Status Report USFS/UCR Joint Research on Wildland Fire Management

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INTRODUCTION

On the average, some 250,000 wildland fires occur in the United States each year on federal, state, and private lands. In order to reduce the tremendous losses due to fires, the U.S. Forest Service established a policy of fire exclusion from wildlands in 1905. Under this policy, wildland fires were immediately suppressed whenever possible and, consequently, numerous fires were suppressed before they could spread over wide areas. Some fires, however, escaped the initial attacks of suppression and caused substantial damage to natural resources and human property.

Suppression alone is neither sufficient nor effective for managing wildland fires. Minnich (1983) suggested that suppression may cause organic fuels to accumulate, thereby preparing for later fires of unnatural size and intensity. Recently, a more flexible approach based on principles of fire ecology has been adopted by fire managers. A major conceptual change in fire management due to this approach is that fires must be recognized as part of an ecosystem and, therefore, should not be considered as all hostile. According to this approach, suppression should only be applied to those fires that pose threats to human property or natural resources. Furthermore, prescribed burning has become an important tool in managing wildland fires (Green, 1981).

Wildland fires are a complicated spatial phenomenon affected by a variety of environmental, human, and spatial factors. Therefore, effective wildland fire management requires the understanding of both the spatial processes of each factor and the complex interactions among them. Recently, due to the development in geographic information systems (GIS), such a difficult task can be handled much more effectively than before .

Since 1985, cooperation has been underway between the U.S. Forest Service and the University of California, Riverside in developing GIS operational procedures and analytical methods for wildland fire management. The joint efforts have resulted in three completed research projects and two ongoing ones. The ultimate goal of these projects is to utilize modern GIS technology for evaluating alternative management plans, designing cost-effective spatial strategies, and making quick-response decisions on fire suppression.

This paper reports the progress made in each project and describes the most important findings. Guidelines for further research will be suggested in the final section.

CONSTRUCTION OF DATABASE

The first project, entitled "The value and design of spatial data for fire management planning," was aimed at the construction of a GIS database suitable for long term management of wildland fires. Among major tasks in GIS projects, the construction of a suitable database is usually most labor intensive and time consuming. This project, conducted from June, 1985 to June, 1990, is of longest duration in the series of cooperative projects.

The San Jacinto Ranger District of the San Bernardino National Forest, 150 km east of Los Angeles, California, was selected for this project (Figure 1). This area provides an ideal case for studying wildland fires. First, this area has a well-recorded history of fire activity, a condition necessary for valid statistical testing and model building (File data since 1911, San Bernardino National Forest). Figure 2 depicts the fire activity between 1911 and 1984 in this area. Second, this area possesses a great diversity in environmental and human factors and, therefore, allows for different ecological components to be compared (Chou *et al.*, 1990). Third, this area has been under strict management for decades, thereby providing a typical case of managed environment. Once a complete database becomes available, long term effects of management can be evaluated by comparing the ecosystem of this area and that of another area of similar environmental conditions yet without wildland fire management. Baja California, Mexico is an ideal candidate for such comparisons (Minnich, 1983).

Complicated ecological databases must be organized into map tiles and map layers. A tile is a delineated geographical area used as a base unit for data organization. In most cases, each tile consists of a number of data layers and each layer contains the data of one or a few similar attributes. In this database, map tiles are delineated by the boundaries of the 7.5-minute topo-

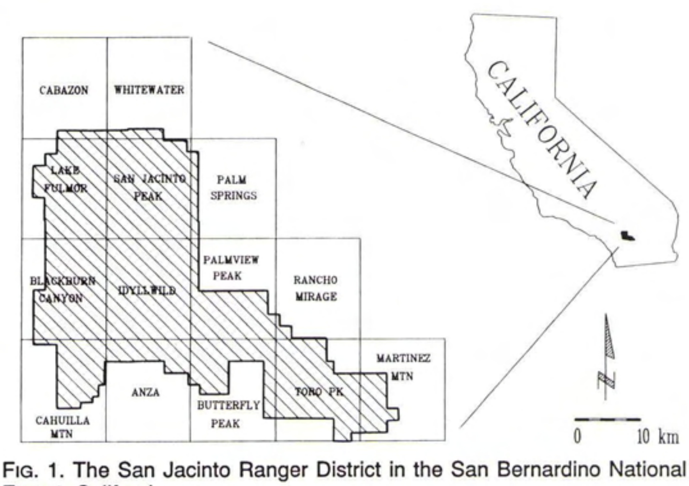

Fig. 1. The San Jacinto Ranger District in the San Bernardino National Forest, California.

