USE OF THE *FARSITE* FIRE GROWTH MODEL FOR FIRE PREDICTION IN U.S. NATIONAL PARKS

Mark A. Finney
Systems for Environmental Management
PO BOX 8868, Missoula MT, 59807 USA
Voice: (406) 329-4832
Fax: (406) 329-4877
E-mail: fswa/s=m.finney/ou=s22101a@attmail.com

Kevin C. Ryan
USDA Forest Service
Intermountain Fire Sciences Laboratory
PO BOX 8089 Missoula MT, 59807 USA
Voice (406) 329-4846
Fax: (406) 329-4877
E-mail: fswa/s=k.ryan/ou=s22101a@attmail.com

KEYWORDS: fire modeling, fire simulation, wildland fire, geographic information systems.

ASTRACT: The *FARSITE* (Fire Area Simulator) is a fire growth model that spatially projects fire perimeters and behavior over complex landscapes. The model uses spatial data themes from a geographic information system (GIS) along with weather and wind data to propagate fire as a spreading wave front. The model runs on a personal computer under the WINDOWS operating environment. Version 1.0 of the *FARSITE* model was distributed by the US National Park Service and US Forest Service beginning January 1995. Its intended use is for management support of active fires and planning for potential fires.

We used *FARSITE* in support of fire management decisions regarding naturally ignited fires at Yosemite National Park, California, and Glacier National Park, Montana during the Summer of 1994. The fire growth projections were used for deciding if fires should be suppressed or allowed to burn under management supervision (termed "prescribed natural fires"). Model output was compared against spread patterns from previous fires at Glacier, Yosemite National Park and Sequoia National Parks. The general features of the observed spread patterns and fire behavior were in reasonable agreement with the model projections, given limitations of available data on fuels and weather. The applications and early validations suggest that accurate data on fuels and winds are crucial to model performance, but that the model is a useful tool for management of wildland fires.

INTRODUCTION

Wildand fires are common to forest and rangelands of North America and increasingly in suburban areas near cities. Whether started by lightning or by humans, most fires are actively suppressed in attempt to avoid damage to natural resources or structures. Fires in the wildland urban intermix can have disastrous consequences, as recently demonstrated in the 1991 Oakland Hills Fire in Oakland California (2500 structures lost), and Colorado (1994, 14 fire fighters killed).

Despite the prevailing policy of fire suppression for most wildland areas, fire plays an important ecological role in many natural ecosystems that evolved with it. Fire maintains the presence of some plant and animal species as well as their diversity. Management objectives for maintaining ecosystems have led to a "prescribed natural fire" (PNF) policy that permits fires under pre-determined conditions to burn with limited hindrance on some lands. The two policies treat fires differently yet both require tools for long and short range fire growth projections. The relative lack of management interference with PNFs makes them an important source of information on fire spread and behavior that is critical to validating models of large fire growth. Fire growth models are useful for planning and management operations on both suppression fires and PNFs (Andrews 1989). In this paper, we describe a new tool for long-range fire growth projection, some example applications, and some lessons for further work in the applying fire growth modeling in fire management organizations.

BACKGROUND

Since the early 1980's, U.S. the Forest Service and other US land management agencies have used the BEHAVE fire behavior prediction system (Andrews 1986) for short term predictions of fire behavior and spread. The BEHAVE system was designed for short range projections (typically shorter than 24 hours) using site-specific information on fuels, weather, and topography (Rothermel 1983). It was not designed for long term projections or for large fire growth in a spatially explicit manner. Models of this type are referred to as fire growth models.

Computerized fire growth models have been described in the scientific literature since the early 1970's. Two basic deterministic approaches to modeling fire growth have emerged, cellular and wave-type models (Finney 1994). These approaches differ much like the methods used for representing landscape data in geographic information systems (GIS): raster versus vector. They also differ in the way time and space variables are used; cellular models rely on the fixed distance between cells to solve for fire arrival time at those cells. Wave-type models provide a finite time-step to calculate fire spread distance, inverse to the cellular models.

