GIS-Based Habitat Modeling Using Logistic Multiple Regression: A Study of the Mt. Graham Red Squirrel

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ABSTRACT: Multivariate statistical techniques were applied to the development of habitat suitability models for the Mt. Graham red squirrel, an endangered species. A digital map database and a Geographic Information System (GIS) were used to support the analysis and provide inputs for two logistic multiple regression models. The models attempted to predict squirrel presence or absence, the dichotomous dependent variable. Independent variables were a set of environmental factors in the first model, and locational coordinates in the second case, where a logistic trend surface was developed. Bayesian statistics were then used to integrate the models into a combined outcome. Potential habitat losses resulting from development of an astronomical observatory were assessed using the environmental model and were found to represent about 3 percent of the currently available habitat.

INTRODUCTION

THE MOUNT GRAHAM AREA, in the Pinaleno Mountains of Graham County, Arizona, 200 km northeast of Tucson, is the third highest mountain in the state, having a maximum elevation of 3278 m at High Peak (Figure 1). The USDA Forest Service is responsible for land management of the area, a part of Coronado National Forest. In 1984 the University of Arizona's Steward Observatory concluded a nationwide search for a site on which to build a new astronomical observatory by identifying Mt. Graham as its preferred location (Columbus Project Science Advisory Committee, 1987). Subsequently, the University submitted an astrophysical site and facility development proposal to Coronado National Forest.

Mt. Graham is an exceptionally interesting mountain from a biogeographic and ecological standpoint. Its steep relief creates the sharpest ascent from desert grassland to spruce-fir forest in Arizona. Chaparral, oak woodland, ponderosa pine, and mixed conifer occur as intermediate life zones. Floristic composition of vegetation communities is influenced by both Neartic and Neotropical floras: the spruce-fir forest is the southernmost pure stand in North America and, at the life zone immediately below, Chihuahuan and Mexican white pines of the mixed conifer zone are at the northern extreme of their distribution area. Biogeographic isolation of the Pinalenos in general, and Mt. Graham in particular, restricts gene flows of several species, giving the mountain a "sky-island" character that facilitates the evolution of endemisms among both plants and animals. One of these is an endangered sub-species of red squirrel, Tamiasciurus hudsonicus grahamensis, the Mt. Graham red squirrel (U.S. Forest Service, 1986).

Concern over the preservation of Mt. Graham's unique ecological values led Coronado National Forest to conclude that Steward Observatory's initial proposal was unacceptable due to its potential negative environmental impacts. Long-term survival of the red squirrel was of paramount importance because part of the proposed development would affect the species' prime habitat. An extensive environmental impact assessment study was initiated by the Forest Service (U.S. Forest Service, 1986), while Steward Observatory revised its proposal, eliminating some of the buildings. The revised project will have two phases. The first will include construction of a new road, facilities for three telescopes, and logistic support structures. The second phase will involve adding three more telescopes, one support building, and a movable interferometer array.

Considering the complex, multidisciplinary character of the resource management problem posed by Steward Observatory's proposal, the U.S. Forest Service Coronado National Forest funded an independent study of habitat for the Mt. Graham red squirrel through the University of Arizona's School of Renewable Natural Resources. That analysis represented a small part of the impact assessment process implemented by the U.S. Forest Service and was meant to determine habitat suitability using quantitative, georeferenced data and assess potential red squirrel habitat and population losses due to project implementation. It was designed to assist U.S. Forest Service personnel with evaluating impacts of observatory facilities and access road locations.

This paper describes the core of the study. The specific objectives were to predict the probability of red squirrel pres-

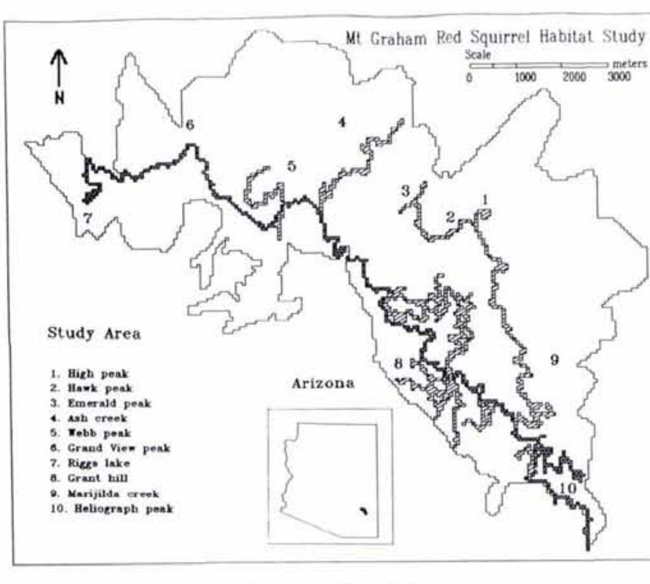

FIG. 1. Map of the study area.