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FIG. 2. Fire activity in the study area, 1911 - 1984.

graphic maps published by the U.S. Geological Survey. The coordinate system adopted for the database is the UTM system, and the map scale is standardized at 1:24,000. With this coordinate system, features available on topographic maps can be directly digitized into the database without the need for coordinate transformation. Furthermore, digital terrain data can be directly imported from Digital Elevation Models (U.S. Geological Survey, 1987).

In the San Jacinto database, each tile contains 17 data layers: vegetation, soils, precipitation, watershed, water sources, streams, mean January temperature, maximum July temperature, mean July temperature, topography, fire history, fire management zones, administrative boundaries, buildings and campgrounds, power lines, roads, and trails. Among them, fire history and fire management zones were digitized into the database by translating the data files of the San Bernardino National Forest into manuscripts based on the standard coordinate system. Vegetation was mapped using standard aerial photointerpretation procedures (Minnich, 1987). Topography was obtained by converting Digital Elevation Models into homogeneous surfaces of terrain characteristics through the formation of triangulated irregular networks (Environmental Systems Research Institute, 1987). Soils were digitized from the soil-map series compiled by the U.S. Soil Conservation. Features of other data layers were directly digitized from topographic maps.

SPATIAL STATISTICS

The second project, entitled "Spatial statistics for wildland fire management," was conducted between October 1988 and October 1989 (Chou, 1989a). The main objectives of this project are to identify spatial statistics suitable for studying the distribution of wildland fires and to develop GIS operational procedures for deriving the selected statistics from the database.

To define geographical units for analysis, three criteria were considered. First, the number of geographical units in each tile must be sufficiently large in order for statistical testing to be valid. Second, the geographical units must completely cover each tile without overlapping one another. Third, each geographical unit must represent a homogeneous surface based on specific ecological characteristics pertaining to fire behavior. With these concerns, geographical units of wildland fire management are defined by natural boundaries of vegetation and topography.

For the explanation of spatial processes of wildland fires, spatial autocorrelation is considered the most important statistic because wildland fires are driven by a contagious diffusion process. Among the available statistics of spatial autocorrelation, Moran's I coefficient was selected for this study because its properties are most appropriate for evaluating the distribution of wildland fires. The coefficient is defined as

$$I = \frac{n}{2a} \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - x)}{\sum_i (x_i - \bar{x})^2}$$

where n is the number of geographic units; w_{ij} denotes spatial contiguity which equals one if the i-th unit is adjacent to the j-th unit, otherwise it equals zero; $2a$ is the sum of neighboring pairs, i.e., $2a = \Sigma_i \Sigma_j w_{ij}$; and x_i is the proportion of burned area in the i-th unit. All statistical tests in this study indicated that the distribution of wildland fires clearly illustrates a significant positive spatial autocorrelation.

The statistical properties of Moran's I coefficient and the procedures for hypothesis testing are described in Cliff and Ord (1981). The operational procedures for deriving the coefficient from the database were developed as a result of this project (Chou, 1989a, 1989b).

MODELING FIRE OCCURRENCE PROBABILITY

The third project of the series, conducted from November 1989 to June 1991, is entitled "Building a spatial model for wildland fire management" (Chou, 1991a). The objective of this project is to build a probability model of fire occurrence for the estimation of fire danger of each geographical unit. Such a model is especially useful for delineating critical zones where the probability of fire occurrence is excessively high. In order for model building and hypothesis testing to be cost-effective, this project employed only a subarea of the San Jacinto District, the Idyllwild quadrangle, as the study area (Chou, 1990).

Moran's coefficient of spatial autocorrelation was evaluated from the distribution of wildland fires. The results show a significant level of autocorrelation and suggest that a spatial factor representing neighborhood effects must be incorporated in the model of fire occurrence (Chou *et al.*, 1990). To determine the specification of this spatial factor, six possible spatial weighting functions were examined: contiguity, area, distance, border length, area and distance combined, and border length and distance combined. The results indicate that contiguity alone effectively represents neighborhood effects and can be used for defining the spatial factor.

