Using Wind Data to Predict Wildfire Spread in Central California

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Abstract

Wildfire growth simulation is important for identifying and mitigating potential wildfires, distributing firefighting resources, and understanding past fire incidents. During wildfire growth simulation, a model is built that integrates information about current active fire locations, fuels, weather, and topography. In this paper, the Rothermel Model was combined with Esri's ArcGIS software to calculate necessary parameters and generate two results: one-hour-after and three-days-after fire spread simulation predictions. Two days of wildfire data from a three-day period were utilized in this simulation, with the first day used as training data and the data for the third day used for model validation. Results showed all of the wildfire locations used for validation were contained in the areas predicted by the three-days-after simulation. Additionally, the one-hour-after simulation generated in FARSITE, one of the most widely used fire-growth-simulation tools, was compared with the results of the custom ArcGIS method in regards to distribution, shape, and size of the predicted areas. In the end, the differences between results were discussed and analyzed.

Introduction

Wildfire is an essential and significant component of forest management and planning. Fire impacts plant growth and movement of wildlife, so managers must be able to predict fire spread depending on fire characteristics (Vasconcelos, Guertin, and Zwolinski, 1990).

In 1972 Richard C. Rothermel, an Aeronautical engineer of the U.S. Department of Agriculture (USDA) Fire Science Lab at Missoula, Montana, created Rothermel's model, which was the first quantitative and systematic tool for fire spread modeling used by the United States Forest Service (USFS) (Wells, 2008). Although some variables in Rothermel's model, such as wind speed, wind direction, and weather conditions, are assumed to be uniform over the prediction area, and thus limit the precision of the result, the model is still widely used by many environmental agencies including the USFS, National Park Service, and other federal and state land management agencies (Rocky Mountain Research Station, 2015). Rothermel's model is further limited due to its empirical approach, which does not adequately address more recent fire management questions that were not recognized in the1970s when the model was developed (Wells, 2008).

Most wildfire models and approaches are implemented using proprietary software, such as BehavePlus, FARSITE, and FLAMMAP, rather than popular GIS software programs, which are widely employed for processing spatial data. In this study, Esri's ArcGIS software,

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a popular GIS tool was used, and a model based on the Rothermel fire spread equation was integrated into ArcGIS. The results of using both the ArcGIS-based custom method and FARSITE program were then compared and analyzed according to their methods, accuracy, and restrictions.

Methods

Study Area

An area in the central region of California was chosen as the study area, and the time period modeled occurred during October 2016. The characteristics of the study area, such as fuel capacity, moisture, precipitation, canopy, vegetation type, and average temperature, are vital for choosing appropriate model parameters. Land cover in the study area is comprised of short grass, and the climate in the fall season is dry with about 5-15 inches of precipitation (Spatial Climate Analysis Service, 2000) (Figure 1).

Figure 1. A photo of central California in the fall (Photo by Author).

Rothermel Model and Empirical Parameters

Formulas (1) and (2) express the rate of fire spread, *R*, in the Rothermel model, which can be decomposed into the contributions from wind, Q_W, and slope, Q_S (Rothermel, 1972); the distance can be calculated by multiplying the rate by the prediction time. Figure 2 illustrates the mechanism of fire spread from one fire source.

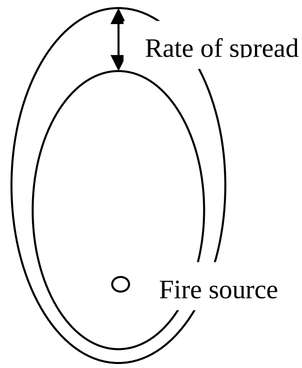

Figure 2. The spread rate of the flaming front is its linear rate of advance in the direction perpendicular to the flaming front.

