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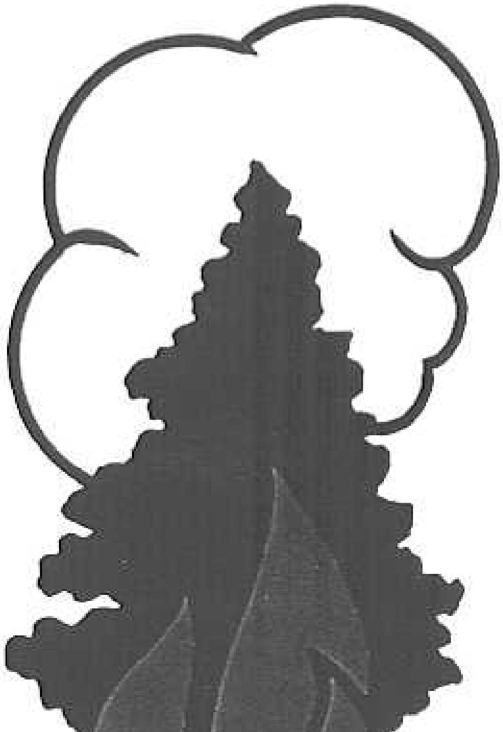

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SPATIALLY RESOLVED FIRE GROWTH SIMULATION[1]

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ABSTRACT: Spatial data analysis and Geographic Information System (GIS) technology offer an opportunity to improve upon spatially unresolved fire behavior models (e.g., BEHAVE). The feasibility of applying the fire spread module of BEHAVE in a spatially resolved manner was determined for a small test area within the Los Padres National Forest, California. Data layers required to build the database of driving variables consisted of elevation information from Digital Elevation Model (DEM) data, cover type, site specific climatic data, and stream networks. Driving variables for the simulation consisted of elevation, and spread-rate derived friction and fireline intensity layers for each time-period of the model. Output included hourly time-contours of fire growth and fireline intensity strata. Database development and model implementation and execution utilized a combination of raster-based GIS and graphics software including pMAP, SURFER, and ERDAS. It was concluded from this project experience that raster-based GIS offers the promise to more realistically estimate wildland fire behavior potential.

KEYWORDS: fire management; fire behavior; fire growth; Geographic Information Systems

INTRODUCTION

Wildfire is a complex physical phenomenon affected by terrain, weather, and vegetative fuels factors. Fire managers rely on these spatiotemporally dynamic parameters along with other spatial data (e.g., road networks, values-at-risk) in order to optimize their activities. Geographic Information Systems (GIS) technology has the capabilities to handle, analyze, and display spatial information. Thus, it appears that GIS can support a wide spectrum of fire management decisions.

A spatially aggregated model that is in current use for the study and prediction of wildland fire behavior potential is called BEHAVE (Andrews 1986, Andrews and Chase 1989). The BEHAVE model predicts the spread rate and intensity of a given fire according to fire site-specific parameters supplied to the model. The rate of fire spread is presumed to be a function of the vegetative fuel type, the moisture content of the fuel, the slope of the terrain over which the fire will travel, and the wind condition (i.e., velocity and direction).

The BEHAVE's fire spread algorithm operates by using assumptions of uniform fuel type, uniform fuel moisture content, uniform slope, and uniform wind for the time and place of application. These assumptions of uniformity over the application area may limit the operational usefulness of BEHAVE. Operationally, only gross estimates of general fire spread rates and directions can be

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gained, which means that estimates of fire growth for any specific location within the potential spread area can be grossly inaccurate. Such inaccuracies can greatly hamper efforts to monitor the fire activity, and complicate decision-making relative to appropriate fire management response.

GIS analysis techniques and spatial database system technology offer an opportunity to improve upon the now spatially, unresolved models of fire behavior. Such technology now offers the potential to develop spatially resolved implementations of fire science knowledge and understanding, so that more operationally useful models may be employed to manage our natural resources relative to the occurrence and activity of wildfires.

In this project, the objective was to investigate the feasibility of applying the fire spread algorithm of BEHAVE in a more spatially resolved manner, to determine the geographic information needed to support implementation of such a spatially resolved model, and to evaluate the results of applying such a spatially resolved model to a small test area within the Los Padres National Forest, California.

