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Using GIS to Predict Fire Behavior

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OVER THE LAST 10 years, geographic information systems (GIS) have emerged as promising tools for analyzing resource management alternatives. In addition to providing the ability to inventory and monitor resources, GIS is a powerful management and policy analysis tool because it allows ecosystem managers to simulate multiple future conditions across space. By linking possible future conditions to values, ecosystem managers can use GIS to narrow options to a spatially feasible set. More importantly, sensitivity analysis can be performed on critical assumptions, allowing managers to focus on pivotal areas of uncertainty.

Fire is both part and partner in ecosystem management. Fire plays a significant role in the dynamics of forest ecosystems throughout the world; both wildfires and prescribed burning affect ecosystem relationships and management activities. In 1994, wildfires burned several million acres of forestland throughout the United States, and 14 fire fighters were killed in a wildfire in Colorado. Conversely, fire exclusion has dramatically altered the ecosystems of the West, changing species composition and increasing tree density (Moore 1994). Resource managers must consider fire at landscape levels where GIS becomes an important management tool.

This paper explores the use of GIS to spatially represent fire behavior under varying assumptions of fuel type, weather condition, and topography. Simulating fire behavior and effects across landscapes facilitates the prediction of future vegetation and habitat conditions. Landscape conditions that result from different management policies or assumptions can be compared, helping ecosystem managers integrate fire into management decisions. The GIS and fire growth model can serve as a basis for further integration of ignition risks, land use values, and suppression costs that could ultimately improve decisions concerning prescribed natural fire, fire prevention, and suppression responses.

Background

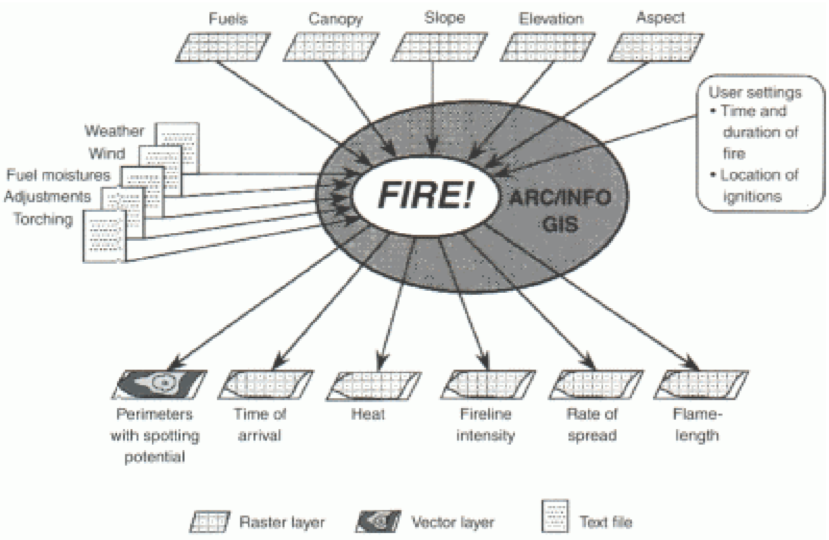
Research scientists and resource managers have long sought spatial models of wildland fire growth (Fons 1946, Van Wagner 1969, Kourtz and O'Regan 1971). Nonspatial models based on the Rothermel (1972) fire spread equation, such as BEHAVE (Andrews 1986), provide a means to predict fire behavior based on inputs of fuels, weather, and topography for a specific location. However, short-term fire growth predictions over complex landscapes require repeated calculations (Rothermel 1983), becoming impractical for long-term projections of large fires over heterogeneous landscapes. Hence, the need for spatial computer models of fire growth.