Raster models (e.g. cellular models) attempt to spread fire as a discrete process of ignitions between adjacent cells on a regular grid. Examples of this type of approach are numerous. The earliest effort by Kourtz and O'Regan (1971), has been followed by many other cellular models too numerous to mention here. This approach has some limitations, although methods do exist for mitigating their impact on fire growth simulation under relatively simple situations (French 1992). Fire shapes are distorted by the gridded geometry of the calculations, different arrival times at cells on the fire edge make temporal changes difficult to implement synchronously around the fire. Long computation times are required for these models.

Vector models treat fire growth as a spreading wave front (Anderson et al. 1982) meaning the edge of the fire is defined by an expanding polygon. A number of techniques for this have recently been published (Richards 1990, Knight and Coleman 1993, Roberts 1989). The first description of this idea applied to fire modeling was by Sanderlin and Sunderson (1975) for the FIREMAN project in Southern California. Anderson et al. (1982) brought the technique and terminology into the fire and forestry literature. The technique is now commonly termed Huygens' Principle in reference to the 17th century mathematician (Christian Huygens) who advanced theories on the travel of light waves. Compared to cellular models, vector based models are computationally efficient and allow a logical extension to 2-dimensions of the 1-dimensional point-vector models of fire spread and behavior (Rothermel 1972, Andrews 1986).

Although a variety of these models have been demonstrated as prototypes most have been confined to research purposes (Finney 1995). Reasons have included limitations on: 1) the power of computers for the required fast computation times, 2) computer availability to wildland managers and, 3) use and familiarity with geographic information systems (GIS) and/or data bases for managers. These restrictions are or have been overcome by the infusion of personal computers in all phases of land management and the proliferation of GIS capabilities and data bases.

DEVELOPMENT OF *FARSITE*

The *FARSITE* (Fire Area Simulator) model has been developed as a management tool for personal computers (Finney 1994, 1995). Personal computers with 32-bit operating systems are now capable of long term simulations. A user interface for the *FARSITE* model was developed for the WIN32s operating system and allows *FARSITE* to run in Windows 3.1x, Windows 95, and Windows NT. Other versions of *FARSITE* for UNIX operating systems are being developed.

Raster data themes required for the *FARSITE* model are elevation, slope, aspect, fuel model (Anderson 1982), and forest cover percentage. Richards' (1990) algorithm is employed for propagating elliptical waves. As with all Huygens' algorithms, the algorithm uses points on the fire's edge as independent sources of elliptical wavelets. The shape, orientation, and size of each wavelet is determined locally by the strength of the wind-slope vector as related to elliptical dimensions (Anderson 1982, Alexander 1985), the vectored wind-slope direction, and the fire rate of spread. The fire spread rate is determined by the local fuel type, fuel moisture conditions, and wind-slope vector using the Rothermel spread equation (Rothermel 1972, Andrews 1986).

Weather and wind data are also required for the simulation as two separate streams. The weather stream consists of temperature and humidity maxima and minima for a given day and elevation, and the hours at which these occur. A simple lapse rate calculation is used to adjust weather for different elevations. Temperature and humidity values for any time throughout the day are obtained by a sine wave interpolation. These are used to compute the suite of fuel moistures (Rothermel *et al.* 1986) required by the Rothermel fire spread equation. *FARSITE* computes fuel moistures for a given point on the fire edge at a given time by starting from initial conditions. This is much faster than computing fuel moisture values for all cells on a landscape at each timestep.

Wind data comprise a separate stream containing wind vectors at specific times; temporal variation in winds can be expressed to the nearest minute. In this version of *FARSITE*, winds are considered spatially constant for a given data stream and parallel to the ground surface at all locations. *FARSITE* allows multiple weather and wind streams to be employed for a given landscape. After loading multiple1 streams, the user can define a grid of arbitrary resolution and specify the cells for which a given stream applies. This is useful for distinguishing wind streams applying to ridgetops and valley bottoms.

USE OF *FARSITE*

The *FARSITE* model was used for fire growth projection on prescribed natural fires in the summer of 1994 during a testing phase. Tests were conducted in several U.S. National Parks: Sequoia and Kings Canyon and Yosemite in California, and in Glacier National Park in Montana (Figure 1). The primary purposes of the tests were to refine the graphical interface, to get feedback from users of the program under active fire management situations, and to evaluate the requirements for using the program as a field tool. Although actual validation of the model was not the purpose during the ongoing fires, data were collected to make later validation possible. Data on fire growth and behavior, weather, and fuel moisture were recorded routinely for all fires.