DATA AND METHODOLOGY

The study site was an area of about 5,000 acres in Los Padres NF with extensive chaparral cover types plus some oak woodlands. The total of six cover types were represented by Intermountain Fire Sciences Laboratory fuel models (Anderson 1982) one (38% of the area), two (25%), four (6%), and six (29%). A river in the southern portion of the project site and other areas of no fire potential were treated as absolute barriers to the spread of the fire. Elevation ranged from a low of about 900 feet on the western edge of the area to a high of 2,500 feet in the NE quadrant. Slopes within the study site ranged from 0 to 150% with predominantly south-westerly through south-easterly aspects.

Elevation information was derived from Digital Elevation Model (DEM) data for the 7.5-minute topographic quadrangle of San Marcos Pass, provided to the project by the U.S. Forest Service (USFS). The 30-meter DEM data were extracted from the full quadrangle and resampled to produce data with 164 ft (50 m) resolution, which was the spatial resolution used in the project. For input data that were in paper map form, the ERDAS software (ERDAS, Inc. 1988) was used for hand digitizing of them. These data consisted of watershed boundaries, cover type boundaries, stream and river locations, road and trail locations, and campground and other point-type cultural features within the area. The watershed boundaries and cover type information provided by the USFS were transferred to the base project map and verified by photo interpretation of color aerial photos prior to digitization. After digitization, each data layer was gridded within ERDAS to a 164-foot on a side cell size. This provided a cell with area resolution of approximately 0.6 ac. Slope and aspect maps were created within the pMAP raster-based GIS software (Spatial Information Systems, Inc. 1986) using the SLOPE and ORIENT commands, respectively. The primary thematic layers for the project maintained within the pMAP analysis package.

Derivation of important intermediate data layers from the primary data layers involved the use of both pMAP and SURFER (Golden Software, Inc. 1989) software packages and were:

a). Regraded elevation surface needed to control the spread of the fire uphill and downhill according to wind flow directions of morning and afternoon uphill winds, and evening downhill winds;

b). Combination of slope and aspect classes in conjunction with temporally explicit weather data for "typical" mid-summer conditions defined fuel moisture contents within the study site (see Rothermel 1983, fuel moisture tables pp. 17-19);

c). Six base spread rate layers (3 daytime periods--morning, afternoon, and evening--times 2 slope directions--uphill and downhill) derived by reclassifying b). into appropriate rate of spread values (R_o) determined from BEHAVE for specific fuel model, fuel moisture, zero wind speed, and zero slope inputs;

d). Six wind effect spread rate layers derived by reclassifying b). into appropriate rate of spread values ($R_o\phi_w$) determined from BEHAVE for specific fuel model, fuel moisture, windspeed, and zero slope inputs.

The pMAP software spread the fire through the spread-rate derived "friction" layers and over the "surface" terrain (i.e., SPREAD <fire> THRU <friction> OVER <surface> UPHILL / DOWNHILL command used by Hay et al. 1989). Equations used to generate the spread-rate derived friction and fireline intensity surfaces are presented in Table 1. A generalized flow chart of model development is shown in Figure 1. The model was operated for two different ignition sites and two different ignition times (i.e., 11:00 AM and 2:00 PM). A non-spatially resolved version of the model was implemented with the intention of replicating as nearly as possible information that would be gained from BEHAVE. Toward that end, the mean slope (35%) and predominant aspect (southerly) for the area, as well as the two predominant IFSL fuel models one (short grass) and six (dormant brush, hardwood slash), the minimum fuel moisture contents (i.e., worst-case scenario), and average wind factor values were input to BEHAVE for the three daytime periods of the spatially resolved model. BEHAVE generated a weighted maximum and base spread rate for each time period. The six weighted spread rates were incorporated into six uniform friction surfaces analogous to the six spatially resolved friction surfaces except for the differences in spatial resolution. The uniform model was implemented and operated within pMAP. Fire extent maps and temporal contour maps were output in the same format as to the spatially resolved output. The uniform model was spread over the regraded elevation since in current usage of BEHAVE an analyst would have taken the spread rate output values and placed them onto the landscape using his/her experience to judge how the fire would have responded to terrain effects. It was felt that this implementation of the uniform model was the most conservative in terms of comparisons with the spatially resolved model output.

