Sensitivity Analysis of a Model of the 2003 Simi Wildfire Event

S.H. Peterson[1*], N.C. Goldstein[1], M.L. Clark[1], K.Q. Halligan[1], P. Schneider[1], P.E. Dennison[2], D.A. Roberts[1]

[1]Department of Geography, University of California at Santa Barbara,
Santa Barbara, CA 93106-4060
*Telephone: (805) 893-4434
Fax: (805) 893-7782
Email: seth@geog.ucsb.edu

[2]Department of Geography, University of Utah,
Salt Lake City, UT, 84112-9155

Abstract

A sensitivity analysis of the FARSITE fire spread model was performed using the fall 2003 Simi wildfire event as a test case. Model inputs that were varied included two different fuels maps and two different sources of wind speed and direction. The model parameter that was varied was perimeter resolution, essentially the spatial resolution at which the model was run. Model accuracy was assessed through a comparison with the MODIS active fires product, using the Lee-Sallee spatial correspondence metric. The FRAP fuels map predicted initial fire growth most accurately, but produced too large of a burn at the later time steps. A fuels map created from a classification of Landsat imagery, smoothed to 270m cells, produced the most accurate fire size at the later time steps. Spatially varying wind inputs increased variability in model output. This research demonstrates that FARSITE is sensitive to model inputs and parameters and suggests that fire behavior analysts should perform multiple runs in order to bracket the range of possible fire behavior.

1. Introduction

In recent years, several extreme wildfires in the western United States and southeastern Australia have burned within the mosaic of natural and residential land uses known as the wildland-urban interface (WUI). One such fire was the Simi Fire, part of the fall 2003 Southern California Fire Complex. The Simi Fire burned from October 25 to November 5, 2003, consumed 44,000 ha, destroyed 315 structures, and cost approximately $10 million to suppress.

Advances in geospatial technology are making it easier for spatial modeling tools to be incorporated into the wildfire fighting and mitigation process. These include GPS-enabled products, remote automated weather stations (RAWS), integrated local and regional GIS databases, and remotely sensed imagery. The focus of this work is the use of state-of-the art geospatial products to simulate the Simi Wildfire, including testing the sensitivity of the fire spread model Fire Area Simulator (FARSITE) (Finney, 1998), to model inputs and parameters. This work illustrates that when using a spatial dynamic model, sensitivity testing is necessary for understanding the variability of model output.

FARSITE is a deterministic, equation-driven fire spread model that implements the semiempirically-based Rothermel equations to predict fire behavior (Rothermel, 1972; 1983). FARSITE models fire propagation as a wavefront, based on Huygens' Principle (Richards, 1990; Finney 1998). The fire front at time, t, is discretized into multiple vertices, with spacing determined by the perimeter resolution parameter. The fire direction and velocity at each vertex are dependent upon wind and fuel conditions, as well as slope and aspect. The individual fire fronts from each vertex at time, t+1, are merged to form the new fire front (Finney, 1998). Models took longer to run as perimeter resolution became finer because the increased number of vertices meant more polygons needed to be generated and combined. FARSITE includes a well-developed user interface, and inputs/outputs are GIS-based.

The FARSITE model requires a variety of inputs, some of which, like elevation, slope and aspect, are readily derived from a digital elevation model (DEM). Weather-related inputs (e.g. temperature, humidity) most commonly come from a RAWS. There are 1500 of these weather stations throughout the United States, deployed by multiple government agencies. Wind-related inputs can come from a RAWS, in which case they are spatially invariant. An alternative approach is to use a forecast model, such as MM5 (Grell et al., 1994), which outputs a spatially varying wind field that may more closely match localized wind patterns. Another advantage of using a forecast model is that future fire behavior can then be operationally predicted. Spatial fuels information is supplied in two layers: Fuel models (Anderson, 1982) and canopy cover. A fuel model is a simplified description of the amount and distribution of surface fuels for a given vegetation type, specifically designed to be used in a fire spread model. Canopy cover reduces temperature and humidity variability in fuels beneath the canopy. For most grassland and shrubland fuels, canopy cover is assumed to be 0%. Live fuel moisture and dead fuel moisture are defined for each fuel model, and are spatially invariant. Other user-defined parameters include the time step of the model run and perimeter resolution of the fire front. There is limited documentation concerning the ideal perimeter resolution for a FARSITE run, and there has been no discussion of the effects of varying multiple input parameters in the literature.

The goal of this research was to perform a sensitivity analysis of FARSITE with respect to fuels data (including data source and spatial resolution), wind inputs, and perimeter resolution. The data for examination were from the 2003 Simi Wildfire. Model validation was accomplished by comparing spatial overlap between simulated fires and fire perimeters derived from the Active Fire Product of the MODIS sensor (Justice et al., 2002; Quayle and Lannom, 2004).

2. Data and Methods

The Simi Fire burned through a southern California chaparral/grassland mosaic. Two different sets of fuel models were used to characterize the vegetation (Table 1): the fuel models developed by Anderson, formally called the Northern Forest Fire Lab (NFFL) models; and custom fuel models that were specifically developed for chaparral, the Riverside Fire Lab (RFL) fuel models (Regelbrugge and Conard, 1996). The 1-, 10-, and 100-hour fuel size classes of Table 1 correspond to <¼, ¼-1, and 1-3 inch diameter woody material, and are based on how quickly dead fuel moisture responds to changes in atmospheric relative humidity.

Table 1. Biomass and fuel bed height for fuel models

| | | Fuel Biomass (Mg/ha) | | | | | |
| | | Dead | | | Live | | |
Fuel Model	Fuel Model Description	1 hr	10 hr	100 hr	Herbaceous	Woody	Fuel Bed Depth (cm)
NFFL 1	grass	1.66	0	0	0	0	30.48
NFFL 2	savana	4.49	2.25	1.12	0	1.12	30.48
NFFL 4	shrub	11.25	9.01	4.49	0	11.25	182.88
NFFL 5	shrub	2.25	1.12	0	0	4.49	60.96
NFFL 6	shrub	3.37	5.61	4.49	0	0	76.20
NFFL 8	timber	3.37	2.25	5.61	0	0	6.10
NFFL 10	timber	6.76	4.49	11.25	0	4.49	30.48
RFL 15	old chamise	4.48	6.73	2.24	1.12	4.48	91.44
RFL 16	ceanothus	5.04	10.76	4.04	6.73	6.28	182.88
RFL 18	sagebrush/buckwheat	12.33	1.79	0.22	1.68	5.6	91.44
Farsite 99	unburnable	0	0	0	0	0	0