The fire season of 1994 in the western United States was relatively active. *FARSITE* was used on a number of fires at the test sites. Two fires in particular provided good opportunity for our tests because of their long duration and large sizes. The Horizon Prescribed Natural Fire at Yosemite (2000 ha), and the Howling Prescribed Natural Fire Complex at Glacier (5000 ha) each burned for several months between July and September.

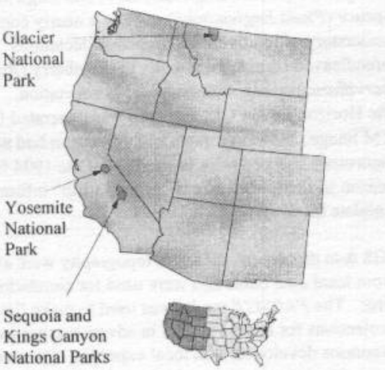

Figure 1. Map of western United States showing National Park test sites for FARSITE during summer 1994.

The Horizon PNF occurred between approximately 1500 and 2500 meters in elevation in the mountains south of Yosemite Valley in the Sierra Nevada of California (Figure 1). The topography is generally north facing and is dominated by granite outcrops that form ridges along the east and west boundaries of the fire. Manzanita chaparral (Arctostaphyllos manzanita), a relatively flammable evergreen shrub, generally grows on the thinner soils surrounding these outcrops and extends into the understory of sparse forests of Jefferey pine (*Pinus jeffreyii*), red fir (*Abies magnifica*), and white fir (*Abies concolor*) that border the chaparral. Denser forests between the outcrops including lodgepole pine (*Pinus contorta*) contain fuels more typical of a forest understory, having varying amounts of large woody material and conifer needle litter. These fuels were relatively easily distinguished from among about 30 spectral categories generated by classifying a satellite image from the Thematic Mapper (TM).

The Howling PNF occurred at approximately 600 to 1000 meters elevation in the lower montane forests of the northern Rocky Mountains of Glacier National Park (Figure 1). The topography at these elevations is moderately steep and facing west toward the North Fork of the Flathead River. Dense forests of ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*) and Englemann *spruce (Picea Englemannii*) contain a nearly continuous understory of relatively inflammable deciduous broadleaved shrubs, principally thimbleberry (*Rubus parviflorus*), along with herbaceous vegetation. As with the Horizon Fire, a GIS fuel map was generated from a TM image. However, fuels and vegetation had not been rigorously mapped prior to the start of the 1994 fire season so there was limited "ground truth" information to validate the map.

GIS data themes for fuels and topography were available from local data bases and were used for simulation of the fires. The *FARSITE* model was used to make fire growth projections for up to 1 month in advance using weather scenarios developed with local expertise. Two weather scenarios were developed for each fire. The first contained "normal" patterns of summer fire weather. This pattern was a composite based on expected typical and recent weather patterns and included high and low temperatures and humidities and typical diurnal fluctuations in wind speed and direction. The second scenarios punctuated this normal pattern with days of extreme fire weather. On the Horizon fire, this meant a strong foehn wind (known locally as a Mono wind) from the east with low relative humidities (15 to 25%) sustained for several days. On the Howling fire, extreme conditions are caused by the passage of late season "dry" cold fronts; winds come from the northwest for approximately 24 hours.

RESULTS

The simulations were more accurate for the Horizon fire than the Howling fire. However, the simulations proved to be useful to managers of both fires. Early projections of the Horizon fire verified conventional expectations for short term fire spread and suggested fire spread patterns weeks into the future that became regarded as reasonably accurate given the uncertainties about weather (Figure 2). The projections of the Howling fire suggested a rate and pattern of fire growth that was far more conservative than more subjective estimates made by local fire specialists (Figure 3). The differences between the fire growth projections led to reexamining the assumptions that contributed to the fire spread projections. The simulation results also suggested wider variability in fire spread than would have been considered during those early stages of the planning process.