Table 1. Equations Used to Generate Fire Spread-Rate Friction and Fireline Intensity Surfaces (Andrews et al. 1986, Rothermel 1983).

VARIABLE	DAYTIME PERIOD	FUNCTION
Spread Rate uphill [R] (chains/hour)	Morning	$R_o(1+\phi_w+\phi_s)$
	Afternoon	$R_o(1+\phi_w+\phi_s)$
	Evening	$\mathrm{Max}[R_o, R_o\mathrm{Max}(\phi_s\text{-}\phi_w, 0)]$
Spread Rate downhill [R] (chains/hour)	Morning	R_o
	Afternoon	R_o
	Evening	$\mathrm{Max}[R_o, -R_o\mathrm{Min}(\phi_s\text{-}\phi_w, 0)]$
Fireline Intensity [I_B] (Btu/ft/sec)	All three	$(66/3600)I_R t_R R$
Slope Factor [ϕ_s]	All three	$\mathrm{Min}[5.275(\beta)^{-0.3}(s)^2, \mathrm{Max}\phi_s]$
Slope [s]	All three	$\mathrm{Min}[(\%\mathrm{slope}/100), 1]$

Morning = 08:00 AM - 12:00 PM   Afternoon = 12:00 PM - 08:00 PM   Evening = 08:00 PM - 08:00 AM

R_o = zero-wind, zero-slope spread rate; ϕ_w = wind factor; I_R = reaction intensity; t_R = residence time; β = packing ratio