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ence or absence, based on a series of environmental and locational descriptor variables. We hypothesized that these variables could explain the spatial patterns of red squirrel habitat use as observed in the U.S. Forest Service's 1986/87 winter survey. It was assumed that probability of squirrel presence could be taken as a measure of habitat suitability, and that habitat losses would be used as a proxy indicator of potential population losses.

The Habitat Evaluation Procedures/Habitat Suitability Indices (HEP/HSI) (U.S. Fish and Wildlife Service, 1980,1981), a structured framework for habitat evaluation developed in the mid-1970s by the U.S. Fish and Wildlife Service, was used in the analysis. Lancia *et al.* (1982) remark that HEP/HSI models are often left untested, or are tested with inappropriate criteria. One of the most frequently used validation methods relies on consulting with experts on the species of concern, who are asked to examine model predictions and judge whether they are satisfactory. Because these models are usually built in a deductive manner, based also on expert knowledge, the entire process becomes highly circular. Multivariate statistical models, being inductive, empirical models, when appropriately tested against real habitat use data (Schamberger and O'Neil, 1986) offer the potential to minimize validation problems and were therefore the approach selected for the present study.

BACKGROUND

Red Squirrel Ecology

The Mt. Graham red squirrel study area, as designated by the U.S. Forest Service (U.S. Forest Service, 1988), covers approximately 6460 hectares of the upper part of the mountain. This site ranges in elevation from 2275 m to 3278 m and is characterized by a series of rolling areas surrounded by steep edges and narrow canyons, especially along the northern and eastern edges. Major land-cover types are conifer forests (spruce-fir, mixed, and ponderosa pine), small patches of aspen, meadows, cienegas, and rock outcrops (U.S. Forest Service, 1986). The relationships between the endangered red squirrel and its environment are primarily shaped by the need for appropriate food sources and cover conditions.

The Mt. Graham red squirrel's diet is not well known, except for the importance of conifer seeds from closed cones and limited evidence indicating that at least eight species of mushrooms are also consumed (U.S. Forest Service, 1988). Seed productivity of Mt. Graham conifers was ranked by Jones (1974), with Douglas-fir as the most productive species, followed by Engelmann spruce, corkbark fir, and lastly Ponderosa pine and White pine. Engelmann spruce and corkbark fir are considered the main suppliers of food to the red squirrel (U.S. Forest Service, 1988).

Red squirrels are territorial animals, very aggressive toward both conspecifics and other species of tree squirrels (Flyger and Gates, 1982). Size estimates of the average activity area vary between 0.5 and 1.0 hectares. Territoriality is expressed as central place foraging behavior, meaning that harvested cones are carried to a central place of the territory or activity area, where they are piled up or buried for winter and the following year's supply (U.S. Forest Service, 1988). These piles, or middens, consist not only of cones but also scales, cone cores, and sometimes needles (Hoffmeister, 1986). It is critical that cones remain humid; otherwise, they crack open and the seeds become susceptible to theft by other animals. Therefore, red squirrels look for damp, shaded spots (Rothwell, 1979), requirements that make obvious the role of tree cover and topography in habitat selection.

Favorable environmental conditions are especially necessary for the Mt. Graham sub-species because the Pinaleno Mountains, located at 32° N latitude, are the southernmost situation for both a continuous spruce-fir forest and a red squirrel population in North America. Therefore, more solar radiation reaches the top of the canopy layer here than anywhere else on the red squirrel's distribution range, and good habitat at the forest floor level can only be created when tree crowns intercept a large part of the incoming radiation. This seems to be in agreement with observations that the Mt. Graham red squirrel is very selective in choosing locations, not only for midden placement but also for general activity areas (U.S. Forest Service, 1988).

GIS in Wildlife Habitat Studies

Given the explicit importance of spatial habitat parameters in the Mt. Graham red squirrel ecology, it was decided to use Geographical Information Systems (GIS) technology as an aid to data management and analysis. A brief review of applications of GIS in wildlife habitat analysis work is provided, in order to set this paper in the broader context of a rapidly growing research field.

Lancia *et al.* (1986), Davis and DeLain (1986), and Ormsby and Lunetta (1987) used GIS in wildlife habitat studies, following the U.S. Fish and Wildlife Service Habitat Evaluation Procedures/Habitat Suitability Indices framework. Lancia *et al.* (1986) developed spatial models to assess habitat quality for three bird species, using georeferenced environmental data to create habitat suitability maps. These maps were validated by comparison with maps of observed frequency of habitat use. Better results were obtained for common, range restricted, or more specialized species, than for rare, wide-ranging, and/or more generalized forms.