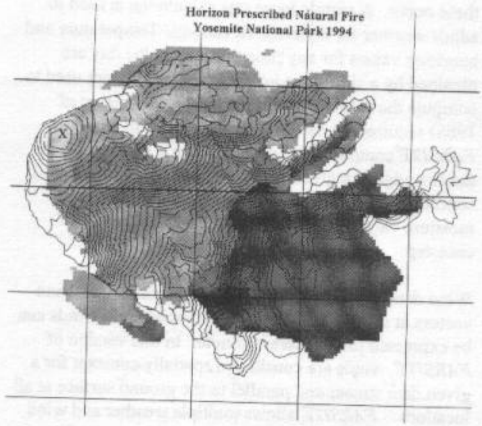

Figure 2. Fire spread patterns recorded for the Horizon prescribed natural fire at Yosemite National Park, California (shading), compared to daily perimeters predicted by the *FARSITE* model (lines).

The simulations of the two fires clearly showed the need for accurate fuel maps and descriptions. Based on several weeks of field reconnaissance, the fuels map produced for the Horizon fire was considered reasonably accurate. The fuel models were descriptive of the physical fuel characteristics as well as the fire behavior generated by the Rothermel spread equation. Timber and shrub fuel types were spatially distinct and burned with spread rates and intensities typical of those predicted. Consequently, fire growth and behavior was simulated to a useful degree of accuracy (Figure 2). Fire spread was generally slow through the forest understories and much faster through the shrub and grass fuels. Exceptions occurred on several days when winds increased and torched small areas of forest (20 ha) that contributed to spot fires approximately 1000 m ahead of the fire front.

Although the fuels map for the Howling fire appeared reasonable, the fuel models themselves did not translate accurately to fire behavior. The Howling fire spread primarily through smoldering or periodic creeping in the litter and dead woody material on the forest floor. Occasionally, spruce trees were torched and cast embers up to 50 meters ahead of the fire front (these often started new spot fires). The fire burning in the surface fuels rarely exhibited "typical" surface fire spread characteristics as required by the Rothermel model. The Rothermel (1972) spread model assumes that fuels are uniformly distributed at the spatial scale over which fire behavior is predicted. Although the shrub and herbaceous fuel layers were relatively uniform, these fuels were above the moisture limit for burning. As a result, the burnable fuel bed consisted of discontinuous pockets of dead forest litter, mostly near tree bases and along corridors of dead logs on the ground. At the scale of fire behavior experienced under the existing weather conditions the distribution of fuels in the howling fire violated the uniformity assumption in the Rothermel (1972) model. Fire behavior predictions strongly depend on the involvement of live shrubby fuels; faster spread rates and higher intensities result if shrubs are assumed *a priori* to be burning. This *a priori* decision is necessary because there are no methods for predetermining the transition of a fire to the canopy of a shrub layer when it is burning in litter. Live shrubby fuels can become available to the fire and contribute to fire spread only when moisture contents are low and densities high enough. These thresholds of moisture content and fuel continuity however, are not well understood.

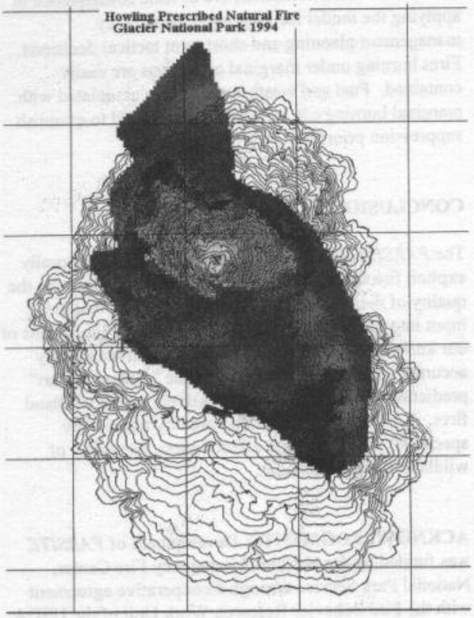

Figure 3. Fire spread patterns recorded for the Howling prescribed natural fire at Glacier National Park, Montana (shading), compared to daily perimeters predicted by the *FARSITE* model (lines).