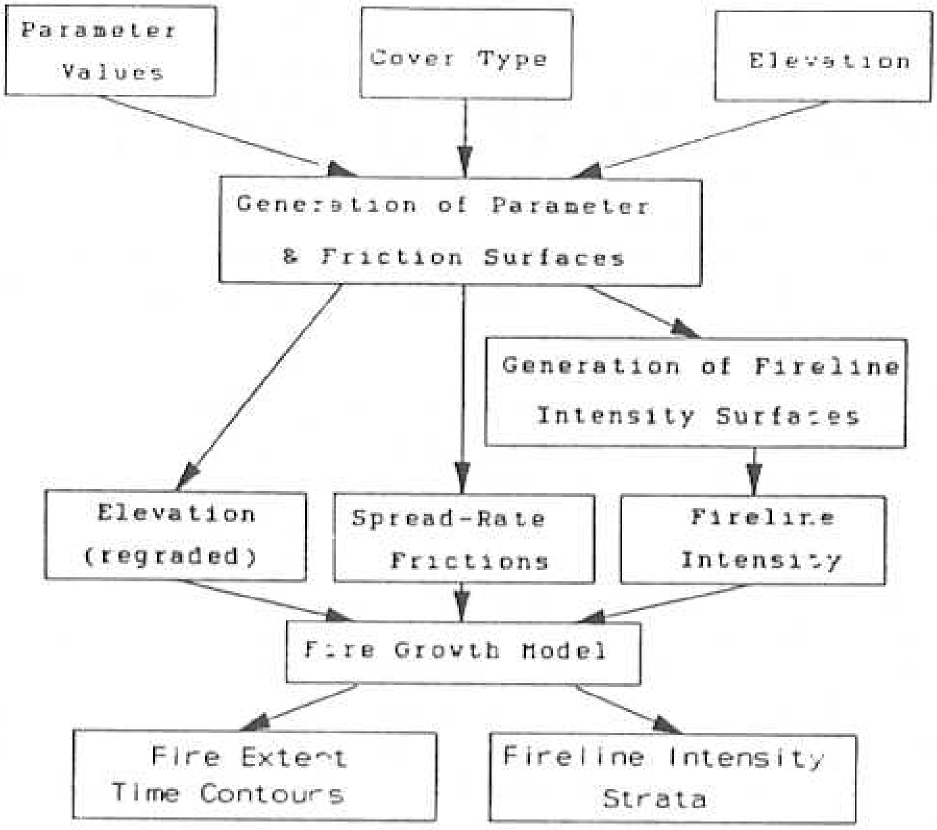


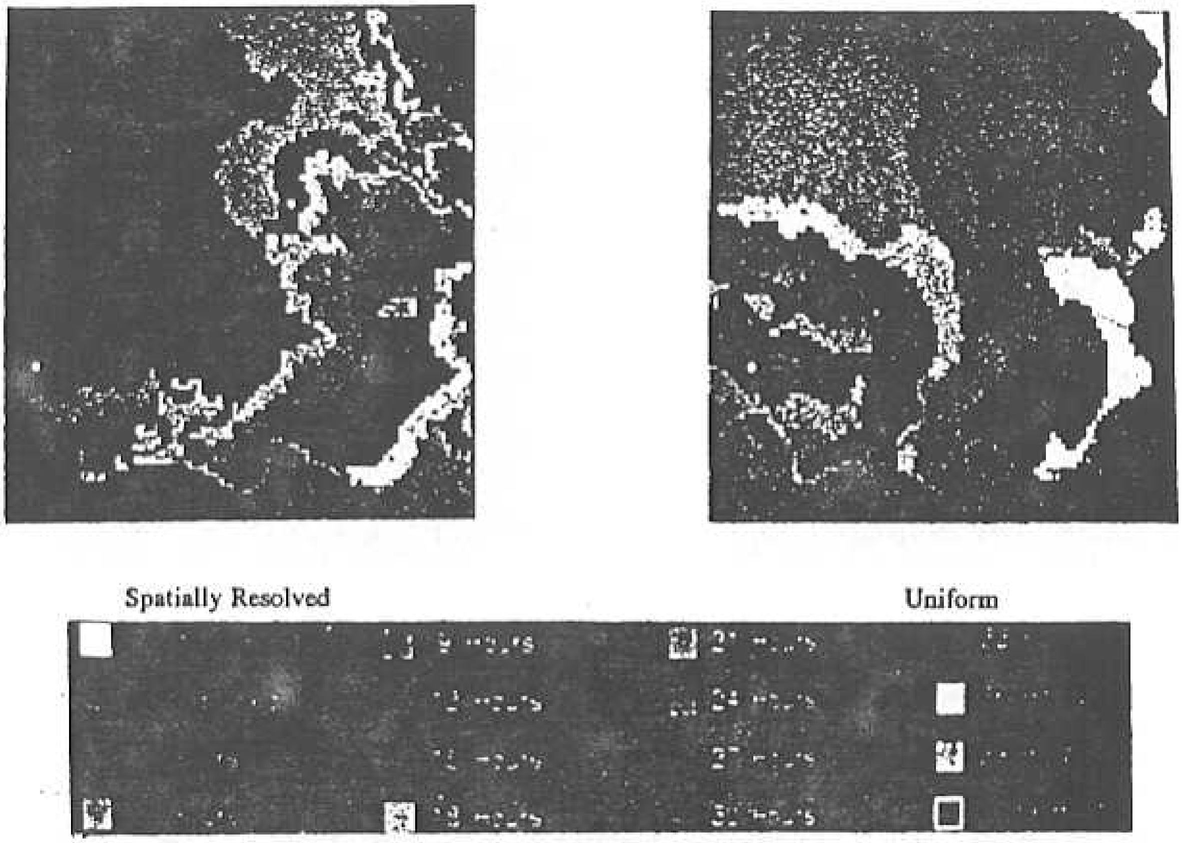
Fig. 1. Generalized Flow Chart of Model Development.

RESULTS AND DISCUSSION

Output from the model runs included maps which present the spatiotemporal pattern of expected fire spread and fireline intensity from a specific ignition point for both the spatially resolved and non-spatially resolved implementations of the model (Figures 2 and 3). Comparison of three-hour contours of fire extent, as well as of fireline intensities between the two different ignition times and points, respectively, for the spatially resolved model are shown in Figures 4 and 5.