Logistic regression was used to model the distribution of fire occurrence probability (Wrigley, 1976). Formally,

$$P_i = \frac{\mathrm{EXP}(U_i)}{1 + \mathrm{EXP}(U_i)}$$

where P_i denotes the probability for the i-th geographic unit to burn. The probability is a function of U_i to be specified in each model; a greater U_i implies a higher probability for a fire to occur in the unit.

Two alternative models, a basic model and a study model, were tested. In both cases, the dependent variable is the distribution of fires. The basic model is expressed as

$$U_i = \beta_0 + \beta_1\mathrm{VEGE}_i + \beta_2\mathrm{PREC}_i + \beta_3\mathrm{TEMP}_i + \beta_4\mathrm{BLDG}_i + \beta_5\mathrm{CAMP}_i + \beta_6\mathrm{ROAD}_i + \beta_7\mathrm{AREA}_i + \beta_8\mathrm{PERI}_i + e_i$$

In the model, VEGE represents vegetation; PREC denotes precipitation; TEMP denotes temperature; BLDG denotes building; CAMP denotes campground; ROAD denotes roads; AREA is the area of the i-th unit; PERI is its perimeter; and e is the random error term.

According to the χ^2 test on the estimated coefficients of the basic model, vegetation, temperature, roads, campgrounds, and perimeter are statistically significant in the distribution of wildland fires. This model generates a 60 percent level of maximum forecasting accuracy.

In addition to the above list of variables, the study model also employs a spatial factor of neighborhood effect defined by contiguity. The inclusion of this spatial factor in the study model significantly improves model performance in both log likelihood test of logistic regression and forecasting accuracy. The study model increases the maximum forecasting accuracy to 97 percent. The most important variables identified in the study model are the spatial factor of neighborhood effects and vegetation. The results suggest that neighborhood effects play a very important role in the distribution of wildland fires and must be incorporated in the model of fire occurrence probability.

An immediate application of the model is the delineation of critical zones of fire danger. In this study, a critical zone is defined as an area within a short distance from human structures where the probability of a major fire occurring is excessively high (Chou, 1991b). Figure 3 depicts the distribution of fire occurrence probability classified into three general classes of probability. Critical zones can be delineated by overlaying the map of fire occurrence probability and that of human structures (Chou, 1992).

Additional efforts were made to examine the effects of map resolution on the measure of spatial autocorrelation. A series of grids covering the study area that vary systematically in resolution (i.e., the number of cells in a grid) was created. Maps showing wildland fire distribution at different resolution levels were created by overlaying the map of wildland fires onto all the grids, and spatial autocorrelation was evaluated from the overlays. Statistical tests clearly identified a log-linear relationship between map resolution and spatial autocorrelation (Chou, 1991c), such that

$$I = \beta_0 + \beta_1 \log_2 RL$$

where I is Moran's I coefficient of spatial autocorrelation; RL denotes the resolution level of a map; and β_0 and β_1 are estimated coefficients. The most important implication of this finding is that scale effects must be separated from neighborhood effects in the applications of spatial autocorrelation statistics.

SPATIAL STRATEGIES OF MANAGEMENT

The fourth project in the series is entitled "Effective spatial strategies in wildland fire management: a GIS spatial analysis." This project, started in September 1991, is expected to be completed in 1993. The central theme of this project is the design of cost-effective spatial strategies for fire prevention and suppression.

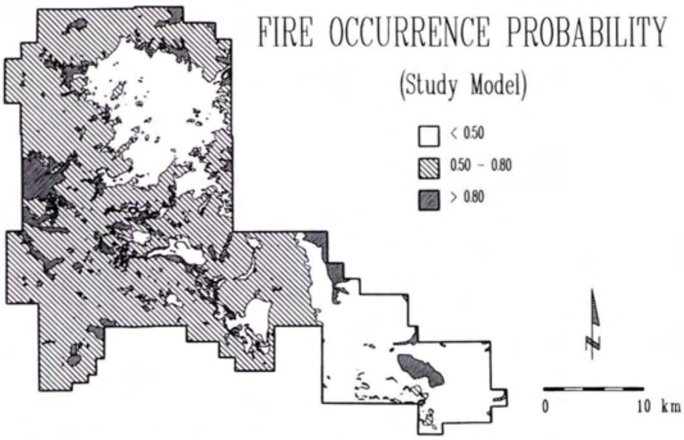

FIG. 3. Distribution of fire occurrence probability based on the study model.

