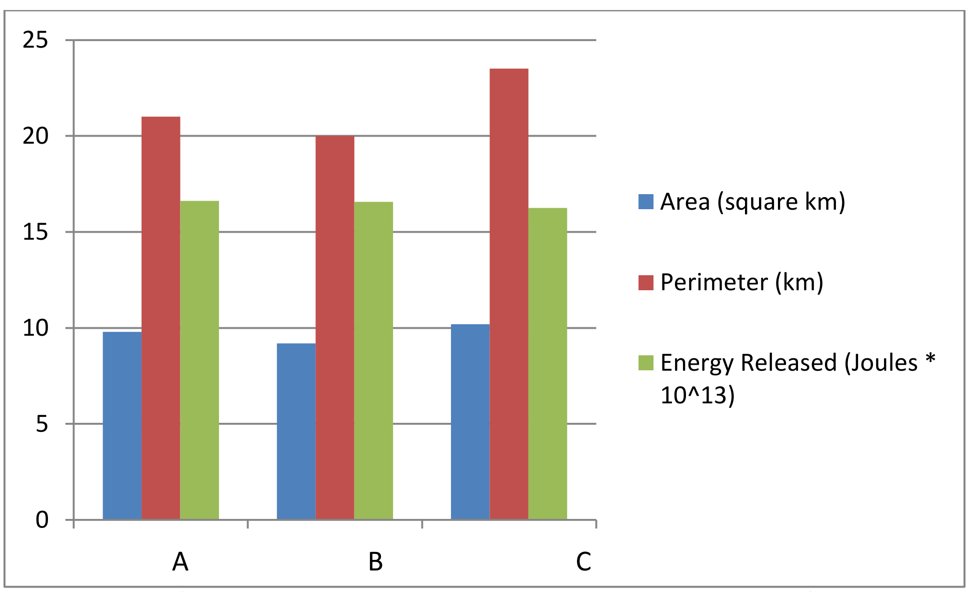

Figure 13: Area (km^2), Perimeter (km), and Total Energy Released (Joules $*10^{13}$) of each scenario

Flame Spread: The Fire Characteristics Charts from the FARSITE simulations can be compared with the simplified BehavePlus results for flame spread on short grass. In Figure 14, a representative fire characteristic chart is shown for Scenario A. The characteristic charts for Scenarios B and C look very similar to the chart from Scenario A and were not included.