$$R = \frac{I_R \xi (1 + Q_W + Q_S)}{\rho_b \epsilon Q_{ig}} \quad (1)$$

$$I_R = \Gamma' w_n h n_m n_s \quad (2)$$

ξ: *Propagating flux ratio.*
I_R: *Reaction intensity.*
Γ': *Optimum reaction velocity.*
w_n: *Net fuel loading.*
h: *Fuel particle low heat content.*
n_m: *Moisture damping factor.*
n_s: *Mineral damping factor.*

In standard fire behavior fuel models, the environment of the study area determines various model parameters. Given the description of the study area, of the available Grass Fuel Type Models (GR), the type of GR1 (101), “Short, Sparse Dry Climate Grass (Dynamic)” was chosen for the experiment’s simulation fuel parameters (Scott and Burgan, 2005; Table 1).

Data Acquisition and Pre-Processing

Three types of data were needed to simulate the wildfire spread:

1. Wind direction (degree)
2. Wind speed (meter/s)
3. Current active fire locations

Table 1. Model parameters related to the fuel model for the Rothermel fire spread model (Scott and Burgan, 2005).

Symbol	**Name**	**Value**
w	Fine fuel load (t/ac)	0.40
σ	Characteristic SAV (ft-1)	2054
$\frac{\beta}{\beta_{op}}$	Packing ratio (dimensionless)	0.00143

Wind Data Pre-Processing

Wind related data were downloaded from the National Weather Service (NWS) National Digital Forecast Database (NDFD). Wind speed and direction data for a period of 6 days and 8 hours, beginning 10/15/2016, were downloaded and converted to shapefile format (Figure 3).The data format provided by NDFD was GRIB2, a proprietary format, so the GRIB2 Decoder Library was used to obtain an alternative data format. Specifically, a version of the GRIB2 Decoder Library developed by NDFD, named “TKDeGRIB” was used for the conversion.

After wind direction and wind speed data were obtained, they required additional processing before use in this experimental simulation. A continuous surface of wind data was needed for the study area, and since wind speed is discrete data, the Inverse Distance Weighted (IDW) method was employed to interpolate a raster of wind speed values (Figures 4 and 5). Wind direction data were also processed using the ArcGIS IDW tool.

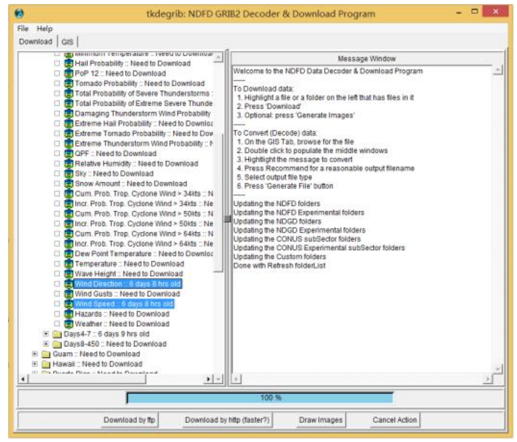

Figure 3. Interface of tkdegrib: NDFD GRIB2 Decoder & Downloader.

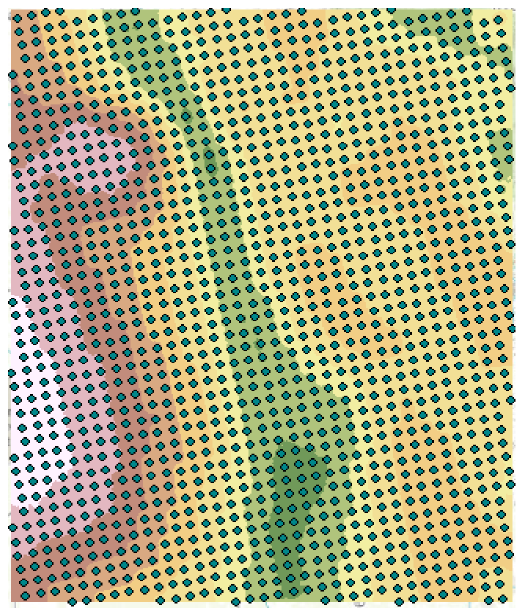

Figure 4. The points represent wind speed monitoring locations and the background image is the result of interpolating a continuous wind speed raster.

