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MODELING A HISTORIC FOREST FIRE USING GIS AND FARSITE

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Abstract. Recent major wildfires may result from a combination of climate change and fuel buildup due to fire exclusion policies of the last century. Are such fires unique to the forests and climate of the 21st century or are they similar to historic fires? Historic fires are recorded primarily by eye witness accounts which seldom contain information needed to examine them with modern fire management tools. The September 1, 1894 fire near Hinckley, Minnesota has well documented accounts from many survivors that allow position of the flame front to be established for a number of times throughout the fire. These accounts allowed us to calibrate a FARSITE model to represent the progression of that fire. FARSITE is a modern fire spread rate simulation model. It requires spatial layers of elevation, slope, aspect, timber type, derived layers of fuel type, canopy cover, stand height, canopy base height, canopy bulk density, duff and coarse woody debris. In this paper we will discuss how we were able to combine present GIS data, historical map data, and present ecosystem properties to provide data needed for these layers. GIS output of FARSITE spread predictions were used to match flame front position to eyewitness accounts and model parameters (primarily, wind speed and direction and fuel model spread rate adjustments) were altered to produce a flame front location and time that matched eyewitness location and timing.

Keywords: 19^{th} century forest fire, Fire visualization, mega-fire, Hinckley MN.

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1 Introduction

Over the last two decades there has been a worldwide increase in number and severity of wildland fires (Williams et al. 2010). Assessments of potential fire risk in association with future climate modes (IPCC 2007) suggest that forest fire risk will increase due to both more severe fire danger and a lengthening of fire seasons (Flannigan et al. 2013, Liu et al. 2013). In addition, across the US large regions have developed heavy fuel loads through intensive fire protection as well as lowered rates of biomass removal (Williams 2013). There is good reason to believe forest fires, that are large, intense, and overwhelm our ability to control, may become more prevalent in the US, and possibly worldwide, in the 21^{st} century. Failure of control in recent fires has renewed interest in understanding "extreme fire behavior" (Pyne 1986), that is fires that vary erratically in spread rate, energy release, and atmospheric interaction (Werth et al. 2011). A number of terms used for such behavior, including " blow up, fire storm, mass fire", have been used to describe sudden changes in fire behavior that have lead to a loss of control and sometimes death of fire fighters and civilians in major forest fires of the past.

Extreme fire behavior is not unique to recent major forest fires. Fires that occurred in the Lake States between 1876 and 1918 were the most deadly forest fires in US history. Over 2500 people lost their lives in three fires in Pestigo, WS, 1876, Hinckley, MN, 1894, and Moose Lake- Cloquet, MN, 1918. Unfortunately, descriptions of those fires were limited to eye witness accounts that often described extreme fire behavior in anthropomorphic or even religious terms. The scientific merit of information given in such accounts has been discounted simply due to the language used. However, many of these descriptions document incidents that are now classified as extreme fire behavior (Werth et al. 2011).

The Hinckley MN fire in particular has a wealth of eye witness information collected into three contemporary books (Aldermark 1894; Brown 1895; Wilkinson 1895), one book of survivor recollections (Anderson and Anderson-McDerrmott 1954), and three scholarly/popular accounts (Brown 2007; Swenson 1979; Larsen 1984). From these sources it is possible to ex-

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tract a series of positions of the fire front during the day of Sept. 1, 1894. These observations allow a number of estimates of average spread rate for differing portions of the fire. Alexander and Cruz (2006) surveyed spread rate of recent severe crown fires across the US and Canada and found that the maximum measured rates where slightly higher than 100 m/min. For a period of five hours and over a distance of 34 km, the Hinckley Fire observed average rate of spread was 114 m/minute (Williams et al. 2013).

The ability to predict fire spread for a set of climatic conditions and fuel loads can be useful for both hazard reduction and active firefighting. FARSITE (Finney 2004) is a spatially explicit model that implements the Rothermel (1972, 1983) fire spread equations in a semi-empirical model of forest fire behavior. Although FARSITE does not have theoretical support for fire to fire or fire-atmospheric interactions of newer spread models (Coen 2011; Kochanski et al. 2013), it is widely regarded as the most reliable model for fire suppression management as well as fire preparedness analysis. In this paper we explore the use of FARSITE to examine the Hinckley Fire. There were three questions that we wanted to answer:

1. Are there sufficient historical data to create the spatial files required to run the FARSITE model?
2. If so: can a model be created that mimics the observed positions of the fire recorded by eye witness accounts?
3. Are model modifications used to fit observed spread rates plausible?