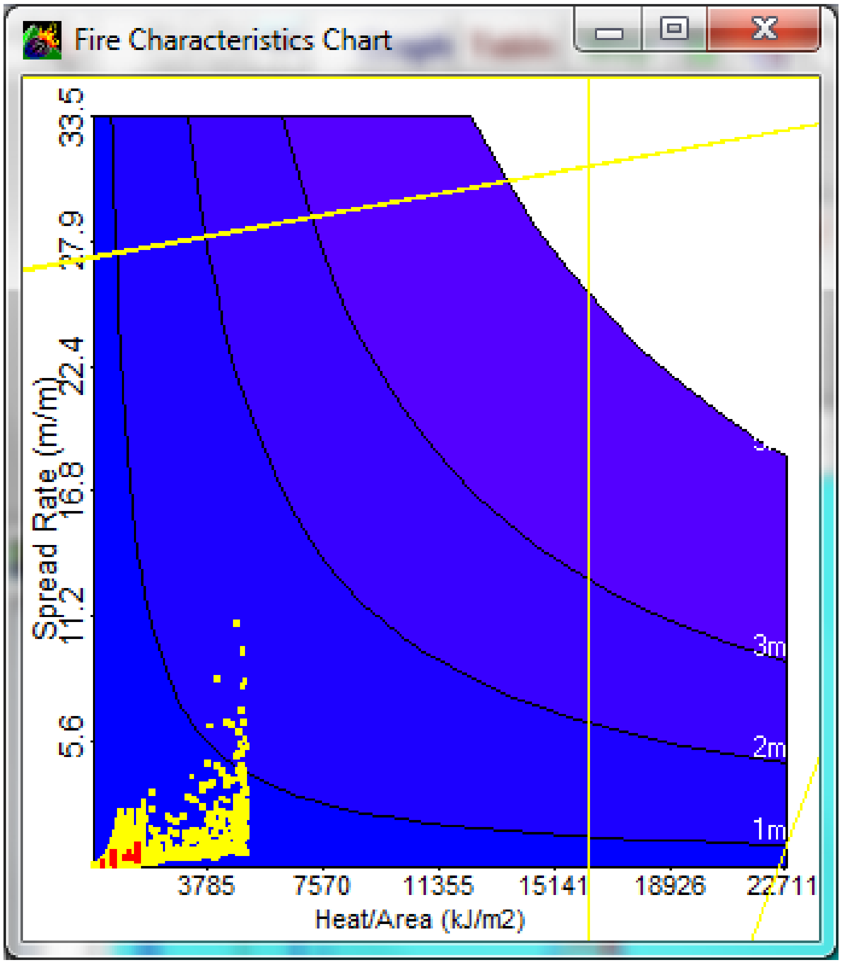

Figure 14: Fire Characteristics Chart from Scenario A in FARSITE. Flameline intensity not shown.

The yellow pixels in Figure 14 represent fire characteristics at the expanding perimeter recorded at each time step. The red pixels are the fire spread behaviors at the end of the simulation. Since the FARSITE simulation included multiple fuel types (though primarily short grasses in the "GR1" category) and dynamic fuel moistures, minor differences in the spread rate when compared to the BehavePlus simulation would be expected. Comparing the spread rates from Figure 13 with the predicted spread rates from Figure 10, however, it is seen that the predicted range of surface spread from 2-11 meters/minute was replicated in the FARSITE simulation. It is expected that the highest wind speeds in the FARSITE simulation during the days of June 26th and 27th caused the increased spread rates, and the reduced winds at night and in the later days of the simulation corresponded with the lower spread rates. The flame position on the chart indicates that the fire can be usually be fought with hand tools, but that at larger flame lengths suppression dozers or pumpers may be required (18). Comparing the FARSITE and BehavePlus flame spread results provides a measure of verification for the simulations, but does not validate that either simulation fits the actual fire processes occurring in the field.

Emissions: FARSITE's post-frontal combustion products analysis also allows the user to view harmful products of combustion that result from the flaming and smoldering inside the combustion zone. The three simulations produced very similar emissions, so the Scenario A results for the total carbon dioxide and carbon monoxide emissions are shown below in Figures 15 and 16, respectively.