We used two different sources of fuel model maps. The statewide surface fuels data layer, was downloaded from the state of California's Fire and Resource Assessment Program (FRAP) website (http://frap.cdf.ca.gov). The 30m FRAP fuels map is released already cross-walked to NFFL fuel models, however the fuel models for chaparral were changed to the RFL fuel models for our analysis (Table 2, Figure 1a). Cross-walking is a process of aggregating like vegetation types into broader classes which are likely to burn similarly, in a manner consistent with the fuel loadings of a particular fuel model. Fuel models 28, 98, 15, and 97 whish represent urban, water, desert, and irrigated agriculture, respectively, were reclassified to fuel model 99, the designated number for unburnable cells for FARSITE. The second map was created using a decision tree classification (Breiman et al., 1984) of two georeferenced Landsat TM scenes acquired on July 18, 1999 and October 22, 1999, and cross-walked to fuel models (Table 3, Figure 1b). The initial fuel model map was smoothed, to reduce fuel heterogeneity, using a mode (majority) filter acting on non-overlapping 3, 5, 7, 9, 11, 13, 15, and 21 cell square windows (the 30m cell resolution was retained). Hereafter these will be referred to as mode-3, mode-5, etc. Table 4 presents cell counts of fuel models, for those cells within the final fire perimeter.

Table 2. Cross-walk for FRAP map

Original Fuel Model	Final Fuel Model
NFFL 1	NFFL 1
NFFL 2	NFFL 2
NFFL 8	NFFL 8
NFFL 10	NFFL 10
NFFL 6	RFL 15
NFFL 4	RFL 16
NFFL 5	RFL 18
FRAP 28	Farsite 99
FRAP 98	Farsite 99
FRAP 15	Farsite 99
FRAP 97	Farsite 99

Table 3. Cross-walk for Landsat map

Original Landcover Class	Final Fuel Model
grass	NFFL 1
riparian/oak woodland	NFFL 8
medium density chaparral/chamise	RFL 15
heavy chaparral/ceanothus	RFL 16
sparse chaparral/coastal sage scrub	RFL 18
soil/impervious	Farsite 99
water	Farsite 99
golf course/agriculture	Farsite 99

Table 4. Cell counts of fuel models, within the final fire perimeter, for each of the maps

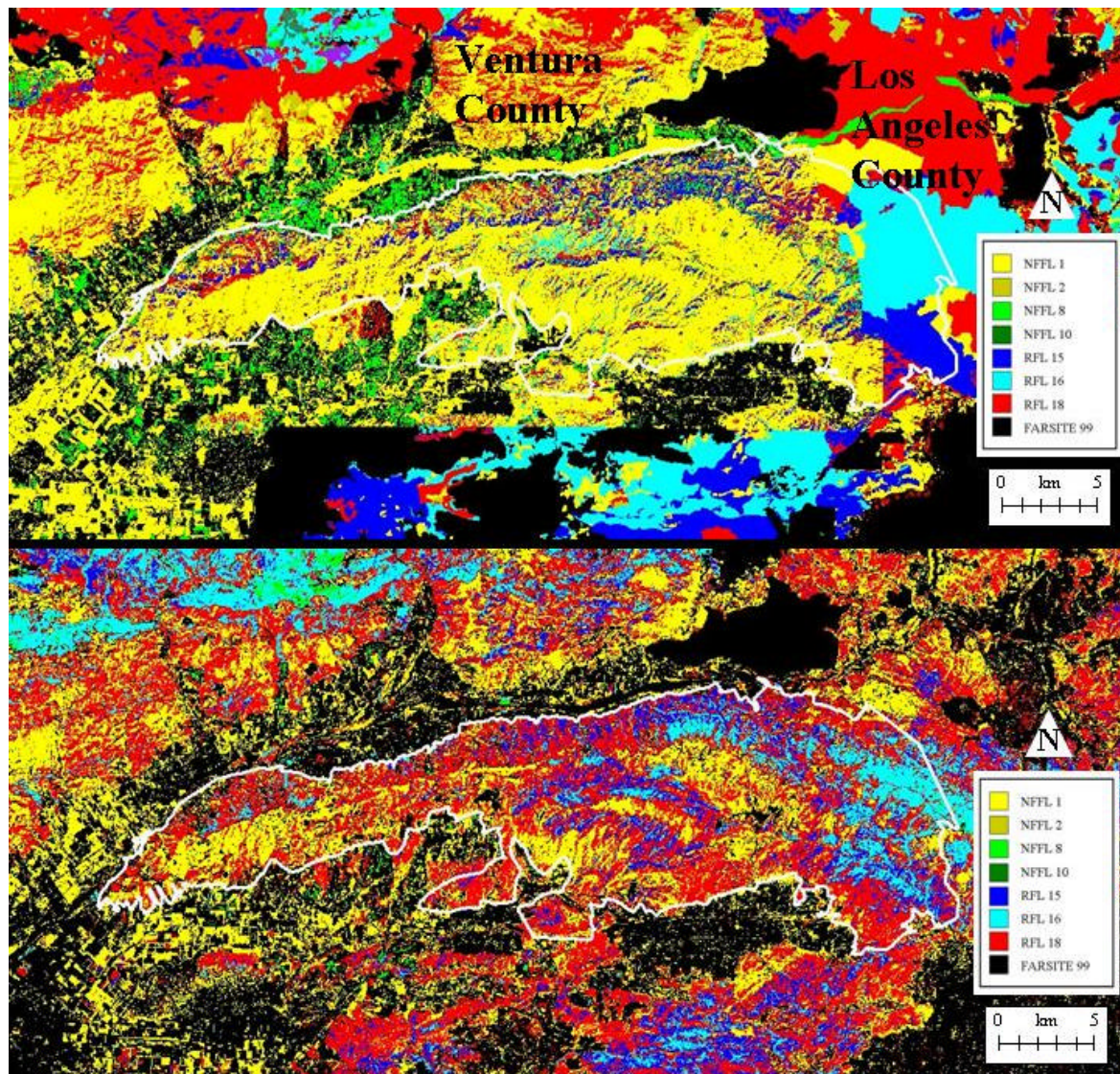| Fuel Model	FRAP	Landsat								
		original	mode 3	mode 5	mode 7	mode 9	mode 11	mode 13	mode 15	mode 21
NFFL 1	251671	103750	105663	102123	100366	98918	98057	96757	95863	94912
NFFL 2	1839									
NFFL 8	19798	660	326	130	56	10	3	3	1	0
NFFL 10	79									
RFL 15	58041	46824	43226	37804	33463	30294	27775	25474	23367	17728
RFL 16	46628	50560	49752	49146	48596	47679	47155	46518	46041	45219
RFL 18	48605	186542	197574	210135	218795	225398	230118	234867	238558	246029
FARSITE 99	15288	53615	45410	42613	40675	39652	38843	38332	38121	38063

Figure 1. FRAP (a) and Landsat-derived (b) fuel model maps. The white polygon refers to the final MODIS burn perimeter.

