Allocating Fire Mitigation Funds on the Basis of the Predicted Probabilities of Forest Wildfire

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Abstract.—A logistic regression model was used with map-based information to predict the probability of forest fire for forested areas of the United States. Model parameters were estimated using a digital layer depicting the locations of wildfires and satellite imagery depicting thermal hotspots. The area of the United States in the upper 50th percentile with respect to predicted probability of forest wildfire was intersected with areas within 25 miles of rural communities needing economic assistance using a geographic information system. The proportion of total forest wildfire mitigation funds to be allocated to each national forest region was calculated as the ratio of intersected area in the region to all intersected areas nationwide.

Among the environmental issues confronting the United States in recent years, none has been more visible or compelling than the frequency and severity of forest wildfires in the Western States. This phenomenon is generally attributed to two causes: several years of widespread and intense drought and a century of aggressive fire suppression practices. These practices have resulted in a substantial accumulation of highly combustible woody material throughout much of the Nation's forested regions, particularly in the Western States.

Numerous agencies of the Federal Government participate in efforts to mitigate forest wildfire risks. Among them, Cooperative Forestry (CF), State and Private Forestry, and U.S. Department of Agriculture (USDA) Forest Service allocate Federal funds to regional, State, and community entities for mitigating wildfire risk and stimulating local economies. In particular, the Economic Action Programs (EAP) of CF seek rural communities to which funds may be allocated, directly or indirectly, to treat forested areas as a means of mitigating wildfire risk and building industrial infrastructure. Because sufficient funds are not available to satisfy all funding needs, EAP needs defensible methods for allocating funds.

The objective of the study was to develop a defensible procedure for determining the proportion of available funds to be allocated to the national forest regions of the USDA Forest Service. The allocation to each region was to be in proportion to the area of forested lands at risk of wildfire that were in close proximity to rural communities that need economic assistance.

Methods

Data

A set of nationally consistent maps in the form of digital data layers was assembled and aggregated into three categories: Community, Ecosystem, and Fire. The Community category consisted of two layers: Populated Places and Economic Need. The Populated Places layer includes the locations and selected demographic attributes of populated places in the United States identified by the U.S. Census Bureau (ESRI 2002). Communities were selected based on CF's definition of rural communities as populated places with populations between 100 and 50,000. Selecting areas of high forest wildfire risk in close proximity to these communities, defined as a distance of 25 miles or less, simultaneously accomplishes two objectives: first, it identifies communities that are at risk of loss due to forest wildfires, and second, it identifies communities with labor forces that are sufficiently close to high wildfire risk to implement treatment prescriptions. The Economic Need layer, based on county income information from the 1980, 1990, and 2000 decennial

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censuses, classifies counties into five categories. Using Geographic Information System (GIS) functions, an overall Communities layer was created that depicts areas of the contiguous 48 States within 25 miles of communities characterized as rural and in the three classes of the Economic Need layer corresponding to greatest economic need.

The Ecosystem category consisted of five layers: Total Biomass (TB), Removable Biomass (RB), Palmer Drought Index (PDI), Historical Natural Fire Regime (HNFR), and Fire Regime Current Condition (FRCC). TB is estimated using individual tree measurements on plots measured by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service. The FIA sampling design is based on a nationwide array of approximately 6,000-ac hexagons, each of which includes at least one FIA plot. These hexagons are derived from the former Forest Health Monitoring Program (FHM) array of approximately 160,000-ac hexagons, which in turn are adapted from the U.S. Environmental Protection Agency's EMAP hexagon array that tessellates the contiguous 48 States (White *et al*. 1992). TB is calculated for each FIA plot, and the mean over all plots in each FHM hexagon is attributed to the hexagon as a whole. RB is an estimate of the biomass per unit area that could be removed from a forest stand to create more optimal forest conditions and partially addresses CF's desire to reduce forest fuels. RB is based on the concept of stand density index (SDI) (Reineke 1933, Avery and Burkhart 1994), a measure of forest stocking, and is estimated as the difference between observed SDI and 30 percent of maximum empirical SDI (USDA Forest Service 2003). Maximum stand density is based on the self-thinning rule (Yoda *et al*. 1963), which describes the maximum ecologically sustainable biomass on a per unit area basis. Greater overstocking is assumed to contribute to greater wildfire risk. As with TB, RB is estimated for individual FIA plots, and the mean over all plots in each FHM hexagon is attributed to the hexagon as a whole.