In general, the rate of spread for the first 20 hours of the fire--measured in cumulative number of cells ignited and burned per hour--showed that the spatially resolved model and the uniform model did not differ dramatically from each other (Figure 6). The fact that there is relative agreement in the burned area extent between the spatially resolved and uniform models is interesting given, of course, the temporal aggregation of weather data in each daytime period. Such agreement would suggest that for many fires, non-spatially implemented BEHAVE would be adequate, particularly if environmental conditions are not too variable. However, where conditions do not meet the uniform average assumptions the differences between the two models are expected to be dramatic (Figure 2). In addition even though the area spread rates are often comparable, the spatial pattern of spread is different. The fire growth pattern was more irregular for the spatially resolved model than for the uniform model (Figure 2). This irregularity of spread pattern is to be expected given the more heterogeneous nature of the friction layers in the spatially resolved model. Such differences in the spatial pattern of spread (Figures 2 and 4) may have important implications relative to fire management decisions (e.g., presuppression activities and strategic placement of fire suppression resources).

Ignition Time: 11 AM

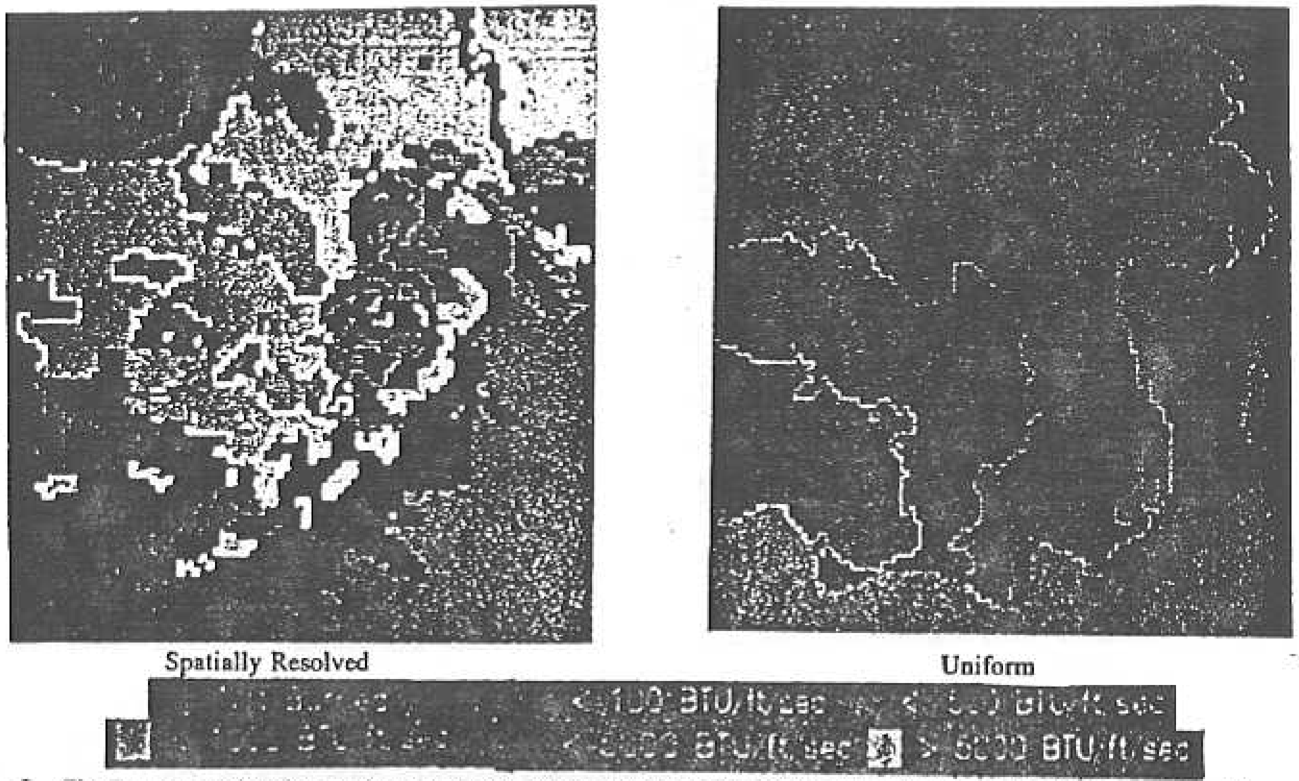


Spatially Resolved

Uniform

Fig. 2. Three-Hour Contours of Fire Extent from Ignition Point 1 for the Spatially Resolved and the Uniform Models.