2 Methods

Throughout the paper units of distance and mass have been made consistent with source materials which were primarily English units, while model outputs and general comparisons use metric units to be more comparable to general scientific literature. The FARSITE model can be run using either system of units. More complete information on FARSITE can be found online at http://www.firelab.org/project/farsite.

FARSITE simulates spread of fire for a specific geographical area and for a given set of fuel and climatic conditions. Data to run the model consists of a set of spatial and non-spatial files that define the physical setting, fuel availability and flammability, and climatic factors (Finney 2004). The physical setting is defined by three spatial files of elevation, slope, and aspect. Two spatial files of fuel availability; canopy cover and fuel model, are required to model fires spreading in fuels along the ground. Fuel model is a combination of values needed to solve the Rothermel (1972) basic fire spread equations based on cover types. For this analysis, the fuel models developed by Scott and Burgan (2005) were used. To model crown fires spatial files of stand height, canopy base height, and canopy bulk density are also needed. Finally, spatial files of coarse woody debris and duff layer are needed to model burning after the fire front passes. In addition to the spatial data, FARSITE also requires a weather file, wind file, and optional fuel moisture adjustments and spread rate adjustments. The weather file defines air temperatures, wind speeds, and relative humidity for a period before and during the fire. The wind file allows greater definition of wind speed and direction during the fire. Fuel moisture adjustment file allows altering the initial fuel moisture of 1, 10, and 100 hour fuels. The spread rate adjustment file can be used to alter the modeled spread rate of each fuel model.

Applying the FARSITE model to the Hinckley Fire required finding and converting historical information into the data files described above. The most important source of spatial data was the online GIS data portal of the Minnesota Department of Natural Resources (MNDNR 2014). From this source the following data were obtained: digital elevation (30m DEM), locations of state and county boundaries, county roads for Pine., Carleton, Aiken, and Kanabec counties, state wide railroads, recreational trails (several abandoned railroad lines are now bike trails), lakes and rivers, county (same four) Public Land Survey township and range lines, and a witness tree layer that included tree locations and attributes of species and size of each tree. In addition, a map of original vegetation which had been interpreted in 1935 (Marschner 1974) was also used.

The outline of the entire area burned by the Hinckley Fire was obtained by a map in Swenson (1979), which was drawn on a state map with county lines, large lakes, rail lines as in 1894, and rivers, and location of several small towns described in eyewitness accounts (Figure 1). Geography of most eyewitness accounts is defined by location, a small lake, and eight small towns; Quamba, Beroun, Brook Park, Mission Creek, Hinckley, Sandstone, Askov, and Finlayson. Fires began in the early morning of September 1, 1894 near Quamba and Beroun. The Quamba fire destroyed Brook Park at 1400h (1400 hours 2:00 PM). The Beroun fire destroyed Mission Creek at 1430h. Both fires combined and destroyed Hinckley at 1530h, Sandstone at 1735h, Askov and Finlayson by 1900h. The fire overtook one of the trains carrying survivors at a small lake called Skunk Lake at 1625h.

All of the small towns (except Mission Creek) are still present and can be easily located on the four county maps. The outline of the burned area was digitized from the Swenson (1979) map using county lines, rivers, rail-