The relative proportions and arrangement of fuel models in the FRAP and Landsat maps were quite different. The main difference involved how the 2 maps treat non-chaparral areas. The FRAP map tended to map more of these areas as NFFL 1 (grassland) than RFL 18 (coastal sage scrub), at a ratio of 5:1. The Landsat maps contained much more RFL 18, the ratios were approximately 1:2. Another difference was in fuel model 99, unburnable. The Landsat map has a higher native resolution than the FRAP map, so small rock outcroppings, and thus unburnable cells, were mapped at a much higher rate. A noticeable feature in the FRAP map is the clear delineation of the line between Los Angeles (south and east part of map) and Ventura Counties, caused by different map production methodologies. Minimum mapping unit was clearly different, and there were sharp discontinuities in fuel model labels.

Topographic variables were derived from a 30m USGS DEM. Slope and aspect were derived using standard techniques.

The weather data came from the Cheeseboro, California RAWS station, which is located just south of the southerly extent and 25km west of the easterly extent of the fuel model maps. RAWS closer to the fire were tested and rejected as they produced modeled fires that were too small, possibly due to more sheltered station locations. RAWS data consist of daily precipitation, maximum/minimum temperature, maximum/minimum humidity, timing of maximum and minimum temperatures (hourly values are interpolated by FARSITE), and elevation of the weather station (needed to interpolate weather variables across the landscape, using environmental lapse rates). Dead fuel moisture is specified at the beginning of the simulation and modified by weather conditions as the simulation progresses. We tested wind variables and cloud cover from 2 different sources. The Cheeseboro RAWS station provided hourly wind speed and direction. The MM5 weather model was used to generate a 60 hour forecast of wind speed and direction, at hourly time steps and a grid spacing of 4km. Cloud cover was negligible during the period of the Simi Fire, and was declared to be 0%.

We ran the FARSITE model at 1 hour time steps for the first 58 hours of the Simi Fire (the period of maximum growth), from Oct 25 at 1300 PST to Oct 27 at 2300 PST. The fire was ignited using the location of the fire at 1305 PST derived from the MODIS active fire product. Perimeter resolution was varied, using the following list of resolutions: 60m, 100m, 150m, 200m, 250m, 300m, 350m, 400m, and 450m. The precise perimeter resolutions from this list were allowed to vary by +/- 2m, this often was the difference between a fire that burned for the full 58 hours and a fire that stopped advancing. For the Cheeseboro wind model runs, 199m and 62m resolutions were required to produce a continuously burning fire for the mode filtered map and 201m, 149m, 99m and 59m were required for the FRAP map. For MM5, 301m, 199m and 151m were required for the mode filtered map and 201m and 98m were required for the FRAP map. Perimeter resolutions of 60m +/- 2m did not continuously burn under MM5 wind conditions. There was no explanation of such behavior in the FARSITE software documentation.

Accuracy was assessed using the MODIS active fire product, which uses data from both the Aqua and Terra satellites. It is produced up to 4 times a day, at 1km cell resolution. Convex hull polygons were generated from the set of all active fire cells (current and past) for each time step. These polygons were then clipped using the official final fire perimeter from the California Department of Forestry and Fire Prevention (CDF) to remove the presence of false positives in the MODIS product and reduce the effect of large pixel size. Ten validation polygons were available during the 58 hours of the Simi Fire that were modeled (Figure 2). Accuracy was assessed using the Lee-Sallee metric (Lee and Sallee, 1970), which measures agreement between two polygons. A Lee-Sallee of 1 indicates that two shapes are congruent, and values less than 1 indicate deviation from congruence.
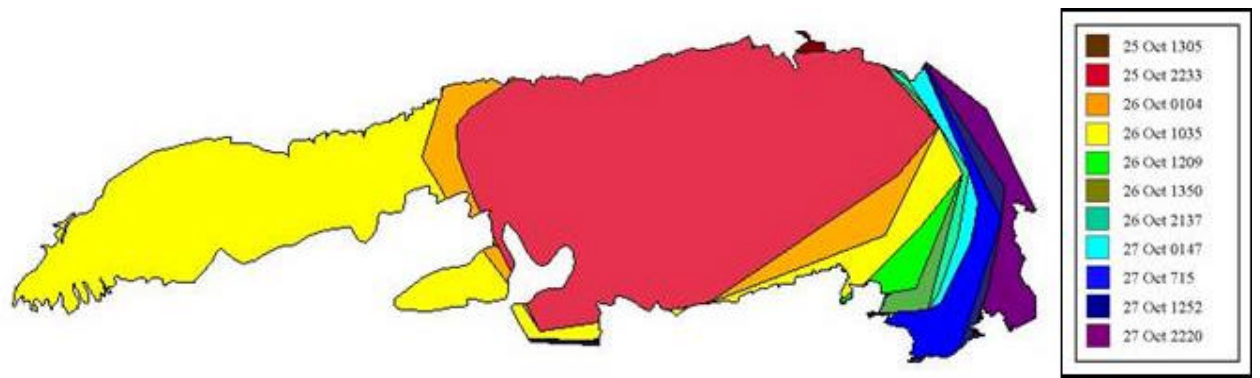
Figure 2. MODIS fire perimeters, including ignition polygon.