In the fall of 1993, the US Marine Corps at Camp Lejeune, North Carolina, retained Pacific Meridian Resources to (1) create a GIS layer of fuels for a 15 million hectare area including and surrounding Camp Lejeune and (2) develop a GIS-based fire behavior model. The result is *FIRE!*, a computer model that integrates state-of-the-art fire behavior modeling into the ARC/INFO® GIS environment. The model's user interface has been designed so that advanced computer and GIS skills are not required for model execution. While model users should have both processional experience and training in wildland fire management or fire behavior analysis to effectively implement the program, *FIRE!* puts comprehensive fire behavior prediction into the hands of fire managers where it can be most effectively applied.

The Model

FIRE! is an ArcTools-based GIS application that integrates spatial fuels and topographic data with temporal weather, wind settings, and initial fuel moistures to predict forest fire behavior across both time and space. *FIRE!* allows a user to model fire behavior by defining a fire "scenario." *Figure 1* presents a flow diagram for *FIRE!*. A graphical user interface (GUI) allows the user to easily specify and edit the data and parameters necessary to execute each simulation scenario. The user specifies the appropriate fire fuels, canopy cover, slope, elevation, and aspect layers required for the simulation. In addition, nonspatial data sets, in-

Figure 1. FIRE! simulation flow diagram.



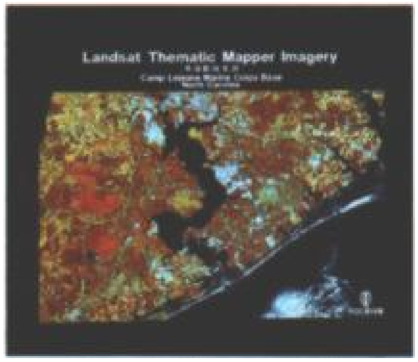
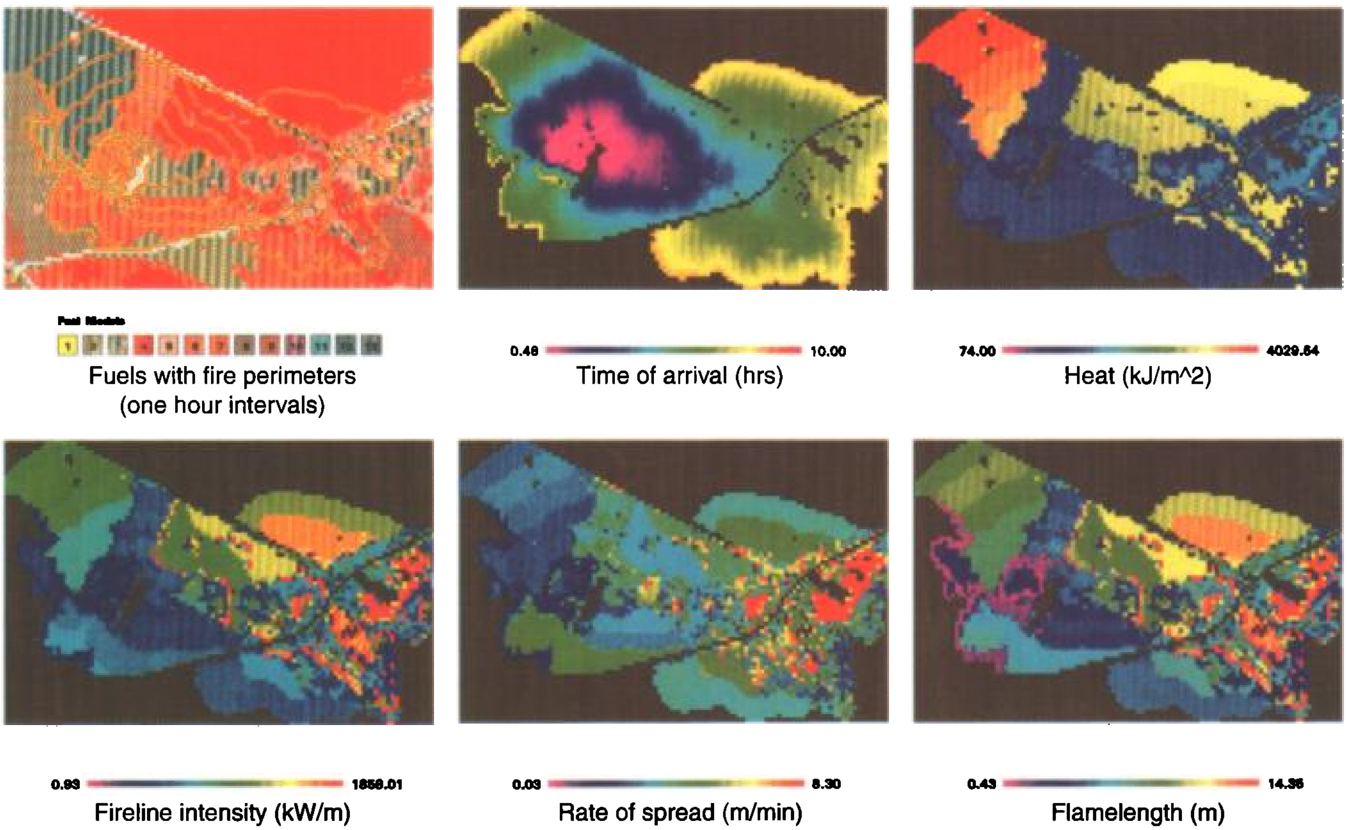