Figure 6 depicts the relationship between wind direction and aspect, and from visual inspection of Figure 6, a strong correlation was determined. Therefore, in subsequent experimental simulation, simulation parameters were simplified by excluding the slope and aspect parameters.

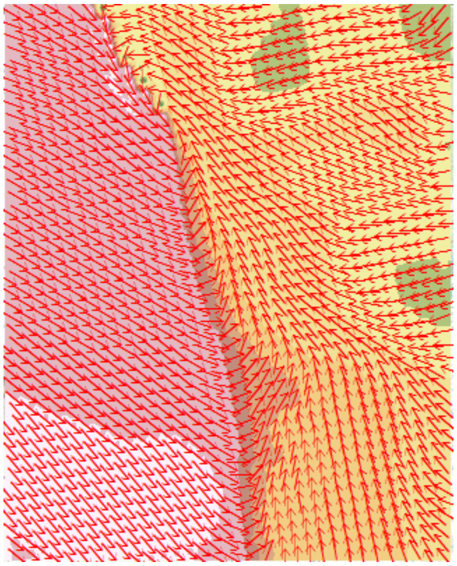

Figure 5. The arrows represent wind direction data points, and the background image represents the result of interpolating a continuous wind direction raster.

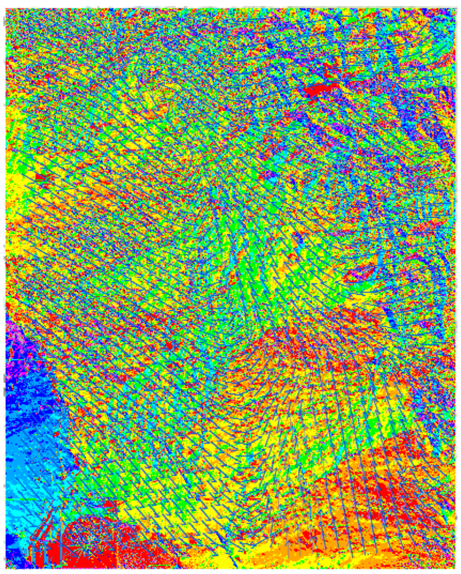

Figure 6. Relationship between wind direction and aspect.

Combining Required Data

After obtaining wildfire data from MODIS for the seven-day period from 10/15/2016 to 10/21/2016 as a shapefile, the fire points were clipped to the study area (represented by the red polygon in Figure 7).

Figure 7. Wildfire data and study area (red rectangle).

To obtain the wind direction and wind speed values for each wildfire point, the ArcGIS Extract Values to Points tool was used (Figure 8).

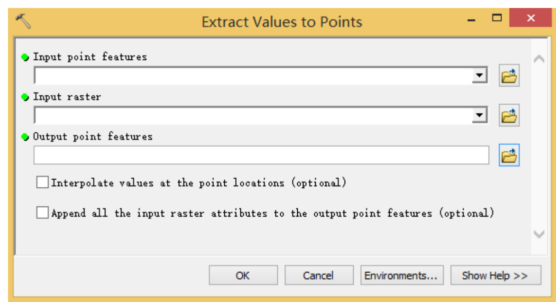

Figure 8. Extract Values to Points tool was used to add wind speed and direction values to the wildfire data table.

Computing Related Parameters for Rothermel Model

According to Formula 1 and the environment of the study area, Formula 1 can be simplified to:

$$R = A(1+\phi_w) \tag{3}$$

$$R_x = A_x(1+\phi_w) \tag{4}$$

$$R_y = A_y(1+\phi_w) \tag{5}$$

$$\phi_w = CU^B\left(\frac{\beta}{\beta_{op}}\right)^{-E} \tag{6}$$

$A_x \approx 9.9;\ A_y \approx 50$

$C = 7.47\exp(-0.133\sigma^{0.55})$,

$B = 0.02526\,\sigma^{0.54}$,

$$E = 0.175 \exp(-3.59 * 10^{-4}\sigma)$$

The above empirical parameters are from Rothermel (1972). Fuel particle surface-to-volume ratio, σ, was set to 2054, and $\frac{\beta}{\beta_{op}}$ (packing ratio) set to 0.00143 (Table 1). *U* represented wind velocity at midflame height and was obtained according to the wind speed at each fire point (Scott and Burgan, 2005). All the required parameters are provided in Table 2.