3. Results and Discussion

3.1 Cheeseboro wind data

Accuracies for fires modeled using the Landsat-derived fuel model map at the earlier time steps were considerably lower than those using the FRAP map; the modeled fire spread too slowly compared with the actual fire (Figures 3 and 4). Aside from the differences in grass/coast sage scrub ratio, we suspect that fuel heterogeneity affected how FARSITE was utilizing the fuel model maps. We thus investigated the affect of spatially filtering the Landsat fuel models layer at a number of perimeter resolutions, using 50m increments from 100m to 450m, for the Cheeseboro RAWS wind data. We found that a mode-9 filter, corresponding to a spatial resolution of 270m cells, provided the best fit of the fire perimeter at most time steps. Figure 5 presents the average Lee-Sallee statistic over all perimeter resolutions for the original data and 8 filtered data sets at the second last (i.e., 27 Oct, 1252 PST) time step (when overall accuracy was highest). The steady increase in accuracy up to mode-9 is due to the modeled fires spreading faster as fuels became more homogeneous. The shallow decrease thereafter is due to the modeled fire spreading too rapidly compared with the actual fire. The 1 standard deviation error bars on Figure 5 show that variability in accuracy decreases as the fuel model layer is smoothed. This occurs because as effective spatial resolution of the fuel model map becomes coarser than that of the perimeter resolution, fire vertices from different model runs are more likely to land in cells having the same fuel model, leading to similar predicted fire spread.
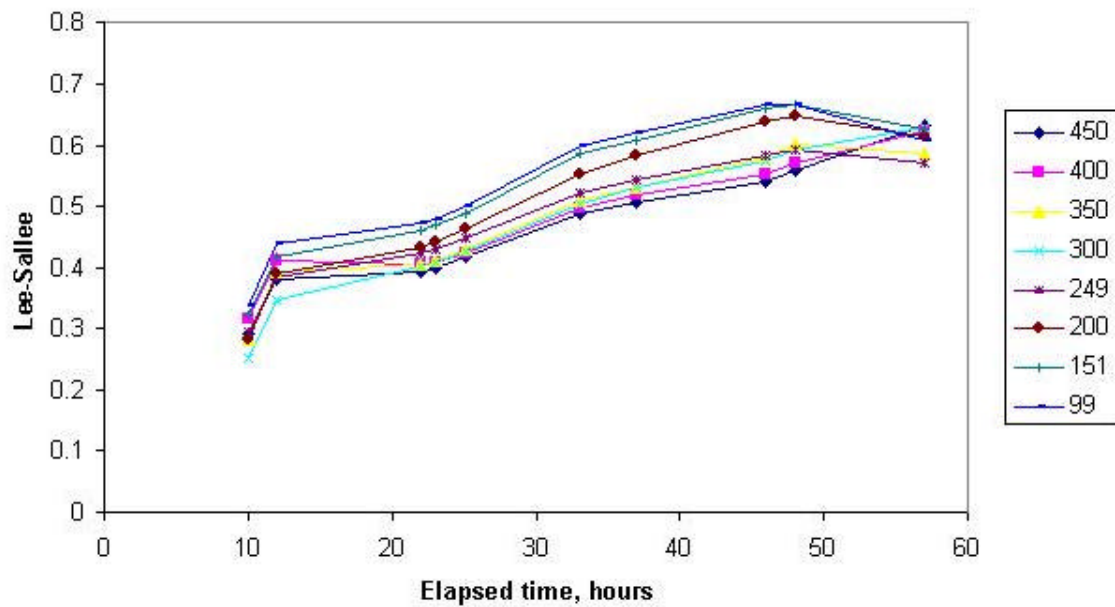
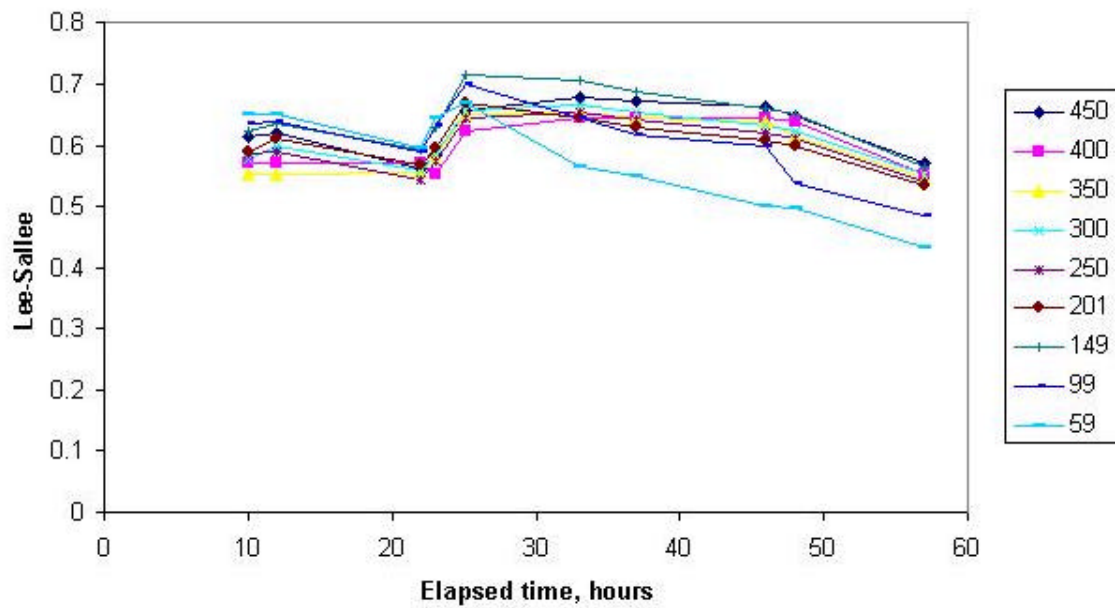Figure 3. Lee-Sallee at 8 perimeter resolutions, for the Landsat map, with Cheeseboro RAWS wind data.