PDI indicates prolonged and abnormal moisture deficiencies or excesses for 350 climatic divisions in the United States (Heim 2000). On the PDI scale, 0 is normal, – 2 is moderate drought, – 3 is severe drought, and – 4 is extreme drought. PDI is an important tool for evaluating the scope, severity, and frequency of prolonged periods of abnormally dry or wet weather and has been used to indicate the potential intensity of forest fires. Mean PDI over June, July, August, and September was calculated for 2000, 2001, and 2002 for each climate division. From the climate division means, mean PDI was calculated for each FHM hexagon and attributed to the hexagon as a whole.

HNFR and FRCC are coarse-scale characterizations of pre-settlement natural fire return intervals and current vegetation conditions (Schmidt *et al*. 2002). The concept of risk is defined in terms of losing key components that define a system as a result of either wildfire or prescribed fire. Current conditions are characterized in terms of departures from historical natural conditions. These measures integrate biophysical information, remotely sensed products, and disturbance and successional processes including combinations of HNFR and potential natural vegetation (Hann and Bunnell 2001). HNFR describes the frequency and severity of pre-settlement fire processes in three categories of fire return intervals: less than 35 years, 35–100 years, and greater than 100 years. FRCC describes the relative risk of losing one or more key components that define an ecosystem in three categories of increasing wildfire risk (Schmidt *et al.* 2002). HNFR and FRCC are mapped at the resolution of 1-km^2 pixels, and classifications are assumed to be unchanging over periods of several years. The proportions of all 1-km^2 pixels in each FHM hexagon were determined for each category of both HNFR and FRCC.

TB and RB values were aggregated to the resolution of FHM hexagons to obtain enough plot observations to produce sufficient precision. HNFR and CFCC values were aggregated to the same scale for two reasons. First, aggregation reduced the size of the data set from approximately 180,000 records, each representing 1 km^2, to a more manageable data set of approximately 7,500 records, each representing approximately 64,800 ha. Second, the assumed low accuracy of the HNFR and CFCC classifications for the 1-km^2 pixels was expected to introduce an unacceptable level of measurement error into the predictor variable set. Aggregation at a coarser spatial scale alleviated some of this problem. Thus, because aggregation was considered necessary, and because TB and RB were already aggregated to the resolution of FHM hexagons, PDI, HNFR, and FRCC were also aggregated to the same resolution.

The Fire category consisted of two layers: fire perimeter data obtained from the Geospatial Multi-Agency Coordination (GeoMAC) Wildland Fire Support site (DOI and USDA 2003) and thermal data obtained from satellite imagery. The scarcity of appropriate wildfire location data makes it difficult to calibrate national models for predicting the probability of forest wildfire. One of the few appropriate sources, GeoMAC, depicts the locations and perimeter boundaries of 2000, 2001, and 2002 forest fires on Federal lands that were sufficiently large to be recorded by geographic information specialists working on the fires. Although the layer provides excellent coverage for Western States, it includes only three fires in the Eastern United States, all of which were in close proximity to each other. Therefore, a second layer not specific to Federal lands was obtained from the Remote Sensing Applications Center, USDA Forest Service, and was used as a surrogate for fire locations and sizes. This layer, based on the thermal band of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor, identifies locations of summer 2001 and 2002 thermal hotspots. Variables related to presence or absence of fires for the GeoMAC and MODIS hotspots layers were also aggregated for FHM hexagons. If a hexagon included any portion of the perimeter of a fire recorded by GeoMAC, a variable was coded 1; otherwise, the variable was coded 0. Although the MODIS hotspots layer depicts the locations of forest wildfires, it also depicts the locations of prescribed burns and prairie, agricultural, and other fires. Thus, four MODIS hotspots fire variables were created, one corresponding to each of the threshold values of 6, 8, 10, and 12 hotspots per FHM hexagon. For each variable, if the number of hotspots equaled or exceeded the threshold value, the variable was coded 1; otherwise, the variable was coded 0.