Through Formulas 1-6, fire spread maximum distance and minimum distance, represented by major and minor axis respectively, were calculated for all the fire points occurring in the study area on October 15, 2016.

Calculating the Results

Wildfire spread simulation conformed to Huygens' Principle (Figure 9); therefore, results of the fire spread simulation took the shape of expanding ellipses. The ArcGIS Table to Ellipse tool generated the resulting ellipses using the five parameters provided (X, Y, Major and Minor Fields, and Azimuth Field) (Figure 10).

Table 2. Wildfire spread parameters for October 15, 2016 fire locations. 1) *wind_dir:* wind direction in Azimuth (degree). 2) *win_sp:* wind speed in meters per second. 3) *POINT_X:* the x coordinate of initial fire source in WGS 1984 Web Mercator. 4) *POINT_Y*: the y coordinate of initial fire source. 5) *minor*: calculated length of semi-minor axis of one-hour prediction area. 6) *major*: calculated length of semi-major axis of one-hour prediction area. 7) *p3minor*: calculated length of semi-minor axis of three-days prediction area. 8) *p3major*: calculated length of semi-major axis of three-days prediction area. 9) *C*: the C value in Formula 6. 10) *Ub*: the value of U^b in Formula 6. 11) *e*: E value in Formula 6. 12) *BBE*: the $\left(\frac{\beta}{\beta_{op}}\right)^{-E}$ value in Formula 6.

wind_dir	win_sp	POINT_X	POINT_Y	minor	major	C	Ub	BBE	e	p3dmajor	p3dminor
280	36	-13312363.9454	4386826.0233	102.8023	519.2034	0.001097	261.4001	2	0.198	37382.64	7401.764
210	18	-13310137.5557	4386548.6185	78.10508	394.4701	0.001097	89.07074	2	0.198	28401.84	5623.566
140	91	-13287317.0601	4376289.6958	223.5169	1128.873	0.001097	1103.709	2	0.198	81278.84	16093.21
160	55	-13302790.4692	4376428.2643	137.6974	695.4416	0.001097	504.8878	2	0.198	50071.79	9914.215
140	91	-13287428.3796	4374627.0126	223.5169	1128.873	0.001097	1103.709	2	0.198	81278.84	16093.21
150	55	-13298560.3286	4374211.3822	137.6974	695.4416	0.001097	504.8878	2	0.198	50071.79	9914.215
140	91	-13289988.7278	4371579.4302	223.5169	1128.873	0.001097	1103.709	2	0.198	81278.84	16093.21
300	109	-13332735.4123	4374765.5597	274.6999	1387.373	0.001097	1460.849	2	0.198	99890.88	19778.39
300	109	-13330397.7031	4374488.4673	274.6999	1387.373	0.001097	1460.849	2	0.198	99890.88	19778.39
290	55	-13312475.2650	4370886.9186	137.3974	685.4416	0.001097	504.8878	2	0.198	50071.79	9914.215
280	36	-13310248.8752	4370609.9266	102.8023	519.2034	0.001097	261.4001	2	0.198	34382.64	7401.764
300	109	-13331288.2589	4373795.7679	274.6999	1387.373	0.001097	1460.849	2	0.198	99890.88	19778.39
280	36	-13310916.7921	4371440.9243	102.8023	519.2034	0.001097	261.4001	2	0.198	37382.64	7401.764
280	36	-13311028.1116	4369778.9933	102.8023	519.2034	0.001097	261.4001	2	0.198	37382.64	7401.764
150	73	-13259821.1459	4346262.5670	177.6632	897.2887	0.001097	783.7563	2	0.198	64604.79	12791.75
140	73	-13257706.0755	4345986.2090	177.6632	897.2887	0.001097	783.7563	2	0.198	64604.79	12791.75
150	73	-13262270.1747	4343361.1624	177.6632	897.2887	0.001097	783.7563	2	0.198	64604.79	12791.75
140	91	-13288652.8940	4374488.4673	223.5169	1128.873	0.001097	1103.709	2	0.198	81278.84	16093.21
140	91	-13289209.4914	4375458.3219	223.5169	1128.873	0.001097	1103.709	2	0.198	81278.84	16093.21
300	109	-13331065.6200	4373657.2333	274.6999	1387.373	0.001097	1460.849	2	0.198	99890.88	19778.39