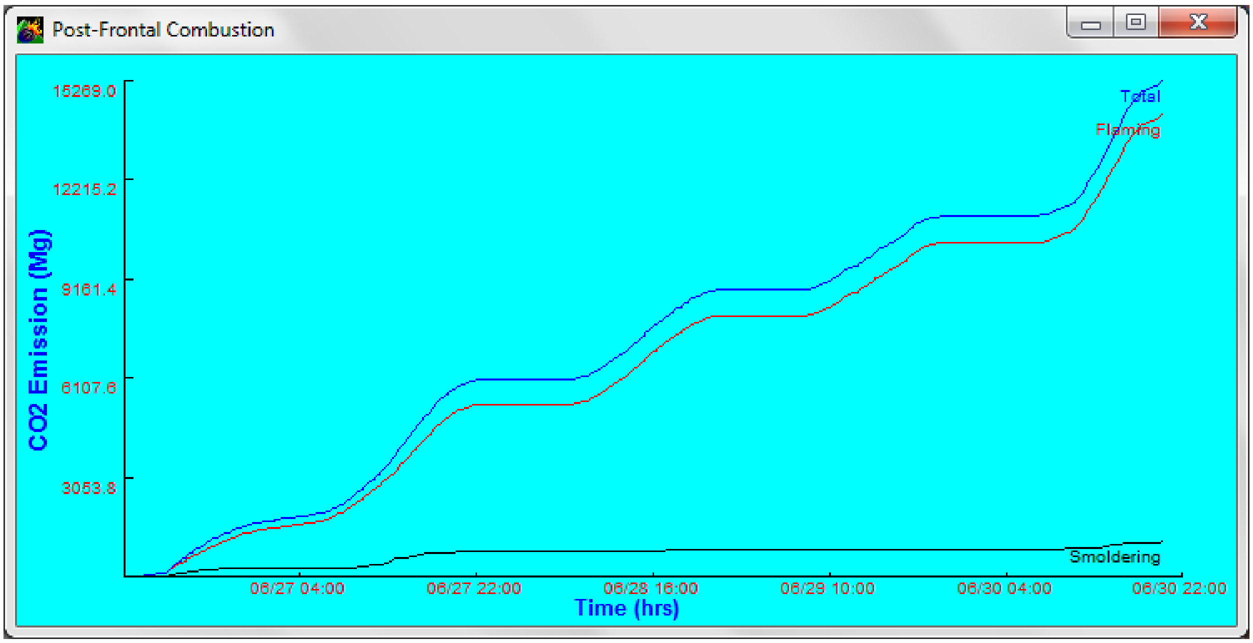

Figure 15: Total Carbon Dioxide emissions from Scenario A (Mg)

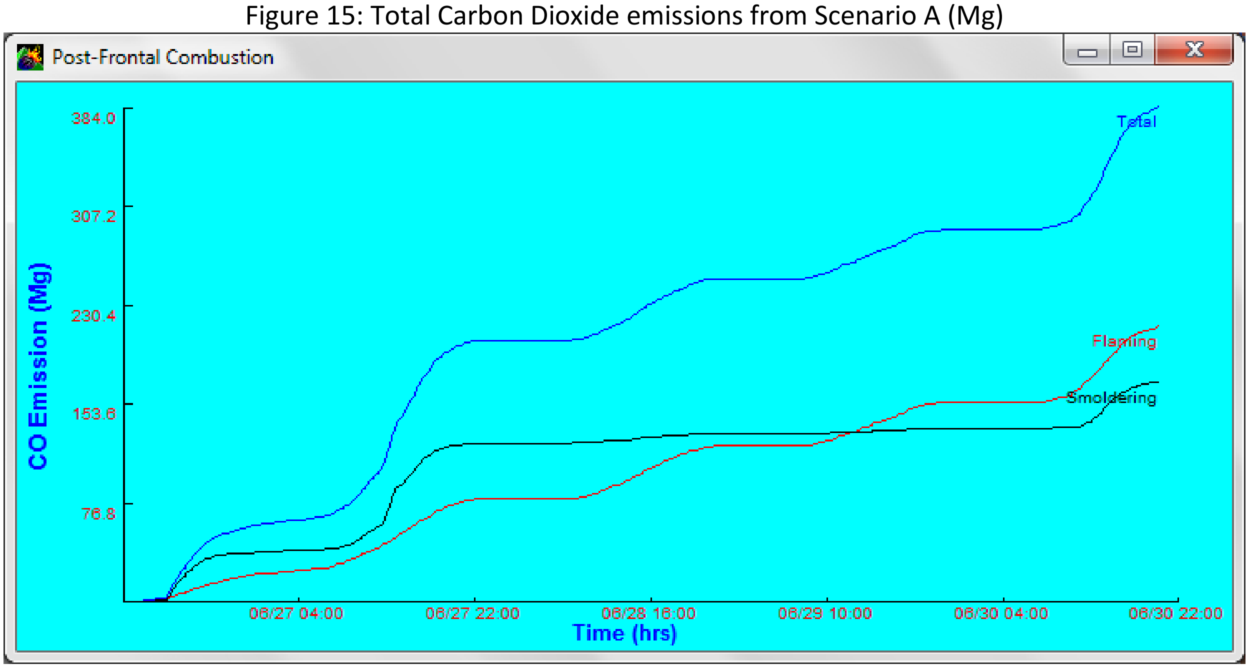

Figure 16: Carbon Monoxide emissions from Scenario A (Mg)

The red lines in the above figures track the total emissions from flaming reactions, and the black lines are the emissions from smoldering reactions. The blue lines are the total emissions. The vast majority of the total carbon dioxide emissions occurred from the flaming reactions, in which the carbonaceous fuel was almost completely converted into carbon dioxide. The flaming reaction emissions steadily increased during the day, when higher temperatures and wind speeds were prevalent. The total carbon dioxide emissions of 15300 Mg from this fire would be two orders of magnitude larger than the estimated 49 Mg yearly carbon footprint of an average US household (19).