With the San Jacinto database completed in 1990, this project is based on the entire district rather than any subarea.

The evaluation of spatial strategies of fire management was based on the distribution of fire occurrence probability (Chou, 1991d). Two principal criteria were considered in comparing alternative strategies. First, a spatial strategy is effective if it minimizes the degree of fire danger for the entire district. Second, the effective strategy must create a spatial pattern in which areas of high fire danger are scattered throughout the district rather than clustered together. A scattered pattern of fire danger zones is desirable because such a pattern minimizes the threat of uncontrolled conflagration.

Two measures were defined according to the above criteria. First, the area-adjusted average of fire occurrence probability for the entire district was defined as the index of district fire danger. Second, Moran's I coefficient of spatial autocorrelation was used to evaluate spatial patterns. The desirable, scattered pattern is associated with a lower level of spatial autocorrelation. With these measures, different spatial strategies of prescribed burning could be evaluated objectively (Chou, 1992).

ANALYSIS OF POST-FIRE MANAGEMENT

Another ongoing project, entitled "A spatial analysis of post-fire management in the Stanislaus National Forest," was started in July, 1990 and will be completed by December, 1993. The objective of this project is to evaluate the impacts of different post-fire treatments on slope protection, soil conservation, and forest regrowth.

As expected, most efforts at the first stage were made on the construction of the Stanislaus database. Twenty basins of varying types and degrees of post-fire treatments, such as salvage logging, were identified from the study area. Each basin is treated as a geographic unit for analysis. By the end of 1991, the following data layers were completed for each basin: topography, vegetation, surface disturbance, roads and trails, watershed, hydrology, and dams. Sedimentation was measured at each dam and preliminary evaluation of sedimentation related to salvage logging was completed (Wells *et al.*, 1991). Currently, the database is being used to evaluate post-fire management in a series of statistical analyses, including cluster analysis, analysis of variance, and multiple regression.

EVALUATION AND RECOMMENDATIONS

The USFS/UCR joint research program has shown that modern GIS technology can be utilized as an effective tool for wildland fire management. Once a database is constructed, a large-scale management plan can be made by building a probability model of fire occurrence, calibrating the best-fit model to delineate critical zones of fire danger, evaluating the cost-effectiveness of alternative spatial strategies of prevention and suppression, and designing effective spatial strategies for the management plan. Conditions of fire ecology change from time to time due to seasonal variation in environmental factors and changes in land use and the urban-wilderness interface. As such, the GIS approach has an important advantage in that the database can be updated as frequently as new data are available and the model of fire occurrence can be revised accordingly. Consequently, the distribution of fire danger zones and the spatial strategies of management can all be updated adequately.

Although it may take eight to ten years to achieve the ultimate goal of making GIS a practical tool for wildland fire management, the cooperative projects of this research have shown that such a complicated, large-scale GIS project can be designed into modules of smaller scale in order to maximize the feasibility and flexibility of each project. As long as the ultimate goal is clearly specified, each project can take the results of previous projects, make necessary revisions on the tasks of the next step, and evaluate the results at the end of the project.

The construction of a GIS database is time consuming and costly. Nevertheless, a suitable database is necessary for valid studies of any spatial phenomenon as complicated as wildland fires. In this research, the first project on database construction took five years to finish while each of the remaining projects on data analysis required about two years. The successful experience of the joint research has proven that, with a well organized plan, projects of statistical analyses and model building can be conducted even before the database had been completed.

Along the lines of this research, the following are of utmost importance for further projects. First, additional data layers on local winds and existing management practice must be constructed. Second, models of fire behavior that relate the spread of a fire to current ecological conditions must be examined and incorporated into the model of fire occurrence probability. Third, once local winds, management practice, and fire behavior have been incorporated, user friendly GIS procedures must be developed for making quick-response decisions on suppression. Finally, in the long run, the database must be extended to including the temporal dimension in order to build a dynamic model of fire occurrence probability.

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