Models

Predictions of the probability of forest wildfire for each FHM hexagon were obtained by combining the Ecosystem and Fire layers using a logistic model,

$$E(P) = \left[1 + \exp\left(\beta_0 + \beta_1 X_1 + \ldots + \beta_m X_m\right)\right]^{-1}, \qquad (1)$$

where:

E(.) denotes statistical expectation,

P is the probability of a forest wildfire,

β is a vector of parameters to be estimated, and

X is a vector of predictor variables consisting of values of TB, RB, and PDI and proportions of pixels in FHM hexagons for each category of HNFR and FRCC.

The Statistical Analysis System (SAS) CATMOD procedure with the maximum likelihood option was used to estimate the model parameters. The model was calibrated twice: once for the two eastern national forest regions collectively and once for the six western national forest regions collectively. The model was separately calibrated for three reasons: first, the model was calibrated using the GeoMAC layer only for the western regions because of the inadequate number of observations for the eastern regions; second, the model was calibrated separately for the western regions using the MODIS hotspots layers to facilitate comparisons of results with those obtained for calibration with the GeoMAC layer; and third, because of differences in species composition, topography, and forest management practices, relationships between the probability of forest wildfire and the predictor variables were expected to differ between the eastern and western regions. Thus, nine sets of model parameters were estimated: one set for the western regions using the GeoMAC layer; four sets for the western regions, one for each of the four MODIS hotspots threshold levels; and four sets for the eastern regions—one for each of the four MODIS hotspots threshold levels. Predictions for the five model calibrations for the western regions were compared by evaluating the similarity in the rankings of individual hexagons with respect to their predicted probabilities of forest wildfire.

Estimation

Using model [1] with estimates of the model parameters, the predicted probability of forest wildfire was calculated for July 2002 for each FHM hexagon, and a map depicting the 50 percent of hexagons with the greatest predicted probabilities of forest wildfire was constructed. Using a GIS, the selected areas from these maps were intersected with the Community layer depicting areas within 25 miles of rural communities in need of economic assistance. The proportion of EAP funds to be allocated to each national forest region was calculated as the ratio of the area selected for each region to the total area selected for all regions.

Results and Discussion

For the Western States, the maps depicting the predicted probabilities of forest wildfire using models calibrated with the four

MODIS hotspots variables were similar to each other and to the map obtained using the model calibrated with the GeoMAC variable. For each of the five maps, each hexagon was classified with respect to whether its predicted probability of forest wildfire exceeded probability percentiles ranging from 0.05 to 0.95 in steps of 0.05. Comparisons of the classifications of individual hexagons for each of the four MODIS-based maps to the GeoMAC-based map revealed that proportions of hexagons with the same classification always exceeded 95 percent. These results indicate that although the models calibrated using different fire location layers produced different predictions of the probability of forest wildfire, the relative rankings of the hexagons with respect to percentiles of the probability predictions were very similar. Thus, for the western regions, the MODIS hotspots data layers were concluded to be acceptable surrogates for forest fire locations for ranking the hexagons.