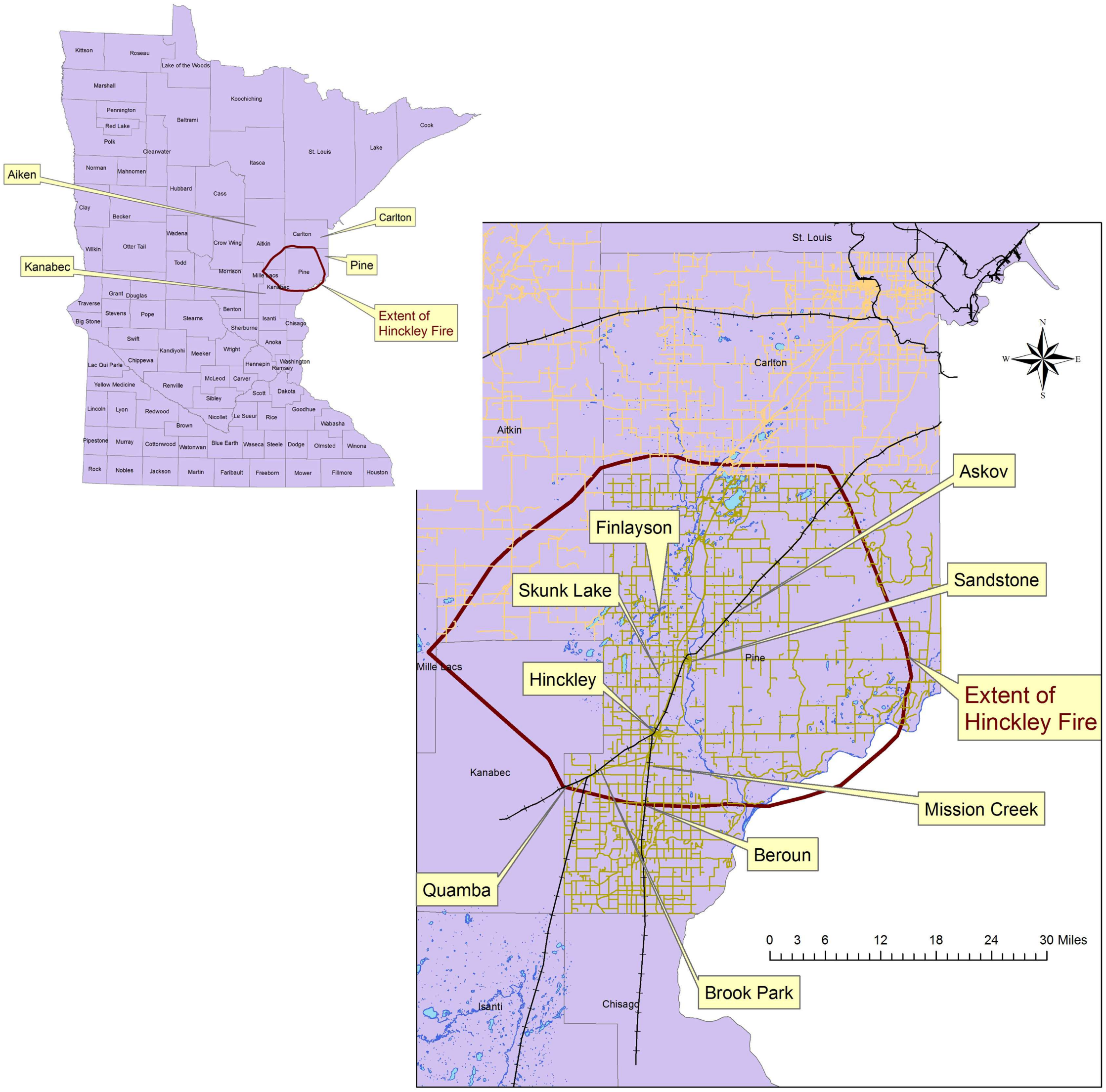

Figure 1: Location of the Hinckley Fire in east central Minnesota. Inset of Pine, Kanabec, Carlton, and Aiken counties includes locations of small towns listed in the text.

roads and town locations as geographic reference (Figure 1). This outline was then used as an area of interest for all spatial layers of the FARSITE model.

Elevation, slope, and aspect were created from the downloaded DEM using the fire outline as a feature mask (Figure 2). Marschner's (1974) original vegetation polygons were then clipped with the fire outline. To these polygons new features of canopy cover, fuel model, canopy height, canopy base height, canopy bulk density, coarse woody debris, and duff were added. All feature values were assigned based on vegetation types found in the area today and fuel models were assigned as the most nearly matching standard fuel model. Canopy bulk density was not assigned but is the default value in FARSITE for each fuel model. Grid files were then created for fuel model, canopy cover, tree height, canopy base height, canopy bulk density (Figure 2), coarse woody debris, and duff (Figure 3).