Figure 4. Lee-Sallee at 9 perimeter resolutions for the FRAP map, with Cheeseboro RAWS wind data.
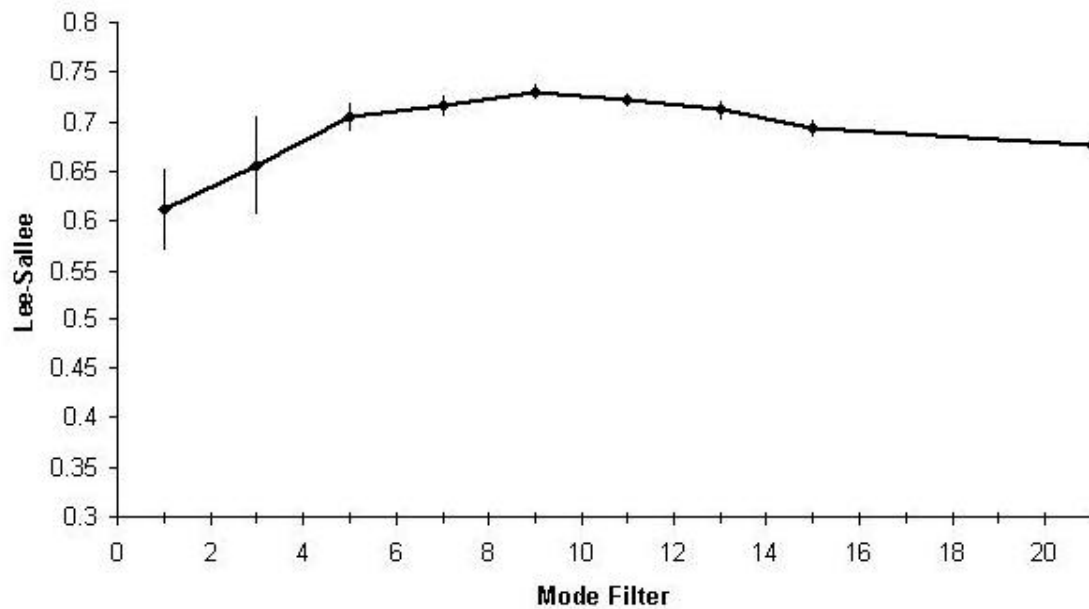
Figure 5. Average Lee-Sallee as a function of mode-n spatial filter applied to the Landsat map, with Cheeseboro RAWS wind data. Error bars indicate +/- 1 S.D. from mean.

The accuracies of the mode-9 fuel model map were then examined (Figure 6). For comparison, the bold blue line in Figure 6 represents the best accuracy attained by the original, unfiltered Landsat fuel model map. At the first 7 time steps, a shallow gradient exists from highest (59m resolution) to lowest (450m) accuracy. The gradient was primarily due to shorter perimeter resolutions causing slightly faster burning fires which corresponded better with actual fire behavior. At the final 3 time steps the accuracies of these shorter perimeter resolutions (62m, 100m, 150m) dropped as too large a fire was modeled. The map of final fire perimeters also shows that finer perimeter resolutions led to larger predicted fires (Figure 7). For 62m, 100m, and 450m perimeter resolution runs, computational times were 1 day, 6 hours, and 6 minutes, respectively on a computer with a 1.67 GHz AMD Athlon XP 2000+ processor.
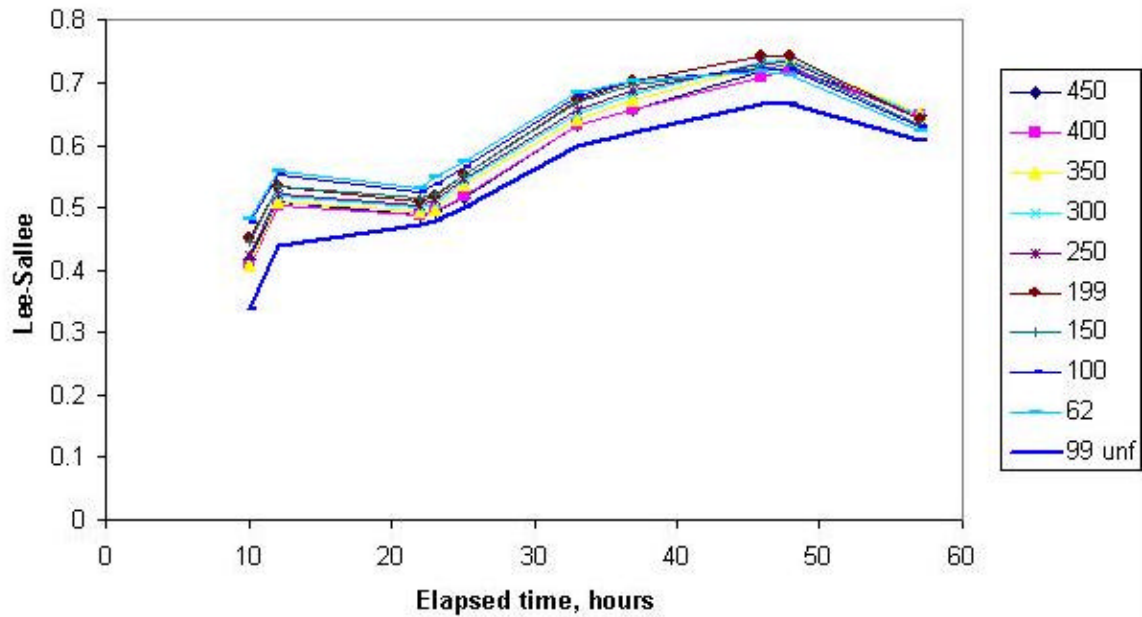
Figure 6. Lee-Sallee at 9 perimeter resolutions, for the mode-9 spatially filtered Landsat map, with Cheeseboro RAWS wind data.
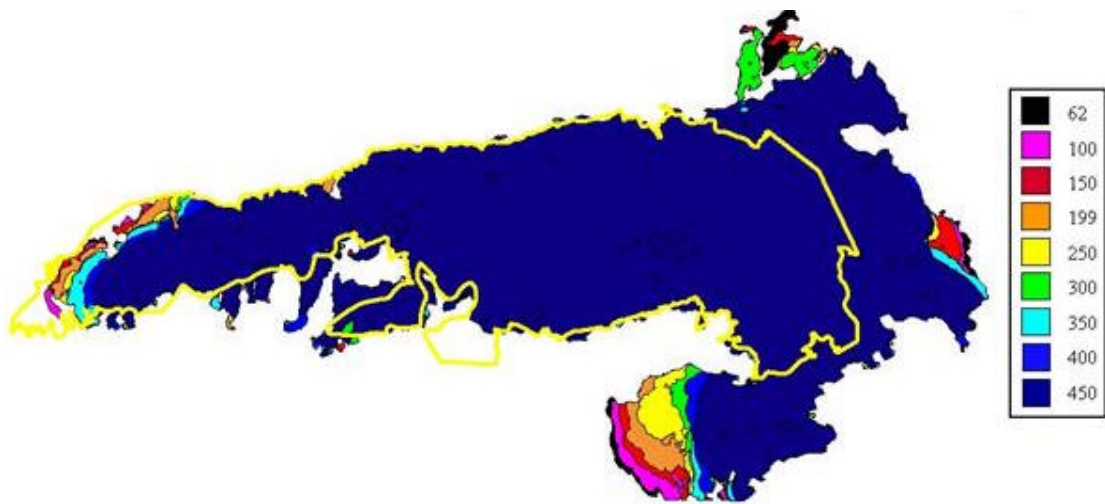

Figure 7. Final FARSITE fire perimeters predicted by 9 perimeter resolutions, for the mode-9 spatially filtered Landsat map, with Cheeseboro RAWS wind data. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.