Figure 2. Bands of imagery for the Camp Lejeune project area.

Figure 3. Final fuel-type classification for the Camp Lejeune project area.

FIRE! Simulation Results *(Figure 4)*



cluding weather, wind, initial fuel moistures, and fuel model adjustment factors, can be created, specified, and edited. Finally, scenario parameters of ignition location, ignition shape, run time, and resolution are designated.

As the simulation progresses, vector representations of fire perimeters are graphically displayed. Maximum spotting distance is computed from user inputs and displayed. At the conclusion of the simulated burn, *FIRE!* also displays raster representations of time of arrival, heat, fireline intensity, rate of spread, and flame length for the burned area. Plots of the simulation results may be generated using built-in plotting templates or customized by the user with the plotting tools available in ARC/INFO. All of the output data is preserved as ARC/INFO coverages and grids. The user may further analyze these with the full range of capabilities of the ARC/INFO GIS environment.

Table 1. Fuel classification system used for the Camp Lejeune project area.

Fuel model/class	Model description	Hectares
Grass and grass-dominated models		
1	Short grass (1 ft)	201,539
2	Timber (grass and understory)	57,374
3	Tall grass (2.5+ ft)	162,109
Chaparral and shrub fields		
4	High pocosin, chaparral (6+ ft)	46,425
5	Brush (2 ft)	23,470
6	Dormant brush, hardwood slash	116,525
7	Southern rough, low pocosin (2–6 ft)	144,084
Timber litter		
8	Closed timber litter	214,103
9	Hardwood litter	81,340
10	Heavy timber litter and understory	0
Slash		
11	Light logging slash	211
12	Medium logging slash	75
13	Heavy logging slash	693
Nonfuel		
14	Water	414,699
15	Bare, nonflammable	48,672

Inputs

As *figure 1* indicates, several types of inputs are needed to run the model, including (1) GIS layers of fuel type, tree cover, slope, aspect, and elevation; (2) tabular data on weather, wind, and initial fuel moistures; and (3) user specifications of scenario parameters.

Fuel class. The Camp Lejeune GIS layer of fuels was mapped to the 13 models described by Anderson (1982) plus 2 nonfuels classes *(table 1)*. Each fuel class represents a specific measure of fuel loading: surface area to volume ratio of each size group, fuel depth, fuel-particle density, heat content of fuel, and moisture of extinction values.