Non-spatial files of weather and wind were developed based on data found in Haines and Sando (1969) and Haines et al. (1976). Air temperatures for the week before the fire were found in those publications while wind speed and humidity were assigned based on air temperature as that data was not recorded. Likewise, the wind file was set at a steady 20 mph wind from the southwest, known from surrounding stations (Haines et al. 1976). That file was modified for calibration. Initial fuel moistures were also lowered to reflect the extreme

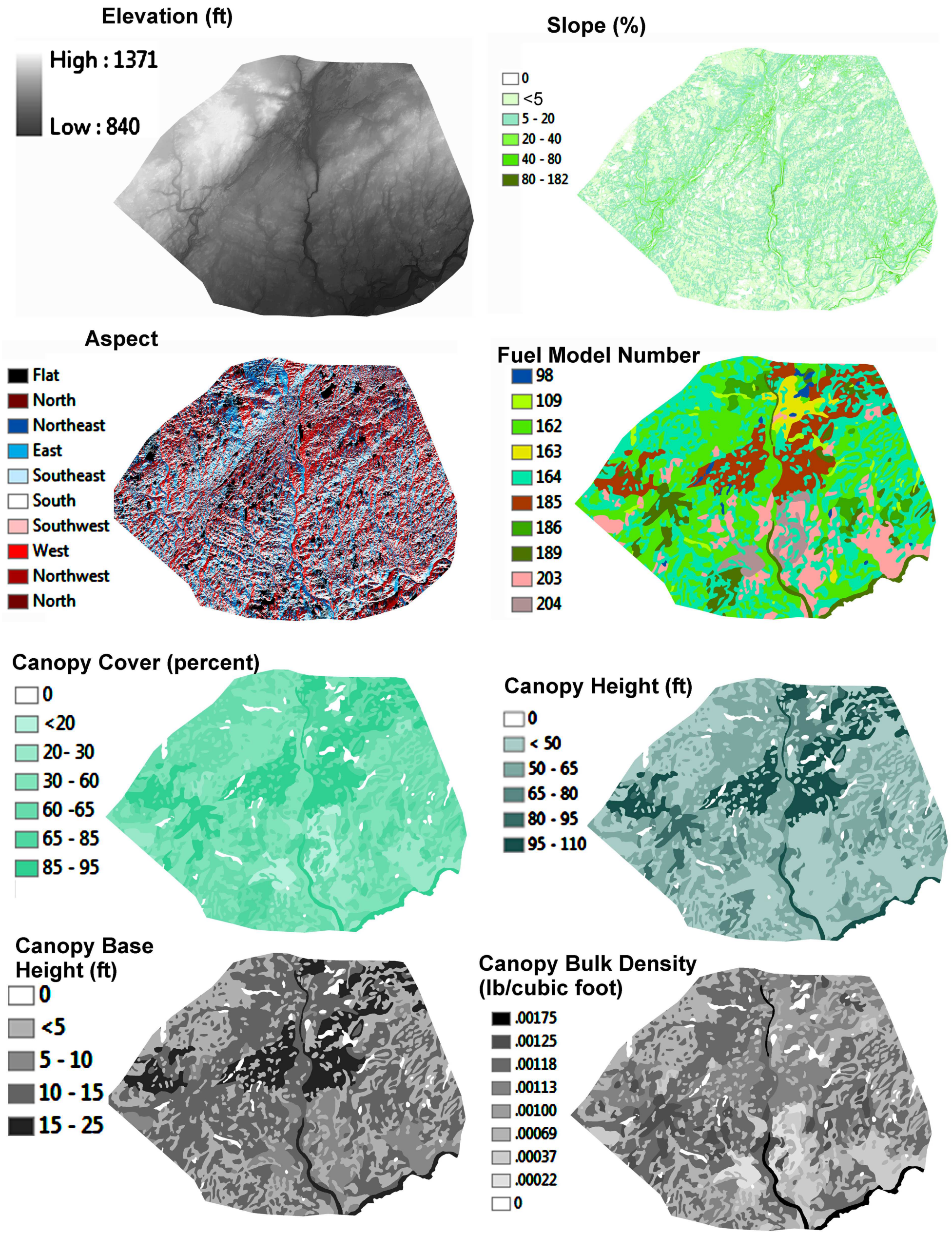

Figure 2: Spatial distributions of land and tree parameters used as input to the FARSITE model of the Hinckley Fire.

drought that preceded the fire (Haines and Sando 1969). Finally, the spread rate adjustment file was modified in calibration. The spread rate adjustment file allows multiplier factors from 0.001 to 20 to be applied to each fuel model. These factors were also used to calibrate the spread rates to match arrival times. Final values of spread rate adjustment are shown in Table 1 and final values of wind speed and direction are shown in Table 2.