The greatest similarity between rankings with the GeoMAC variable and a MODIS variable was obtained for the MODIS variable corresponding to a threshold value of eight hotspots per hexagon. Thus, this MODIS variable was used as a surrogate for the presence or absence of a forest wildfire for calibration of the model for the two eastern regions also. A map depicting areas of the country in the upper 50^{th} percentile with respect to the probability of forest wildfire was constructed by selecting the hexagons at or above the median predicted probability separately for the Eastern and Western United States (fig. 1). The map indicated much more area with high relative probabilities in the Southeastern United States than the Northeastern United States, but the area with high relative probabilities was more concentrated in the western regions. Because separate models were calibrated for the eastern and western regions, the relatively greater amount of area selected in the Eastern United States should not necessarily be construed to mean that more area is at greater risk of wildfire in the East. This phenomenon may possibly be attributed to different calibration data sets, responses to predictor variables, species compositions, forest management practices, and climate.

This digital layer corresponding to the upper 50^{th} percentile of the country relative to the probability of forest wildfire was intersected with the Community layer (fig. 2). Proportions of funds to be allocated to national forest regions were calculated as the ratios of areas in the intersections for a particular national forest region to the collective area of the intersection for all national forest regions. Based on the intersected areas, the proportional allocations were estimated for the East as 0.739 to Region 8 and 0.261 to Region 9, and for the West as 0.216 to Region 1, 0.211 to Region 2, 0.220 to Region 3, 0.084 to Region 4, 0.129 to Region 5, and 0.141 to Region 6 (fig. 2).

Figure 1.—*Percentile identity of hexagons with respect to relative probability of forest fire for July 2002 (light gray = nonforest; dark gray = 50% of forested area with smallest predicted probabilities; black = 50% of forested area with greatest predicted probabilities; white = hexagons with eight or more MODIS hotspots in 2002).*

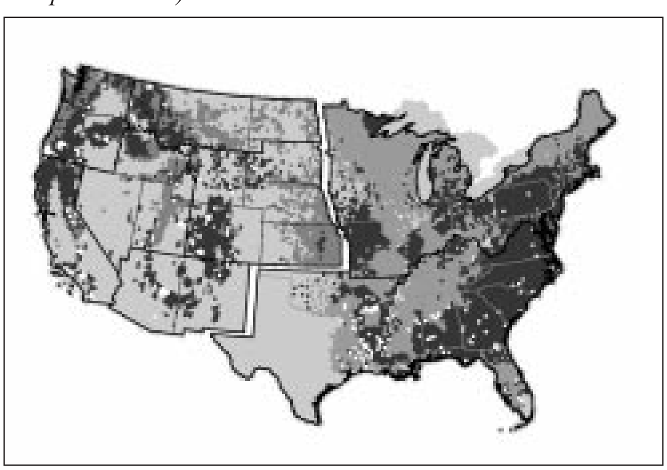
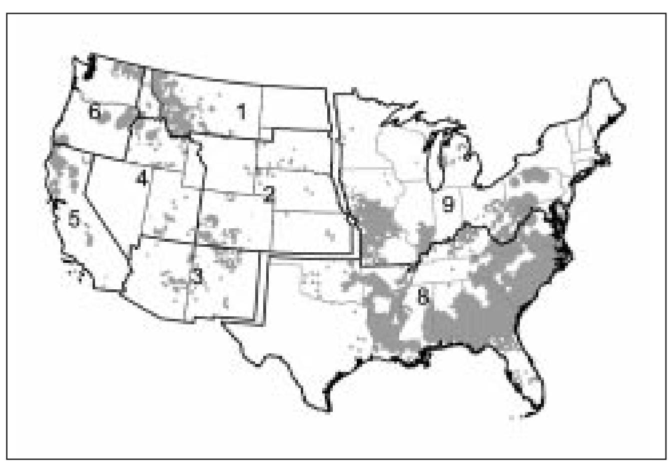


Figure 2.—*Areas with the 50% largest predicted probabilities of forest wildfire for 2002 within 25 miles of a rural community needing economic assistance (light gray); numerals refer to national forest regions.*



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