Perimeter resolution had a similar effect on the fire spread rate for model runs using the FRAP map, smaller perimeter resolutions led to quicker modeled fire spread. At the first 3 MODIS time steps, accuracies were ranked approximately the same as for the Landsat-based fuel model runs. Thereafter the fires generated at the 2 smallest perimeter resolutions became far too large; this can be seen in the accuracies (Figure 4), as well as in a map of the predicted final fire perimeters (Figure

8). The fact that predicted final fire perimeters from the FRAP map were too large is likely due to two factors. First, although no quantitative accuracy assessment of the fuel model maps was performed, knowledge of the area suggests that grassland may be over mapped in the FRAP map, and the rate of fire spread through NFFL fuel model 1 fuel is much higher than the rate of spread through RFL fuel model 18 (unpublished data available at UCSB, http://www.physics.ucsb.edu/~complex/research/hfire/fuels/usfs_18_desc.html). Second, the fire extents that were unique to the FRAP map occurred in the homogeneous fuels of Los Angeles County, not the more heterogeneous fuels of Ventura County. Computational times were longer for the FRAP map, due to the larger fire fronts necessarily having more vertices: for 59m, 99m, and 450m perimeter resolution runs, computational times were 7 days, 26.5 hours, and 10 minutes, respectively.

Figure 8. Final FARSITE fire perimeters predicted by 9 perimeter resolutions for the FRAP map, with Cheeseboro RAWS wind data. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.

3.2 MM5 wind data
Similar patterns were revealed for the mode-9 fuels map when wind data from the MM5 model were utilized. Accuracy was higher for the shorter perimeter resolutions initially, due to the finer perimeter resolutions leading to more rapid fire spread. At the final time step the accuracy of the 100m burn was lowest and accuracy of the other perimeter resolutions was similar, with the 400m burn being highest (Figure 9). This was again due to finer perimeter resolutions predicting larger fires. Figure 10 shows that the final burn sizes are ranked in order of perimeter resolution, with the 450m burn being smallest, burns from 400m to 150m being similar in size, and the 100m burn being largest. One counter-intuitive result was that the only fire to reach the far western edge of the MODIS 27 Oct, 2220 PST burn perimeter was the 450m burn. This is masked out in Figure 10 due to the order that the layers occur in the figure. The other perimeter resolutions predicted final extents approximately 3km to the east of the 450m prediction (scale is in Figure 1).
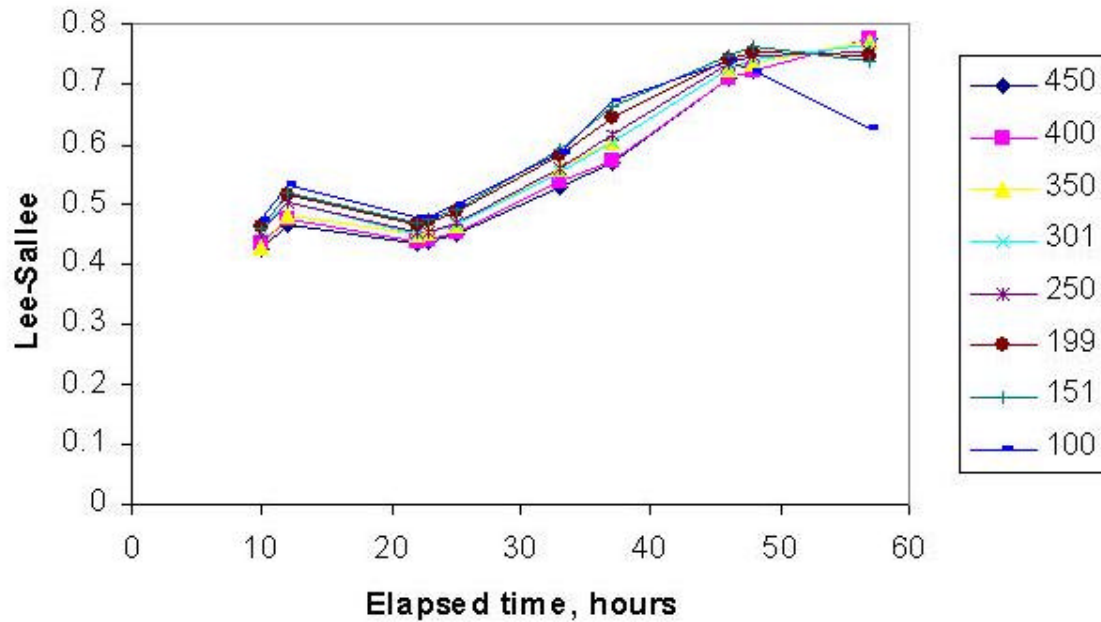
Figure 9. Lee-Sallee at 8 perimeter resolutions, for the mode-9 spatially filtered Landsat map, with MM5 wind vector data.
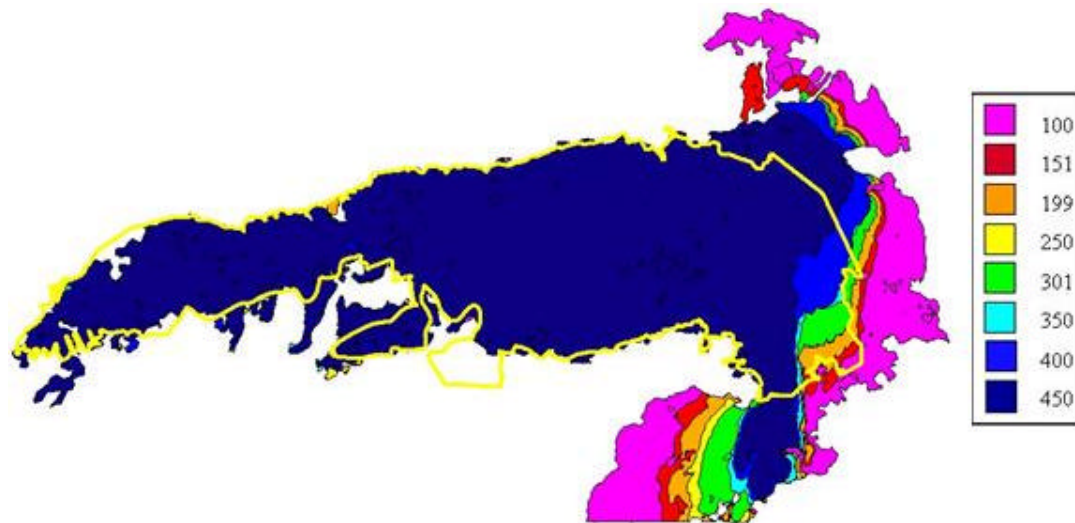