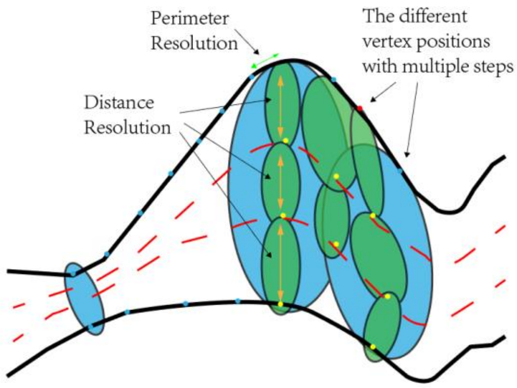

Figure 9. Huygens' principle in fire spread (adapted from Finney, 2007).

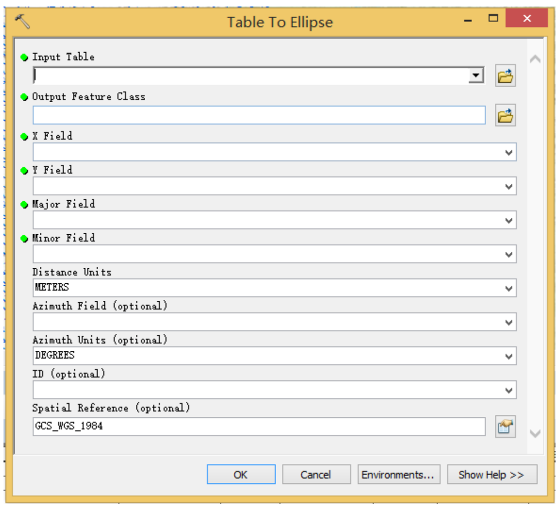

Figure 10. Table to Ellipse tool used to draw the results.

Comparison with FARSITE Simulation and Validation

To explore results of the ArcGIS method was regarding acceptability, the result was compared to a widely employed software in the industry, FARSITE. According to the website of the Rocky Mountain Research Station (2015), FARSITE, a fire growth simulation modeling system, is designed to use heterogeneous spatial and environmental information of terrain, fuels, and weather. It also contains existing models for surface fire, crown fire, spotting, post-frontal combustion, and fire acceleration in a two-dimensional fire growth model. In addition to the mechanisms of wildfire spread mentioned above, the users of FARSITE are required to be familiar with fuels, weather, topography, and wildfire situations. Users include employees of the USFS, National Park Service, and other federal and state land management agencies.

FARSITE Project Development

In order to simulate fire spread, the following parameters were required by FARSITE: Landscape, which includes Fuel Model, Slope, Aspect, Elevation, and Canopy Cover; at least one of five weather files; at least one of five wind files; an adjustment file; and an Initial Fuel Moisture file (Figure 11, Table 3). After all required parameters were prepared, the one-hour prediction result was confirmed (Figure 12).