Ignition Time: 11 AM



Spatially Resolved

Uniform

Fig 3. Fireline Intensity Strata from Ignition Point 1 for the Spatially Resolved and the Uniform Models.

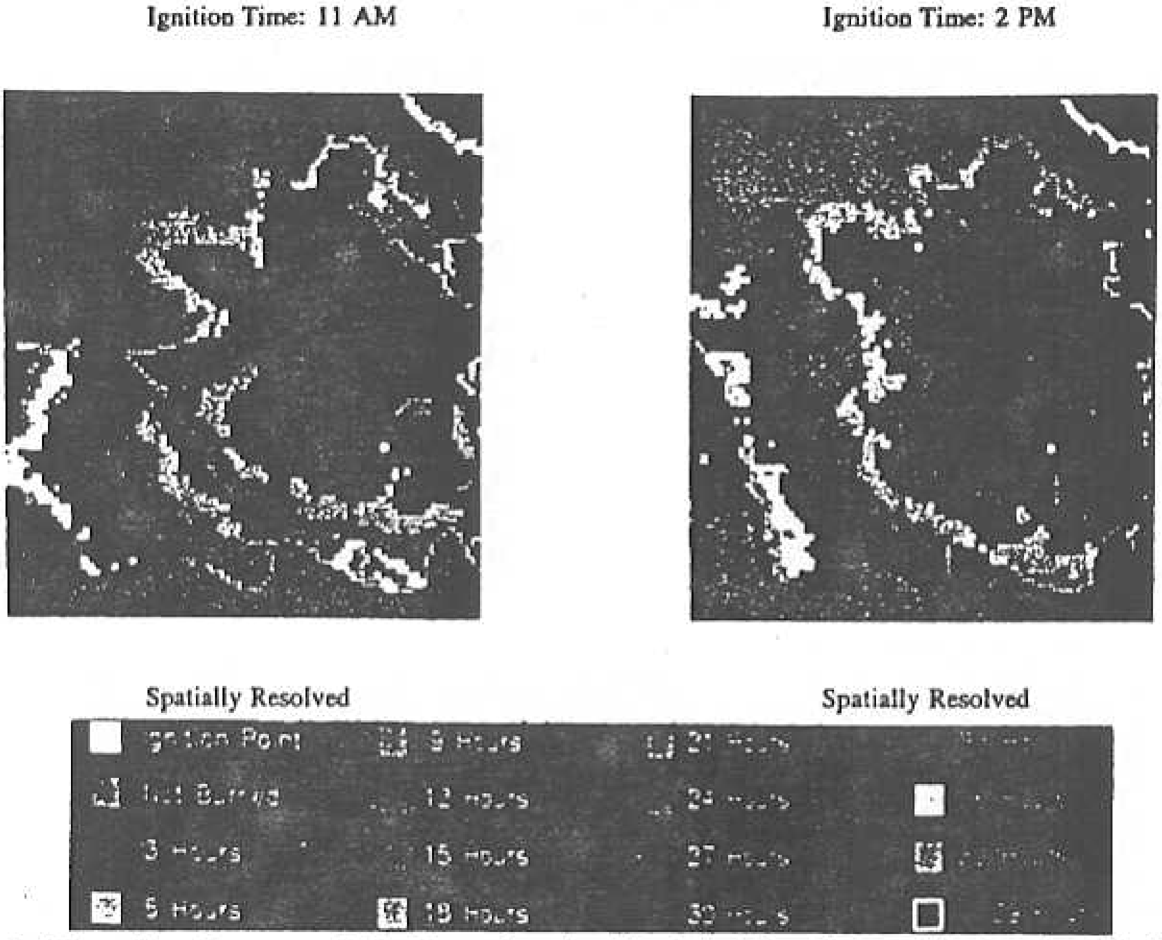


Fig. 4. Three-Hour Contours of Fire Extent from Ignition Point 2 for the Spatially Resolved Model.