Figure 10. Final FARSITE fire perimeters predicted by 8 perimeter resolutions, for the mode-9 spatially filtered Landsat map, with MM5 wind vector data. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.

The FRAP map produced similar burn patterns when MM5 winds were used. However, initial accuracies were lower, there was more variation in accuracy at intermediate time steps (Figure 11), and final perimeters were slightly smaller (Figure 12). The fact that one perimeter resolution (201m) clearly had the highest accuracy was unique to this model permutation.
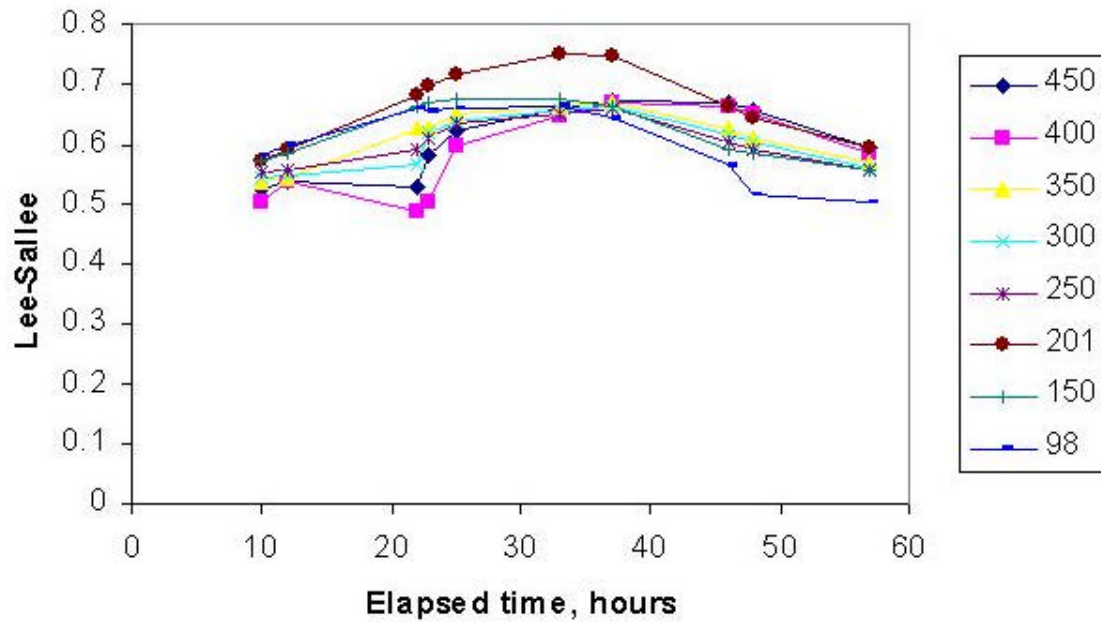
Figure 11. Lee-Sallee at 8 perimeter resolutions, for the FRAP map, with MM5 wind vector data.

Figure 12. Final FARSITE fire perimeters predicted by 8 perimeter resolutions, for the FRAP map, with MM5 wind vector data. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.

3.3 Discussion

Trends in Lee-Sallee accuracy suggest that model runs using MM5 winds produced more accurate fires. For mode-9 fuel models, initial accuracy was slightly lower for MM5 winds, but only the 100m perimeter resolution showed a drop in accuracy at the final time step, compared with all 9 of the perimeter resolutions dropping in accuracy for Cheeseboro winds (Figures 3 and 9). For FRAP fuels, accuracy at the third time step, when the actual fire made the largest gain in area, was noticeably higher using MM5 winds at the finer perimeter resolutions.

Comparing the effects of wind field on final extent (Figures 7 and 10, and 8 and 12) reveals some

interesting trends. The mode-9 model runs using Cheeseboro winds all predicted too large of an eastward extent. Variability in the final perimeter extents was low, the only area of disagreement was in the south east portion of the map. In contrast, aside from the 100m model run, all of the MM5 wind runs were more accurate in predicting the eastern extent than the Cheeseboro wind model runs. Additionally, the entire eastern perimeter of the fire showed variability in final extent. There were fewer differences between the final extents of FRAP map burns as most available fuels were consumed within the 58 hour burn at all perimeter resolutions. However, the Cheeseboro wind burns did extend farther to the east. Combined, these results suggest that a spatially varying wind field is preferable for FARSITE fire modeling.