3 RESULTS

The goal of this exercise was to produce a FARSITE model that mimicked the observed spread of the 1894 Hinckley Fire. Alteration of files that defined wind speed and direction and the file of multipliers were used to vary spread rate among the various fuel models. Using the model parameters described in Figures 2-3 and Table 1-

Table 1: Vegetation types. Fuel models (Scott and Burgan 1972), and multipliers used in the development of the Hinckley Fire FARSITE model. Aspen-birch is a pioneer community that occurs on both hardwood and conifer sites.

Vegetation Type	**Dominant Tree Species**	**Fuel Model**	**Multi-plier**
Aspen-birch			
tending conifer,	Pt, Pgt, Bp, Ab, Pg	162	15
tending hardwood	Pgt, Pt, Bp, As, Ar, Ta	186	18
Wet prairie		109	16
White and red pine	Ps, Pr, Bp		
uncut		185	20
cut		203	18
Mxd pine-hardwood	Ps, Pr, Qr, Ar	189	18
White pine	Ps	204	18
Hardwood	Ta, As, Fn,Ua	189	18
Jack pine	Pb	163	18
River bottom	Ar, Ua, As	189	18
Conifer bogs	Ll, Pm	164	20
Water		98	1

Species abbreviations: *Abies balsamea*-Ab, *Acer saccharum*-As, *Acer rubrum* – Ar, *Betula papyrifiera*-Bp, *Fraxinus nigra*-Fn, *Larix laricina,*-Ll *Picea gluaca*- Pg, *Picea mariana*- Pm, *Pinus banksiana*- Pb, *Pinus strobus*- Ps, *Pinus resinosa*-Pr, *Populus grandidentata*-Pgt, *Populus tremuloides*-Pt, *Quercus macrocarpa*-Qm, *Quercus rubra*-Qr, *Tillia Americana*-Ta, *Ulmus Americana*- Ua

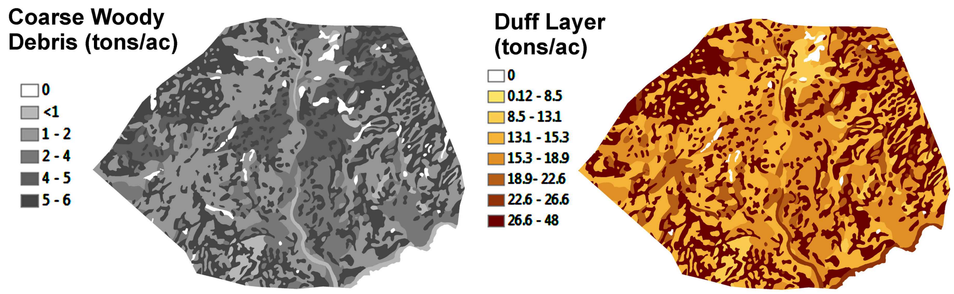

Figure 3: Spatial distributions of surface parameters used as input to the FARSITE model of the Hinckley Fire.

2, FARSITE output produced flame front perimeters as shown in Figure 4. Individual ignitions at Quamba and Beroun at 0600h burned to the north and east until combining between 1300h and 1400h just to the southeast of Hinckley. The combined fire had two distinct heads until roughly 1700h and burned rapidly during the rest of the day. The model reproduced a flame front at Hinckley, Sandstone and Skunk Lake very near the observed time and was slightly early at Mission Creek. The model was considerably early at Brook Park and late at Askov and Finlayson (Table 3).

The model also produced data that could be used to examine fire spread in a geographic manner. Consistent estimates of spread rates and area burned can be extracted from the model. Linear spread rate seems mostly related to wind speed although there is a significant increase following the joining of the fires (Figure 5). An interesting and perhaps most frightening aspect could be extracted from the model burn perimeters. Each perimeter presented in Figure 4 is a raster of the area burned during each hour of the fire. In the GIS, these raster areas had 30x30 m pixels so that each pixel represented 900m^2 on the ground, allowing an estimate of area burned. In Figure 6 those estimates are expressed as a burn rate in hectares per second.

4 DISCUSSION

A FARSITE model of the 1894 fire in Hinckley could be developed with a variety of historic sources and current data. In fact, most of the data could be developed from online information from the Minnesota Department of Natural Resources. The map of original vegetation was used to develop most of the spatial layers needed

Table 2: Summary of wind data used in the final FARSITE model. Each hour was divided into 15 minute intervals and wind speed and direction was defined for that period. Summary shows maximum and minimum values used during the hour. Order shows if speed was increasing or decreasing during the hour.