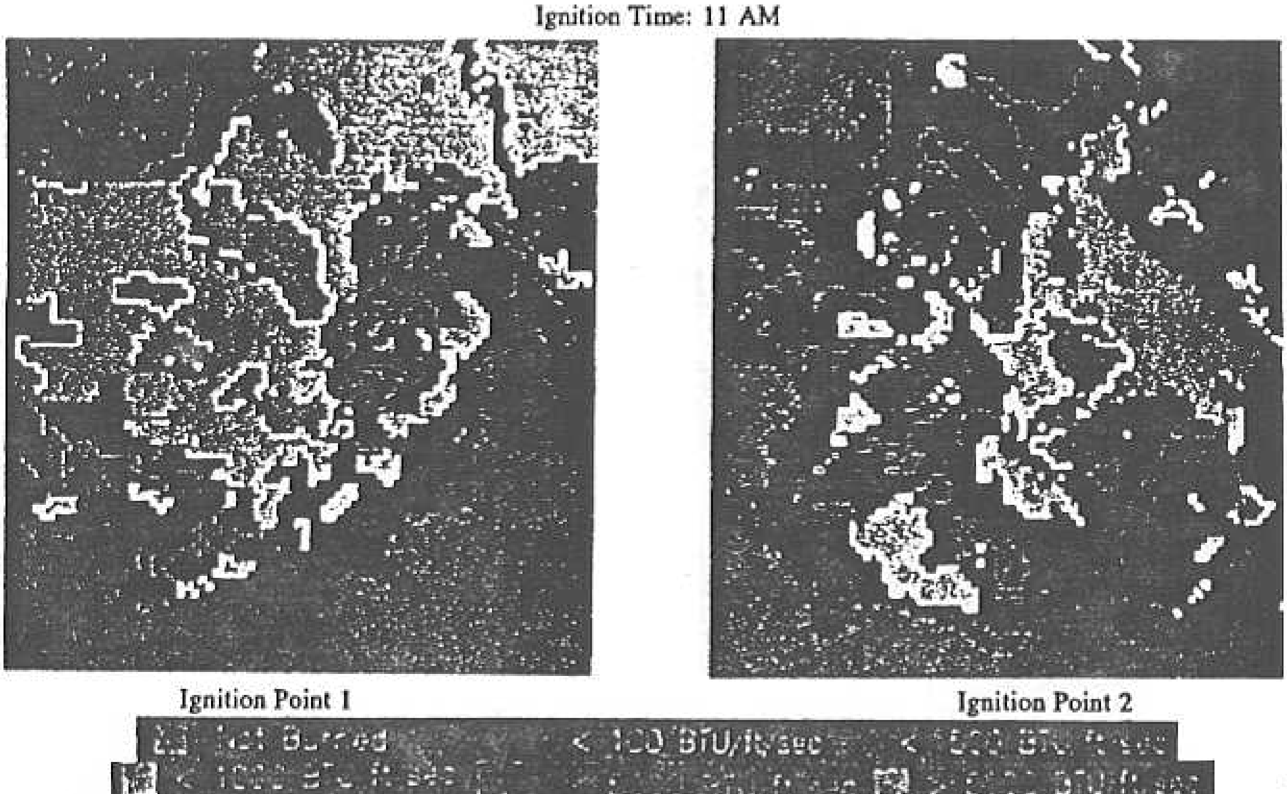


Fig. 5. Fireline Intensity Strata from Ignition Points 1 and 2 for the Spatially Resolved Model.