The fuels layer was created from Landsat Thematic Mapper (TM) imagery using a combined supervised/unsupervised approach (Congalton et al. 1993). *Figure 2* shows three bands of the imagery for the Camp Lejeune area. Image classification was enhanced through the use of ancillary GIS data layers, including various past and present land-use and land-cover characteristics, and aerial photography. The fuel classification was further refined through the development and application of GIS models, which examine the relationship between overstory vegetation types, soil types, recent forest management activities, and forest fire fuels. Extensive use was also made of field-collected data, which was critical to both fuel classification and calibration of the fire behavior model. Ground data for fuels, overstory and understory vegetation cover, and tree-crown cover were collected for sample locations throughout the project area.

Following initial image classification, both Pacific Meridian and Camp Lejeune personnel reviewed and evaluated draft forest fire fuel-type maps on the ground for accuracy and consistency. They noted errors and corrected them through reclassification and manual editing. *Table 1* lists the hectares by fuel type in the project area.

The fire fuels and tree-crown cover classifications developed using digital satellite imagery render raster data layers that depict the continuous variation of fire fuels and tree-crown cover present across the landscape. In contrast, photointerpreted delineations of fuels, tree-crown cover, et cetera can portray a deceptively homogeneous pattern of fuel and crown-cover variation across the landscape, resulting in an unrealistic prediction of fire behavior. The spatial detail provided by the pixel classification of satellite imagery provides a more realistic prediction of fire behavior by the GIS-based model because the imagery's 30-meter resolution portrays the complexity and composition of land-cover characteristics. *Figure 3* displays the final fuel-type classification of the Camp Lejeune project area.

Tree-crown closure. Tree-crown closure influences wind speed reduction to midflame height and incoming solar radiation, which in turn affect fire behavior. A raster forest tree-cover layer was also developed through classification of the Landsat TM imagery. Initially, "water," "bare/nonflammable," and other nonforest fuel classes previously identified in the mapping of the forest fire fuels were masked from the imagery. These areas were assigned a crown-cover class of 0 percent. For the remaining areas, a series of unsupervised classifications were completed and labeled with one of the following crown cover classes: 1 to 20 percent tree-crown cover, 21 to 50 percent tree-crown cover, 51 to 80 percent tree-crown cover, and 81 to 100 percent tree-crown cover.

Topographic layers. Variation in slope, elevation, and aspect can significantly affect fire behavior. *FIRE!* accepts raster coverages of the topographic layers in a variety of units (e.g., degrees or percent for slope). The Camp Lejeune topographic coverages were created in ARC-GRID from raster contour layers provided by Camp Lejeune. However, within the base, the effect of topography is minimal. A total elevation change of approximately 35 feet occurs across the project area.

Weather and wind data. Weather and wind data can be obtained from a variety of sources and are input as ASCII files. Weather data are expressed for each day and include precipitation, hour of minimum temperature, hour of maximum temperature, minimum and maximum temperatures, minimum and maximum humidity, and elevation. Winds are assumed to be constant in space but to vary