Figures 13 and 14 compare the effect of fuel model map on fire spread rate. The difference in fire spread at the 26 Oct 1035 time step is most obvious. The homogeneous grassland in the FRAP map led to modeled fire extending to the western edge of the final fire perimeter, while the mixed grassland/coastal sage scrub of the mode-9 map produced a slower moving fire. The portion of the FRAP map with mixed fuels, immediately north of the homogeneous grassland, burned at a rate more similar to that of the mode-9 map; a majority of that area burned by 0147 PST on 27 October for the FRAP map and by 0715 PST for the mode-9 map. The differences in fire spread in the southern portion of the map are likely due to fuel homogeneity in Los Angeles County as discussed above.
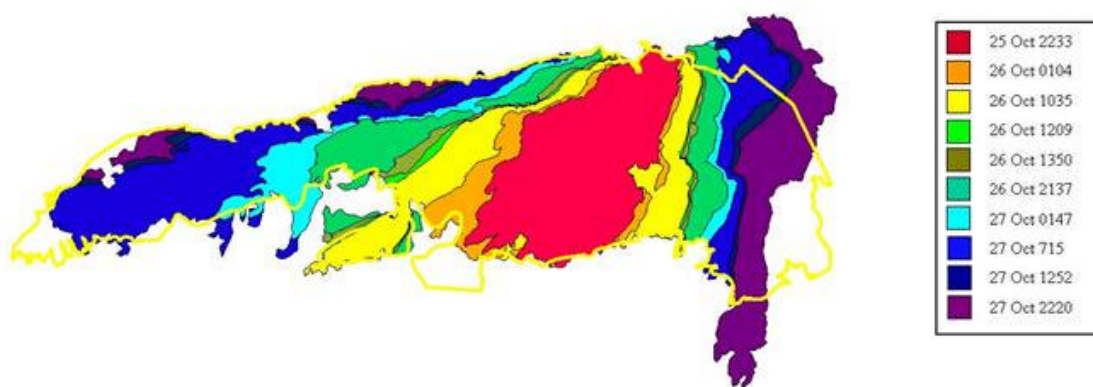

Figure 13. Fire perimeters at 10 time steps, for the mode-9 spatially filtered Landsat map, with MM5 wind vector data, 350m perimeter resolution. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.
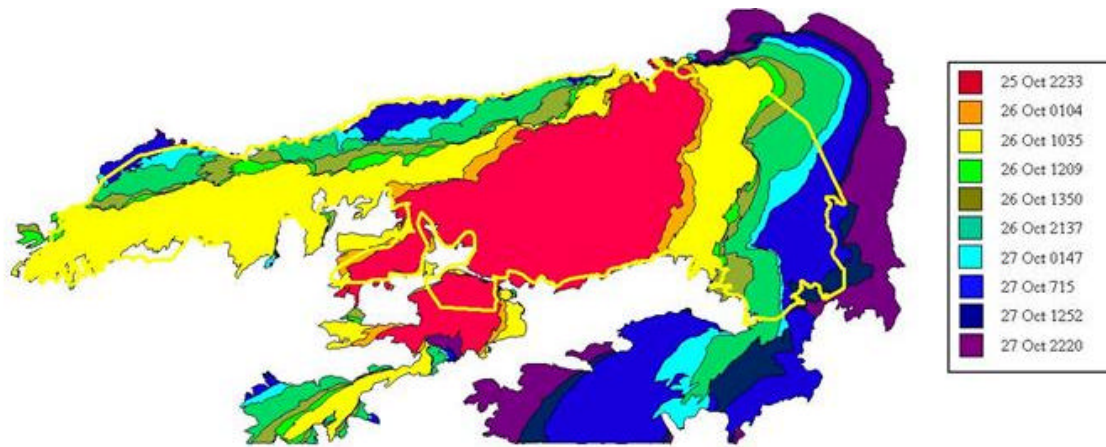
Figure 14. Fire perimeters at 10 time steps, for the FRAP map, with MM5 wind vector data, 350m perimeter resolution. The yellow polygon refers to the MODIS 27 Oct, 2220 PST burn perimeter.

An additional finding, while not explored in detail in this research, was that the shape and location of the fire ignition had a significant impact on modeled fire spread behaviour. We tested various ignition locations including the reported ignition point of the fire, as well as points along the fire front at the 1305 PST MODIS time step, but settled on a polygon corresponding to the 1305 PST MODIS time step for this research. We found that point ignitions tended to produce smaller, slower moving fires. By using a polygon to ignite the fire, fire behavior was calculated at multiple vertices, and initial fire growth was more rapid.

4. Conclusions

FARSITE has become a valuable tool for resource and land managers who need to plan for seasonal wildfire risk and response, natural prescribed fires, or prescribed burning. Its widespread use necessitates a strong testing methodology to give assurance to its predictions. We have explored the sensitivity of the FARSITE model to a range of data sources and model parameters. Specifically, fuel model map source, spatial resolution of fuels map, spatial resolution of the model run, source of wind input and precise location of ignition all affect FARSITE fire spread.

Our findings suggest that the source of the fuel models map is an important consideration. FRAP fuels maps are freely available for the entire state of California. However, discontinuities at administrative boundaries and the over-prediction of fire spread in the homogeneous fuels mapped within Los Angeles County suggest that an alternative fuel model data layer should be used to better understand the variability in potential fire spread.

Spatially filtering (coarsening) the Landsat-derived fuels map caused the simulated fire to spread more rapidly, increasing agreement with actual perimeters. The best level of filtering for this study was a 9x9 window, corresponding to 270m. This is encouraging as alternate data sources to Landsat must be utilized for fuel model map generation due to data problems with Landsat ETM+ (http://landsat.usgs.gov/slc_off.html); MODIS data are a possible alternative to Landsat data as their 250m spatial resolution are compatible with the results of this research. The FRAP map was not filtered as the modeled fire already travelled too quickly.

Smaller perimeter resolutions increased fire spread rate and increased the final fire extent. This may be because the increased number of vertices on the fire front led to a more uniform advancement of the front. This affected accuracy similarly in all 4 model permutations. Initial accuracies were always ranked by perimeter resolution. The time step at which finer perimeter resolution fires became too large and coarser resolutions attained higher accuracies was later for fires using Cheeseboro winds than fires using MM5 winds. Final fire perimeter extents for the mode-9 Landsat map showed a clear order in size due to perimeter resolution. The trend for the FRAP map is less clear as most available fuels were consumed at all perimeter resolutions.

Wind data from the MM5 forecast model produced slightly slower moving, smaller fires for both fuel model maps when compared to the Cheeseboro RAWS wind data. The slightly improved accuracies and fire extents suggest that wind vectors from the MM5 model can be successfully utilized by FARSITE. This has implications for active fire management in that forecast model results could be used for modeling fire spread. For prescribed fire planning over a large area, spatially varying wind vectors should be more useful than winds at a fixed location.

We have found that running FARSITE with various permutations of data and parameter settings would give wildfire modelers a set of predictive fire outcomes, bracketing the range of potential fire behavior, on which to make decisions. This would be a good exercise when planning prescribed burns, especially if one accounted for the uncertainty in the model inputs by varying the resolution of the inputs, or at least the perimeter resolutions. As available computation resources increase, the computational costs required for repeat model runs and, particularly, finer perimeter resolution model runs may be substantially reduced.

5. References

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