For carbon monoxide, about half of the emissions occur from the smoldering reactions. Smoldering is a flameless surface process characterized by limited oxygen rates at the reaction zone. Although lower temperatures lead to smaller fuel mass loss rates, the products of incomplete combustion such as carbon monoxide can be substantial because in general, smoldering can sustain itself for prolonged periods of time (20). In Figure 16, it appears that most of the emissions of smoldering reactions occurred as the fire perimeter grew during the day on June 26th and 27th with much fewer emissions during the nights and subsequent days. In this wildland fire and in general, products of incomplete combustion pose a major threat to air quality and have serious life safety implications as well as economic and environmental costs.

Conclusions: This analysis indicated that the FARSITE simulation as presented did not adequately describe the results of the June 26th, 2012 fire in Oberlin, KS that were detailed in a newspaper report. Data inputs to the model would need to be further adjusted to fit the actual situation. The analysis of the wind data inputs showed that wind direction is an especially important variable to characterize, and that wind speed estimations also affect the flame spread behavior. From a life safety perspective, foresters need to be extremely cautious in using FARSITE to predict fire motion and decide whether or not to evacuate surrounding areas. Depending on the data used in the simulation, an inexperienced forester might have misallocated resources or neglected to warn northern residents of the fire. The large quantities of carbon dioxide emitted by flaming combustion and the carbon monoxide resulting from smoldering and flaming reactions add additional health hazards to the already potentially deadly fire scenario.

There are many ways to run a FARSITE simulation incorrectly. Errant data, careless entry, poor file management, wrong measurement units, and neglected model parameter terms can easily and significantly impact the results of a simulation. If these simulations are being used to develop prescribed burns or analyze the fire spread potential of a model, these errors could be costly and even lifethreatening. Methods that users could use to address these issues include proper software training, peer validation and review of simulation parameters, and result comparison against previous simulations, BEHAVE point measurements, and fire experience. Tuning the time step parameters and fuel models to match experimental results can be time intensive and must be performed well in advance of anticipated use even for simple surface fire cases such as the fire considered here. When a FARSITE simulation is properly prepared and utilized, however, foresters and fire engineers can gain great insight on the complicated flame spread process and act accordingly.

This report has examined some of the basic principles of semi-empirical flame spread models, assembled data from diverse sources to attempt to recreate a fire in FARSITE, performed a general validation check in BehavePlus, studied the impacts of different wind input estimations, and gauged basic life safety issues that could result from an unchecked wildland fire. As modeling techniques advance in the upcoming decades, developers need to keep in mind the spatial and temporal input data available to the user, and users must recognize the need to carefully train and study complex models such as FARSITE before attempting to apply the modeling tools in practice. A concerted effort from all sectors to improve the accuracy of the data, the knowledge of the average user, and the software's modeling abilities could help professionals better manage and prevent wildland fires.