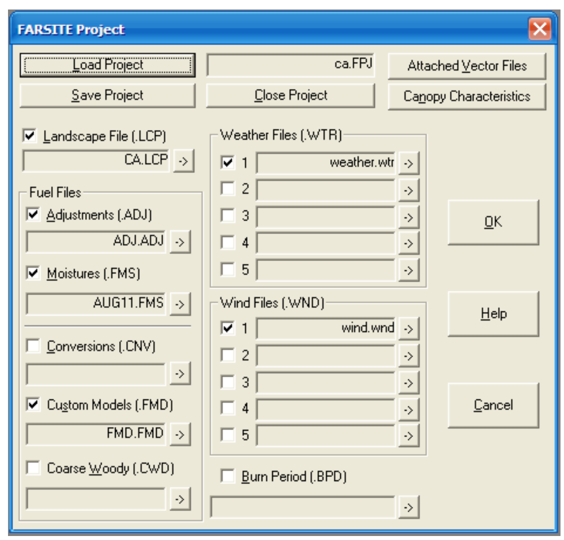

Figure 11. FARSITE project dialog with corresponding files selected.

Results

Validation by Wildfire Data

The green points (wildfires on October 15, 2016) shown in Figure 13 were used to generate the predicted spread polygons (purple); the wildfire points for October 18, 2016 (orange in Figure 13) were used as validation. The resulting area represented the three-days-after prediction area that would be ignited by the October 15th wildfire points. As displayed in Figure 13, the prediction area contained all wildfire locations existing on October 18th.

Table 3. FARSITE Landscape parameter requirements.

File Theme	Required	Default Unit	Alternate Unit
elevation	yes	meters	feet
slope	yes	degrees	percent
aspect	yes	category	degrees
fuel model	yes	13 NFFL models	custom, converted models
canopy cover	yes	categories	percent

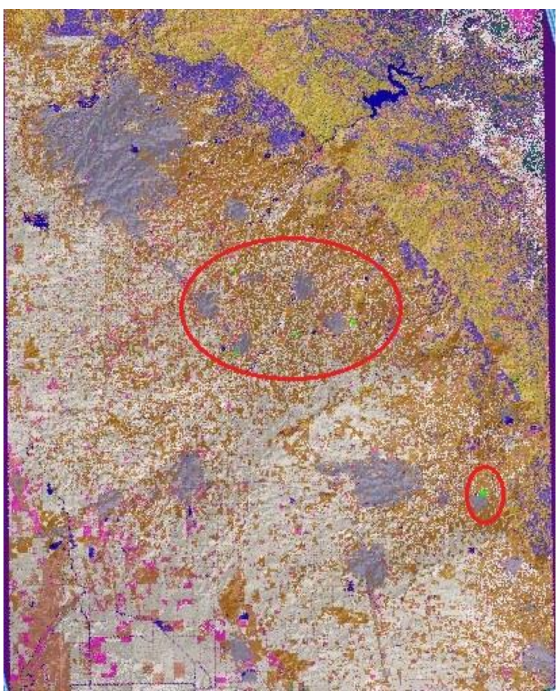

Figure 12. One-hour prediction result using FARSITE. The green spots inside of the red circles indicate the areas of fire spread.

Validation by Comparison

Results from the ArcGIS analysis, using the customized tool and assumptions, were compared with results from the widely used software, FARSITE, for validation of the model. Overall, the custom ArcGIS method generated a greater number of prediction areas, 20 prediction areas, in comparison to 7 prediction areas in FARSITE (Figure 14 and 15). Figure 16 indicates the fire spread direction and distribution of the results of both methods were similar, although the resulting shapes of the two methods were different.