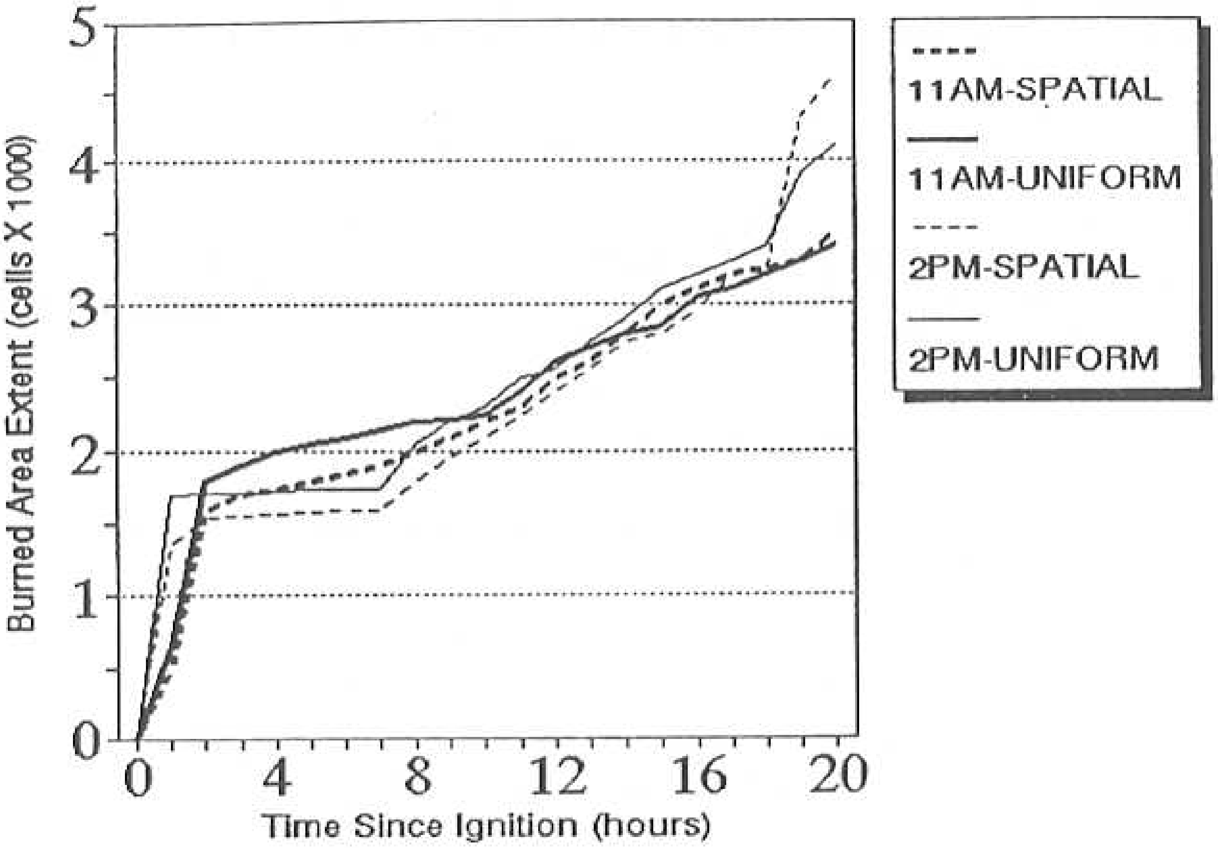


Fig. 6. Cumulative Area Burned from Ignition Point 2 for the Spatially Resolved (Spatial) and the Uniform Models.

Fireline intensity information was more site specific for the spatially resolved model than for the uniform one (Figure 3). The uniform model can only estimate ranges of fireline intensities based on the weighted average spread rates expected within each given time frame. The banding in the fireline intensity strata for the uniform model in Figure 3 reflects this fact. The bands correspond to the different daytime periods of fire growth. There are also spatiotemporal differences of fireline intensities among various ignition points (e.g., Figure 5) and times that emphasize even more the importance of fireline intensity's prediction in relation to suppression difficulties, and fire behavior and effects potentials.

CONCLUSION

This study supports the contention that building a spatially resolved fire growth model is feasible. Elevation, fuel type, and weather information required to build and operate the model at the level of spatial and temporal aggregation used in this project is not difficult to obtain. However, the simulation is only as realistic as the assumptions used in the model, and is subjected to a number of limitations (e.g., truncation of watersheds boundaries, temporal aggregation of weather data, no account of fire suppression activities, and no validation). With this model focused on increasing spatial resolution, it is obvious that comparable increases in temporal resolution are simultaneously necessary. As a result, it is recommended that a more extensive test of the concepts be performed on a larger study site for which observed data on historical fires are available, since it is believed that GIS-based fire growth simulation can be proved a useful and realistic tool for fire management decision-support.

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