Time	Wing Speed (mph)	Direction maximum	Direction minimum
0600-0700	4-10	250	170
0700-0800	10-15	225	160
0800-0900	15-19	225	175
0900-1000	19-28	255	175
1000-1100	28-30	245	175
1100-1200	28-30	245	175
1200-1300	30-35	245	215
1300-1400	35-40	255	185
1400-1500	40	245	215
1500-1600	40-45	245	215
1600-1700	40-35	245	205
1700-1800	40-30	245	225
1800-1900	30-25	235	215
1900-2000	20-28	245	225
2000-2100	25-20	280	225

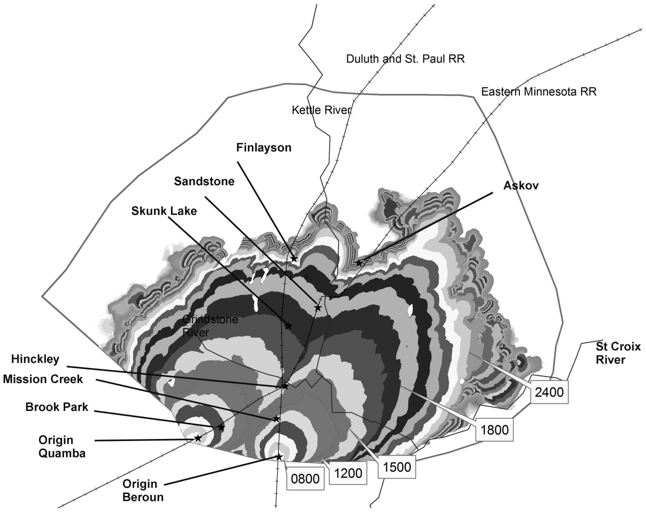

Figure 4: Estimated flame front locations from the final FARSITE model.

Table 3: Arrival times of the Hinckley Fire based on eye witness accounts and derived from model perimeter files. All times refer to Sept. 1, 1894 unless noted.

Location	Arrival Time Observed	Arrival Time Modeled
Brook Park	1400	1000
Mission Creek	1430	1330
Hinckley	1500	1530
Skunk Lake	1615	1600
Sandstone	1725	1800
Askov	1900	0900 Sept.2
Finlayson	1900	0200 Sept. 2

to run the model. The original map was developed from Public Land Survey witness trees, but from professional judgment rather than modern analytic tools. This was quite evident in the witness tree data downloaded for this paper. Although the map showed stand types as white or red pine, often these trees were completely missing form witness trees in that area. However, that is not hard to understand since surveyors were required to use witness trees that were expected to remain for long periods after the survey was completed. Since cruisers for timber companies often accompanied those surveyors (Larson 2007) it would be pointless to expect pines to remain long after the survey. The map was also produced before the modern forest classification scheme (Erye 1990) making correlation to current data compatible with FARSITE (Ryan and Opperman 2013) difficult. Essentially the data used in this model is the product of profession judgment of a Minnesota trained forester in 1935 and the author, another Minnesota trained forester that lived in east central Minnesota for the first 27 years of his life.

The FARSITE model was able to produce a set of fire perimeters that mimicked the observed timing very well for the most intense and important period of the fire. It was able to predict the timing of the town of Hinckley, Sandstone and at Skunk Lake. With the exception of Brook Park, it also predicted the fire well for the period in which human fatalities occurred. The shape of the modeled fire also explains apparent very rapid spread from Hinckley to Skunk Lake (175m/min- Williams et al. 2013). The model suggests that Hinckley was burned as two heads of the combining fire burned to the north and southeast of town. By the time the town burned the northern head was already very near the track of the St. Paul to Duluth railroad on which the escape train was overtaken at Skunk Lake. The model fire also shows the Eastern Minnesota Railroad tracks between the two heads and burning late. The train on this track was able to evacuate over 800 people from the fire. The modeled fire reproduced a number of observations that were independent of the calibration data used. FARSITE appears to be capable of producing a retrospective model of a major forest fire.