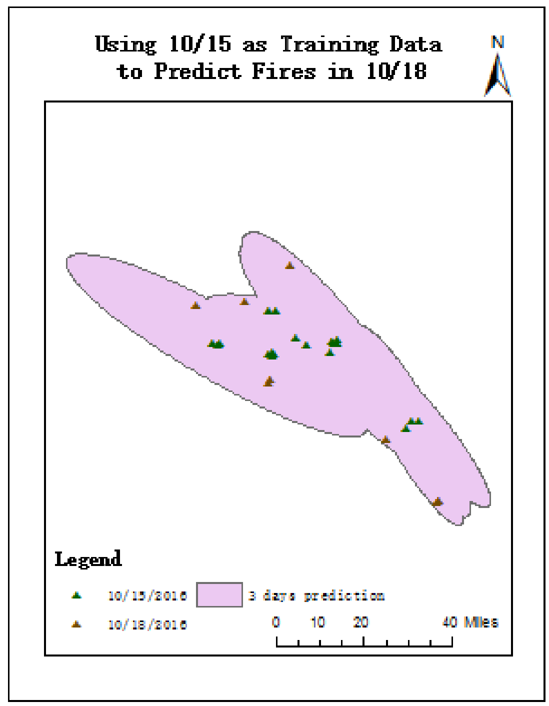

Figure 13. Three-days-after fire spread prediction result.

Discussion

The Differences Between the Custom Method and FARSITE

As seen in Figures 14 through 16, three obvious differences between the results were found: distribution, shape, and size of the prediction areas. From an overall distribution perspective, the custom method resulted in a greater number of prediction areas, which indicated that every active fire spot would spread forced by wind and terrain regardless of other factors, such as land use, fuel, moisture, etc. In comparison, the result of FARSITE included fewer areas representing the spread of fires for a few reasons. One, in FARSITE, other factors such as fuel type and moisture of the fuels are able to constrain the spread of fires. In this case, some active fires were predicted to be dead within the prediction time, so the number of future fire spots were reduced.

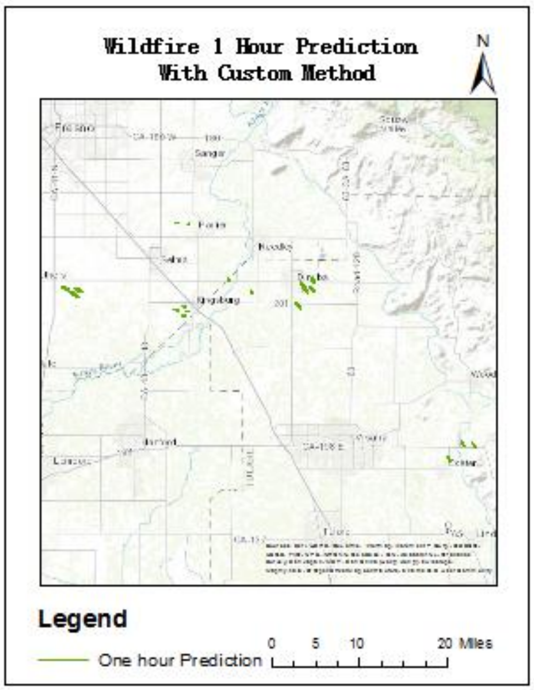

Figure 144. One-hour prediction of wildfire spread generated by the customized method in ArcGIS (green).

To compare the shape of the resulting predicted areas, Figure 16 illustrates that the shape of the results of using the custom method were elliptical; however, the FARSITE method generated irregular polygons. The reason for this difference is that in the custom method a one-time calculation was used to model the result. In comparison, FARSITE employed multiple iterative calculations. Thus, although both methods were based on the assumption of elliptical spread of fire, the final shapes differed.