Works Cited

1. Vertuno, J., & Graczyk, M. "Bastrop wildfires destroy 1,000-plus homes" *Houston Chronicle,* 6 Sept. 2011. Associated Press. Web. 12 Dec 2012. http://www.chron.com/news/article/Bastrop-wildfires-destroy-1-000-plus-homes-2157848.php
2. Zybach, B., Dubrasich, M., Brenner, G., & Marker, J. "U.S. Wildfire Cost-Plus-Loss Economics Project: The "One-Pager" Checklist." *Advances in Fire Practice,* Wildland Fire Lessons Learned Center, 2009. Web. Accessed 12 Dec 2012. http://wildfirelessons.net/uploads/Wildfire_Economics_LongL_pdf.pdf
3. Fire Models, *Fire Behavior and Fire Danger Software*, Missoula Fire Sciences Laboratory, 2012. Web. 10 Dec 2012. http://www.firemodels.org/
4. Jones, C. "Wildfire Activity Unique, Extreme This Dry Kansas Summer." *Topeka Capital Journal* 2 Sept. 2012. Web. 11 Dec 2012. http://cjonline.com/news/2012-09-02/wildfire-activity-unique-extreme-dry-kansas-summer
5. Discoe, C. J. "Grassfire Scorches Oberlin-Area Farms." *McCook Daily Gazette* 27 June 2012. Web. 11 Dec 2012.http://www.mccookgazette.com/story/1864782.html
6. Rothermal, R. C. "A mathematical model for predicting fire spread in wildland fuels." USDA Forest Serv. Res. Pap. , INT-115, 1972.
7. Andrews, P. L. "BehavePlus Fire Modeling System: Past, Present, and Future," Proceedings of *7th Symposium on Fire and Forest Meteorological Society*, US Forest Service, Rocky Mountain Research Station, Missoula, Montana, 2007.
8. Ryu, S., Chen, J., Zheng, D., & Lacroix, J. J. "Relating surface fire spread to landscape structure: An application of FARSITE in a managed forest landscape." Landscape and Urban Planning 83 (2007) 275–283. Web.
9. Finney, M. A. "FARSITE, Fire Area Simulator – model development and evaluation." Ogden, UT : U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, 1998 .Accessed online 11 Dec 2012.
10. FERA (Fire and Environmental Research Applications Team), *Wildland Urban Fire Models,* US Forest Service, 2012. Web. 11 Dec 2012. http://www.fs.fed.us/pnw/fera/research/wfds/
11. Andrews, P. L. "Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model." Gen. Tech. Rep. RMRS-GTR-266. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39 p., 2012.
12. Landscape Fire and Resource Management Planning Tools Project (LANDFIRE), *LANDFIRE Data Distribution Site,* U.S. Department of the Interior and U.S. Geologial Survey, 2011. Web. 9 Dec 2012. http://landfire.cr.usgs.gov/viewer/
13. Scott, J. H., & Burgan, R. E. "Standard fire behavior fuel models : a comprehensive set for use with Rothermel's surface fire spread model" Fort Collins, CO : U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, 2005. Accessed online 11 Dec 2012.
14. Quintiere, J. G. "Fundamentals of Fire Phenomena," West Sussex: Wiley, 2006. Print.
15. Wildland Fire Assessment System (WFAS). *Search Archive.* US Forest Service, 2012. Web. 13 Dec 2012 http://www.wfas.net/index.php/search-archive-mainmenu-92
16. Kansas City Fire Access SofTware (KCFAST). *Weather Station Information.* US Forest Services Fire and Aviation Management, 2012. Web. 11 Dec 2012. https://fam.nwcg.gov/fam-web/kcfast/html/stnstmenu.htm

17. Zachariassen, J.; Zeller, K.; Nikolov, N., & McClelland, T. “A Review of the Forest Service Remote Automated Weather Station (RAWS) Network.” General Technical Report RMRS-GTR-119, US Department of Agriculture, December 2003. Web. 13 Dec 2012. http://www.fs.fed.us/rm/pubs/rmrs_gtr119.pdf
18. Andrews, P. L., Heinsch, F. A., & Schelvan, L. “How to generate and interpret fire characteristics charts for surface and crown fire behavior.” Gen. Tech. Rep. RMRS-GTR-253. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 40 p. 2011.
19. Pappas, S. “The Carbon Footprint of Daily Activities.” *LiveScience Journal,* 21 April 2011. Web. 12 Dec 2012. http://www.livescience.com/13835-carbon-footprint-daily-activities.html
20. Ohlemiller, T. J. “Smoldering Combustion” Chapter 9; Section 2; NFPA HFPE-02; SFPE Handbook of Fire Protection Engineering. 3rd Edition, DiNenno, P. J.; Drysdale, D.; Beyler, C. L.; Walton, W. D., Editors, 2/200-210 p., 2002.