RESEARCH NEEDS

Testing of the *FARSITE* model on the Horizon and Howling fires points to the need for additional basic research into several aspects of fire behavior. We currently have a poor understanding of how live fuels affect the spread and intensity of wildland fires. The average heat content of live fuels, ca. 19,000 kJ/kg ± 20 percent, is more than adequate to evaporate the moisture within these fuels but live fuels appear to retard fire spread and intensity until some threshold is reached. This threshold is probably related to complex heat transfer interactions between fire burning in the dead surface litter and the shrub and forest canopy. Fires burn poorly in densely packed dead surface litter, particularly when shaded and sheltered from wind such as was common in the Howling Fire. The amount of these fuels was greater beneath spruce canopies. When these fuels burned during low midday humidities sufficient heat was generated to initiate torching of the spruce canopies. Spruce foliage has a relatively high heat content, relatively low moisture content, and a relatively dense uniform fuel particle packing as compared with the deciduous broadleaf shrub canopy. Spruce canopies burned rapidly and intensely. However, these fuels were imbedded in a larger fuel matrix of relatively poor burning potential. The 1994 fire season was one of unusually high lightning occurrence and low precipitation in Glacier National Park. Several fires were ignited. Fires that burned in fuels dominated by dense coniferous forest canopies or uniform evergreen shrubs exhibited relatively uniform predictable spread rates and intensities as contrasted with the discontinuous spread of the Howling Fire. However, the one unusual factor in 1994's fire weather was the relative lack of high wind. In 1988 a nearby fire, the Red Bench fire, demonstrated that under high wind conditions fuels similar to those on the Howling Fire will burn rapidly and intensely (Bushey 1989). More basic research is needed to better understand how heat source versus heat sink relationships are affected by spatial and temporal changes in fuels as vegetation and weather change daily and seasonally.

There has been an active fire research program at Yosemite National Park for several decades. As a result there has been a considerable effort devoted to spatially mapping fuels. These data are indispensable to quality fire behavior predictions. However, they are costly and time consuming to obtain. Research currently being conducted at the Intermountain Fire Sciences Laboratory is aimed at developing a National Fuels/Vegetation map for regional fire planning (Burgan and Hardy 1994). This mapping efforts relies on spectral data from the Advanced Very High Resolution Radiometer (AVHRR) which has a 1 km spatial resolution. Also, research has demonstrated that AVHRR data can be used to monitor seasonal changes in the relative greenness, an indication of moisture status, of vegetation. While these data appear to be very valuable for large scale regional fire planning they lack the spatial resolution necessary for many fire applications. Additional research is needed to develop reliable methods for deriving fuel inputs to fire behavior prediction models such as *FARSITE*.

POTENTIAL APPLICATIONS

There are several potential applications of the *FARSITE* model both in long range fire management planning and in short range tactical decisions. Provided good spatial fuels and terrain data are available, *FARSITE* can be used to predict spatially explicit fire spread and intensity under multiple fire weather scenarios. Thus the model can be used as a gaming tool to simultaneously account for numerous varying factors affecting fire behavior. It also has potential as a tool for training fire specialists.

The predicted behavior of wildland fires is critical for deciding to allow prescribed natural fires to burn. Indeed this was the primary motivation for developing the model. *FARSITE* also has potential application in the suppression of wildland fires. In rugged terrain it is often necessary to attack the fire indirectly by constructing fire lines kilometers ahead of an advancing fire. *FARSITE* fire behavior predictions can aid in developing criteria for control line location and width.

In the wildland-urban interface *FARSITE* is a potentially useful tool for presuppression planning. Fuel inputs can be modified to evaluate the effectiveness of various proposed fuel management treatments. Fire behavior outputs can be compared to the values at risk to establish priorities for the safe effective deployment of suppression forces and to establish standards for development in the wildland-urban intermix. Once areas of severe fire potential have been spatially identified *FARSITE* can display the model inputs for such areas thus helping to identify common hazard elements (e.g., fuel type or terrain slope).

The limitations of the *FARSITE* model which were identified as a result of the Howling Fire are primarily limitations concerning using the model for projections involving extended durations and marginal burning conditions. Such limitations are of little consequence in applying the model for long range emergency management planning and short term tactical decisions. Fires burning under marginal conditions are easily contained. Fuel and weather conditions associated with marginal burning can be described and used to establish suppression priorities.