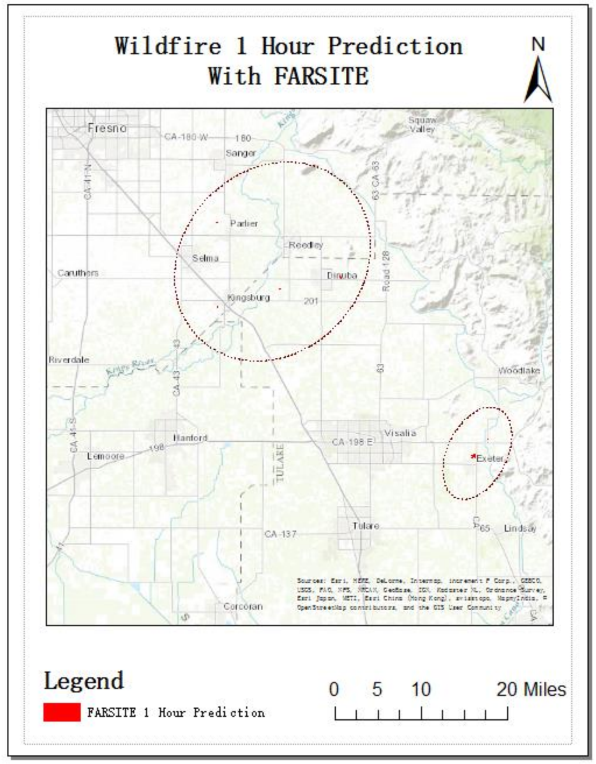

Figure 15. One-hour prediction of wildfire spread by FARSITE (red). Red outlines indicate the areas containing results.

Regarding size of the predicted area, the result of the custom method using the one-time calculation often resulted in a larger predicted spread area; however, FARSITE did have some large results (Figure 13). This is likely because FARSITE, which incorporated more contributing factors, was more likely to detect areas in which factors beneficial to fire converge.

In FARSITE, a consistent wind condition was assumed to simplify the process of computation compared to using more accurate wind data values with wind speed and direction varying across the study area. Multiple iterative spread was mimicked in FARSITE; however, a one-time spread calculation was adopted in the custom method. This is one reason why the distribution, shape, and size of results from FARSITE differed from the custom method.

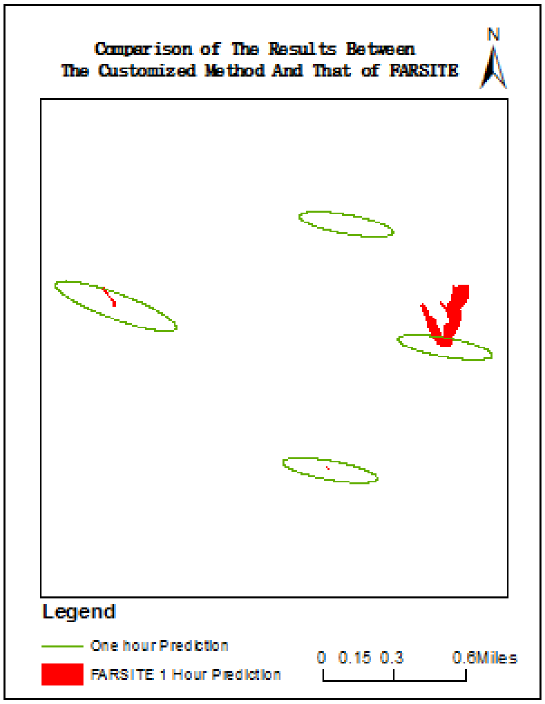

Figure 16. Comparison of the results between the customized method (green ellipses) and that of FARSITE (red areas).

Limitations

The number of iterations had a decisive impact on the resulting wildfire spread prediction. If too many iterations were to be incorporated into the custom method, many calculations would need to be processed, potentially beyond the capability of computer; if too few iterations are used, then the resulting area could lose accuracy due to the coarseness of the determining factors.

One possible cause of error was that according to Formula 3 assumption, the simplified model was applied and certain factors (e.g., terrain slope, fuel capability, temperature, and moisture) were ignored. Another possible cause of error is inaccuracies in Rothermel's model that did not account for advances in fire model prediction occurring in the 40 years since its development in the 1970s (Wells, 2008).

Conclusions

This project used ArcGIS to implement Rothermel's wildfire model using simplified parameters. All steps were evaluated and calculated using the tools in ArcGIS. Along with the simplified parameters and toolset in ArcGIS, only one model iteration was adopted.

Future research could analyze other methods, such as the cellular automaton based fire spread method and the fluid dynamics based method, as well as investigate using ArcPy to implement the Rothermel's wildfire model with multiple iterative processes according to Huygens' wave principle.

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