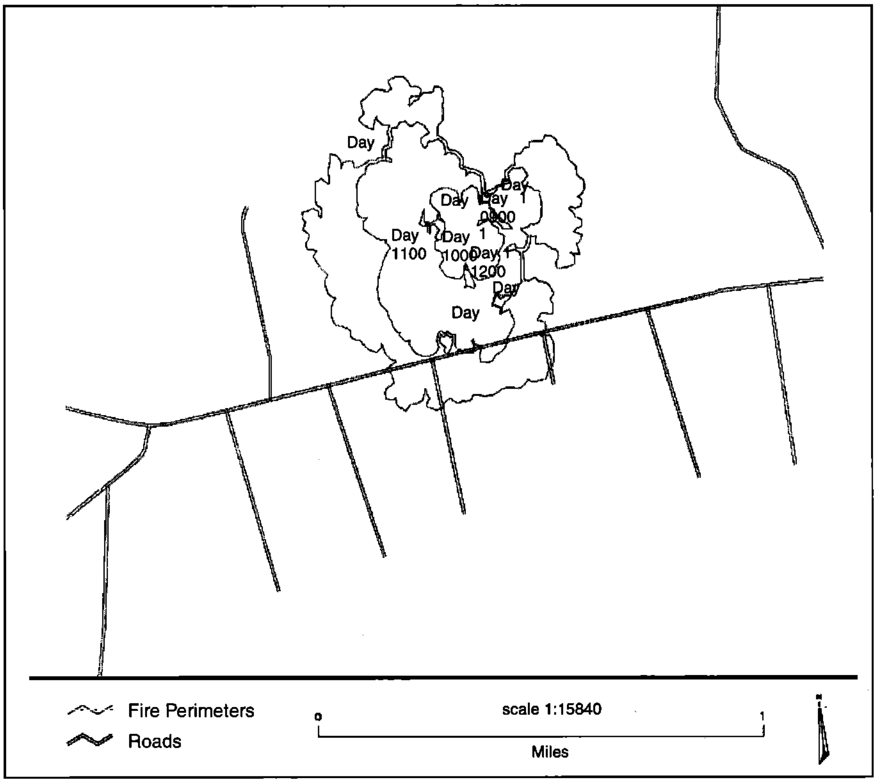


Figure 5. Example of an output file from a FIRE! simulation.

in time. Wind data are specified for each hour as 20-foot open windspeed, azimuth direction, and cloud cover percentages.

Scenario parameters. User-specified scenario parameters include the burn simulation start and end dates and times, and the spatial and temporal resolution of calculations performed during the simulation. For instance, a spatial resolution of greater than 25 meters may be specified for scenarios covering very large areas in which only a gross estimation of fire behavior over a long time period is desired. Specifying a greater spatial resolution reduces the computational requirements of the model, resulting in a faster simulation. However, scenarios requiring detailed information on fire behavior throughout a simulation area should use a spatial resolution at least as small as the input data sets provide.

Finally, a data set identifying the location and configuration of a fire ignition must be specified. Fire ignitions may be established as points, lines, and/or polygons and are entered interactively by clicking on the screen at the desired ignition locations. The user may also adjust the predicted rate of spread to match actual observed rate of spread by fuel type.

Model Development and Calibration

The engine of the *FIRE!* application, responsible for all the complex computations necessary for simulating fire behavior, is *FARSITE* (Fire Area Simulator) (Finney 1993), a C++ program developed by Systems for Environmental Management. *FARSITE* interacts with the ARC/INFO environment as a component of *FIRE!*, enhancing the spatial display and query capabilities of the GIS for fire modeling and analysis.

FIRE! employs recent developments in vector-based fire modeling, thereby avoiding problems encountered with cellular automation models of fire growth. Cellular models use the constant spatial arrangement of a cell or rasters landscape to solve for the time of ignition. With cellular models, a fire shape is propagated through the raster with cells igniting based on characteristics of other cells in their neighborhood. Studies have shown cellular techniques to yield distorted fire shapes because of the geometry inherent in having a fixed number of directions available for fire spread. Effects of temporal variations in wind or weather are also difficult to implement in cellular models because the fire edge is not represented continuously at a given time.

Vector or wave type models have been shown to closely simulate fire growth with varying winds (Anderson et al. 1982, French 1992). The vector approach in *FARSITE* and *FIRE!* propagates the fire front in a fashion similar to a wave, shifting and moving continuously in time and space. Vector models solve for the position of the fire front at specified times (Finney 1995). *FARSIGHT* uses a technique for vector propagation, known as Huygen's principle (Anderson et al. 1982), to expand surface fire fronts in two dimensions (Richards 1990). While rasters are still used to represent the underlying landscape and to record fire characteristics during the simulation, the fire perimeters are processed and stored as continuous vectors.

Field data regarding past prescribed burns and wild fires collected by Camp Lejeune Forestry Division personnel were used extensively in the fire behavior model calibration process. This involves fuel-specific adjustments to rate of spread similar to those used for the BEHAVE system (Rothermel and Reinhardt 1983). Base forestry division personnel consistently collect detailed data regarding fire behavior (spread rates, flamelengths, burn perimeter, etc.) for fires burning on the base. Global positioning system units are used to map fire perimeters. The fire behavior model was calibrated using this detailed data from past fires to ensure the most accurate and reliable fire behavior predictions under local conditions. The incorporation of this past fire behavior data during the fire behavior model calibration was among the most important tasks of the entire project.