CONCLUSIONS

The *FARSITE* model simulates spatially and temporally explicit fire spread and intensity. It is limited both by the quality of the fuels, weather, and terrain data that are input into the model and by the fundamental limitations of our knowledge about fire behavior. Given reasonably accurate inputs the model can provide "state of the art" predictions of the behavior of relatively active wildland fires. *FARSITE* outputs can be used by trained fire specialists to improve the effectiveness and safety of wildland fire management.

ACKNOWLEDGMENTS: Development of *FARSITE* was funded by the National Interagency Fire Center, National Park Service through a cooperative agreement with the Fire Behavior Research Work Unit of the USDA Forest Service, Intermountain Fire Sciences Laboratory (INT-93854-RJVA). Its current applications were also supported in part by grants from Sequoia and Kings Canyon National Parks and the Glacier National Park Global Change Research Program.

REFERENCES

Anderson, D.G, E.A. Catchpole, N.J. DeMestre, and T. Parkes. 1982. Modeling the spread of grass fires. J. Austral. Math. Soc. (Ser. B.) 23:451-466.

Anderson, H.E. 1983. Predicting wind-driven wildland fire size and shape. USDA For. Serv. Res. Pap. INT-305.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system- BURN subsystem, Part 1. USDA For. Serv. Gen. Tech. Rep. INT-194.

Andrews, P.L. 1989. Application of fire growth simulation models in fire management. Proc. 10th Conf. Fire and Forest Meteorology, Ottawa Canada. pp 317-321.

Burgan, R.E. and C.C. Hardy. 1993. Ground truthing a national AVHRR based vegetation fuels map. Proc. 12th Conf. Fire and Forest Meteorology, pp 428-433.

Burgan, R.E. and R.A. Hartford. 1994. Monitoring vegetation greenness with satellite data. USDA For. Serv. Gen. Tech. Rep. INT-297.

Bushey, C.L. 1990. The 1988 Red Bench Fire: Documentation of fire behavior, fire weather, and the preburn fuel conditions in the North Fordk of the Flathead River Valley. Final Report to USDA For. Serv. INT-89439-RJVA. On file at the Intermountain Fire Sciences Laboratory.

Finney, M.A. 1994. Modeling the spread and behavior of prescribed natural fires. Proc. 12th Conf. Fire and Forest Meteorology, pp 138-143.

Finney, M.A. 1995. *FARSITE*: A fire area simulator for fire managers. Proc. Biswell Symposium, February 1994, Walnut Creek, CA. *in press*.

French, I.A. 1992. Visualisation techniques for the computer simulation of bushfires in two dimensions. M.S. Thesis University of New South Wales, Australian Defence Force Academy, 140 pages.

Knight, I. and J. Coleman. 1993. A fire perimeter expansion algorithm based on Huygen's wavelet propagation. Int. J. Wildl. Fire 3(2):73-84.

Kourtz, P. and W.G. O'Reagan. 1971. A model for a small forest fire.. to simulate burned and burning areas for use in a detection model. For. Sci. 17(2):163-169.

Kourtz, P, S. Nozaki and W. O'Regan. 1977. Forest fires in the computer- A model to predict the perimeter location of a forest fire. Fisheries and Envioronment Canada. Inf. Rep. FF-X-65.

Richards, G.D. 1990. An elliptical growth model of forest fire fronts and its numerical solution. Int. J. Numer. Meth. Eng. 30:1163-1179.

Roberts, S. 1989. A line element algorithm for curve flow problems in the plane. CMA-R58-89. Centre for Mathematical Analysis, Aust. Nat. Univ. (Cited from French 1992).

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

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143.

Sanderlin, J.C. and J.M. Sunderson. 1975. A simulation for wildland fire managment planning support (FIREMAN): Volume II. Prototype models for FIREMAN (PART II): Campaign Fire Evaluation. Mission Research Corp. Contract No. 231-343, Spec. 222. 249 pages.

Wallace, G. 1993. A numerical fire simulation model. Intl. J. Wildl. Fire 3(2):111-116.