Winds up to 45 mph were required despite data that suggests wind speed of only 20 mph in surrounding stations (Haines and Sando 1969). Also, the spread rate ad-

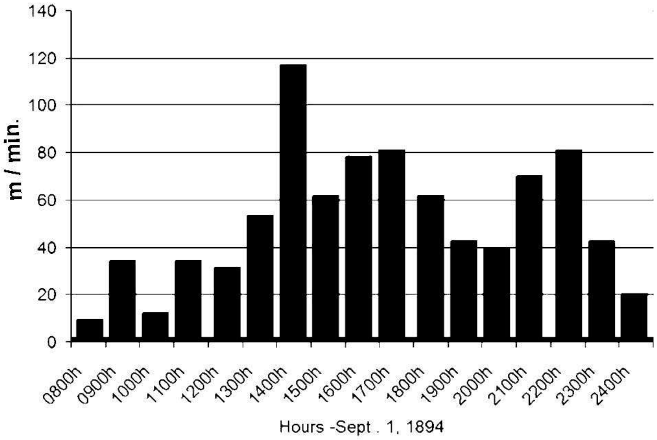

Figure 5: Model estimates of the rate of spread of the Hinckley Fire. Rates are calculated at the most distant point of each hourly FARSITE model perimeter.

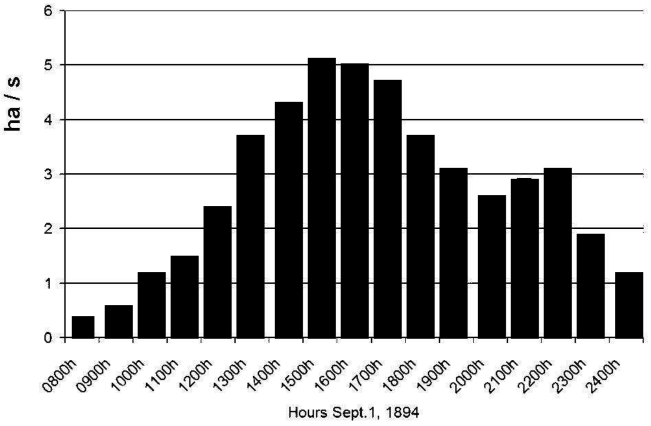

Figure 6: Estimated rate of area burned during each hour of the Hinckley Fire. Rates are estimated from the fire perimeters of the FARSITE model.

justment file was used to multiply the spread rate of several fuel types to the maximum 20 times normal. Were model modifications used to fit observed spread rates plausible? Although the winds are completely speculative, variations in direction of 90 degrees are not unlikely in early morning and 45 mph is not completely unreasonable for maximum sustained winds. Eyewitness accounts often described cyclone winds, which then could refer to either hurricanes or tornados.

The FARSITE model we used did not include spread by spot fires, although "firebrands falling like rain" was a common comment by survivors. The FARSITE method of solving spread equations of spot fires results in an exponential increase in the number of numerical solutions required. With spot fire enabled the model would require 5+ hours of computation for the spread from 0945h to 1000h. Using a computer with twice the computing power encountered the same problem at 1045h. For the period the spotting model could produce perimeters, spread rate multipliers of 5-10 times normal resulted in similar perimeters to the final version (Figure 4) which used multipliers that were generally twice as large (Table 1). It seems that increasing the rate of spread of fuel models has a roughly equivalent effect as modeling spot fires.

The theoretical base of FARSITE is primarily spreading equations of Rothermel (1972) and does not include atmospheric interaction beyond a single estimate of wind speed. It cannot model fire induced convection nor does it include atmospheric effects of two approaching fires. Newer models include Rothernmel (1983) models of surface ignition and spread with atmospheric models to account fire induced wind and fire-atmospheric interactions that produce extreme fire behavior (Clark et al. 2004; Filippi et al. 2009; Kochanski. et al. 2013). Application of these models to the Hinckley Fire would also be an interesting exercise but would require even more speculation for the various upper and lower atmospheric data needed to parameterize these models.

5 CONCLUSIONS

We were able to obtain sufficient historical data to create a FARSITE input dataset for the 1894 Hinckley Fire. When calibrated to known locations of the fire front, FARSITE produced a model that fit the known locations of the fire during the intense burning period. Model results also explained aspects of the historical account that were not used in the calibration. Calibration included adding speculative wind data and altering the spread rates normally associated with fuel models (Scott and Burgan 2005) up to 20 times the normal rate. It would seem the ability to increase the spread rate within FARSITE allows it to be used for fires which include spot fires, atmospheric interactions, and merging of fires that are not explicitly accounted for in the theoretical derivation of the FARSITE model.

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