The GUI developed for the execution of the GIS-based model allows natural resource managers not intimately familiar with computers or GIS to effectively use the fire behavior model. By developing and incorporating a user-friendly interface for model execution, this model puts the full power of the fire behavior model into the hands of a much wider range of resource managers and technicians. With minimal computer training and experience, nearly anyone can identify and edit the necessary input data, develop a burn scenario, execute the model, analyze the results, and produce hard-copy results output without ever being required to specify command line instruction for direct computer interfacing. The results of *FIRE!* are, of course, only as good as the information and assumptions entered into each scenario.

Outputs

After defining the burn scenario, the model simulation can be executed. As the model performs the necessary fire behavior calculations, vectors are displayed indicating the fire's perimeter at a user-specified time interval. The vectors may be displayed over the fuels raster data layer or the original Landsat TM imagery. At the completion of the simulation, raster data layers are produced providing the flamelength, fireline intensity, time of arrival, heat per unit area, and rate of spread of the fire for every pixel within the burned perimeter. *Figures 4* and *5* present example output files from a *FIRE!* simulation.

Discussion

FIRE! is one example of GIS models that go beyond inventory, monitoring, and display to allow ecosystem managers to simulate the spatial outcomes of management and policy decisions. By making the ability to vary critical model assumptions readily accessible to the manager, *FIRE!* allows ecosystem managers to test the sensitivity of decisions to assumptions of weather, fuels, and topography. Future applications will allow the economic costs and benefits of those decisions to be considered by incorporating ignition risk, suppression costs, and land value into the model. JOF

Literature Cited

Anderson, D.G., E.A. Catchpole, N.J. DeMestre, and T. Parkes. 1982. Modelling the spread of grass fires. J. Austral. Math Soc. (Ser. B) 23:451–66.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv. Gen. Tech. Rep. INT–122.

Andrews, Patricia L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system–burn subsystem, part 1. USDA For. Serv. Gen. Tech. Rep. INT–194.

Congalton, R.G., K.Green, and J. Teply. 1993. Mapping old growth forests on national forest and park lands in the Pacific Northwest from remotely sensed data. Photogramm. Eng. and Remote Sensing 59(4):529–35.

Finney, M.A. 1993. Modeling the spread and behavior of prescribed natural fires. *In* Proceedings of the 12th Conference on Fire and Forest Meteorology, October 26–28, 1993, Jekyll Island, Georgia. Soc. Am. For., Bethesda, MD.

———. 1995. FARSITE. Fire area simulator. User's guide and technical documentation. Version 1.0. Systems for Environmental Management, Missoula, MT.

Fons, W.T. 1946. Analysis of fire spread in light forest fuels. J. Agric. Res. 73(3):93–121

French, I.A. 1992. Visualization techniques for the computer simulation of brushfires in two dimensions. MS thesis, Univ. New South Wales, Australian Defence Force Academy.

Kourtz, P., and W.G. O'Regan. 1971. A model for a small forest fire to simulate burned and burning area for use in a detection model. For. Sci. 17(2):163–69.

Moore, M.M. 1994. Analysis and mapping of late-successional forests in the American Southwest. *In* Remote sensing and GIS in ecosystem management. Island Press, Washington, DC.

Richards, G.D. 1990. An elliptical growth model of forest fire fronts and its numerical solution. Int. J. Numerical Meth. Eng. 30:1163–79.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT–115.

———. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT–143.

Rothermel, R.C., and G.C. Rinehart. 1983. Field procedures for verification and adjustment of fire behavior predictions. USDA For. Serv. Gen. Tech. Rep. INT–142.

Van Wagner, C.E. 1969. A simple fire growth model. For. Chron. 45:103–4.

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