Davis and DeLain (1986) used a GIS database as the key element to linkup wildlife habitat models with the ECOSYM forest planning system. They developed arithmetic HSI for the spotted owl in two spatial databases, and included habitat suitability maps in a cost-benefit analysis of timber management alternatives.

Lyon *et al.* (1987) presented three spatial habitat analysis models, one of which was supported by a multiple variable GIS database. They analyzed habitat suitability for the wood duck (Aix sponsa) in a forested wetland using topographic, vegetation, hydrologic, and infrastructure data. Model calibration, verification, and parameter sensitivity analysis are emphasized as necessary requirements of habitat modeling. These tasks are performed for a kestrel falcon non-GIS habitat model, whose performance was evaluated by comparison with both expert opinions and field habitat use and population data.

Ormsby and Lunetta (1987) developed whitetail deer food availability maps from Thematic Mapper land-cover digital data. These data were integrated with other cartographic information in a GIS and provided input to an arithmetic, expert-based habitat suitability model. Palmeirim (1988) used Landsat TM remote sensing data and a geographic information system to map avian species habitat, considering not only land-cover types but also habitat spatial characteristics, such as minimum patch size and distance to edge. These data were combined with bird counts to automatically generate distribution, suitability, and density maps, and to produce estimates of population size.

Broschart *et al.* (1989) used a stepwise multiple regression model to predict the density of beaver colonies in boreal landscapes, by relating vegetative and hydrologic landscape patches resulting from beaver impoundments with beaver presence/absence. They emphasize the usefulness of their results to estimate beaver abundance and determine historical and present population trends.

Hodgson *et al.* (1988) inventoried and analyzed availability of wetland foraging habitat for the wood stork, and its variability between wet and dry years.

METHODS

THE DIGITAL DATABASE

Figure 2 summarizes the overall analysis procedure followed in this study, from the selection of environmental variables and database development, to habitat suitability analysis and impact assessment. Detailed descriptions of the steps represented in this flowchart are provided throughout the text.

Digital cartographic data capable of supporting analysis and decision making, and based on previously collected information, were assembled. Elevation (Figure 3a) and road network (Figure 3e), as well as project location data (Figure 4f), were digitized from USGS 7-1/2 minute quadrangles. Vegetation data (Figures 4a to 4d) and squirrel activity data (Figure 3d) were digitized from a U.S. Forest Service stands map and a U.S. Forest Service survey map, respectively. The study area boundary was delineated by Coronado National Forest personnel while censusing the red squirrel population and habitat and does not correspond to any political or administrative units. Topography, vegetation, and road network are the major determinants of the study area shape. All maps were referenced to the UTM rectangular coordinate system and were available at a scale of 1:24,000 (Pereira, 1989). Digitization was performed with the CADGRID software package (Itami, 1988).

The elevation, road network and project location, vegetation, and squirrel activity data were transfered to the Map Analysis Package (MAP) (Tomlin, 1986), a PC-based raster geographic information system. MAP was used to develop a set of nine other layers using various GIS operations. Slope and aspect maps were derived using the DIFFERENTIATE and ORIENT operations, respectively. Both maps contain continuous interval data, with slope measured in percent values and aspect in degrees azimuth, but were categorized for display purposes (Figure 3b and 3c). Because aspect refers to angular data, this variable was transformed to a format suitable for conventional statistical analysis by decomposing the information for each cell into a north-south and an east-west component (Pereira, 1989).

The vegetation-related maps, land-cover types, canopy closure, food productivity, and tree diameter at breast height (d.b.h.) were obtained using the RECODE operation on the original Forest Service stands map. The first of these maps contains nominal information, while the others use ordinal scales (Figures 4 to 4d). The roads map (Figure 3e) was combined with the canopy closure map (Figure 4c) to produce the distance to openings map (Figure 4e). The squirrel activity map (Figure 3d) is a binary presence/absence map, and the project location map (Figure 4f) simply displays the location of project phases 1 and 2.

A cell size of 0.5 ha, corresponding to a length of 70.7 m on a side, was selected, resulting in a minimal bounding rectangle of 164 rows by 193 columns, for a total of 31,652 grid cells. Of these, 12,920 are contained within the study area and 18,732 outside of it. Three reasons dictated the choice of a cell size of 0.5 ha. First, it corresponded approximately to the smaller sizes of the range of red squirrel activity areas, which was the basic unit of analysis of the study. Second, mapping accuracy in the original map of activity areas provided by the Forest Service made it unadvisable to use a smaller cell size. Third, there were software limitations imposed by MAP. It cannot handle arrays larger than 32,767 grid cells, very close to the total actually used for the Mt. Graham data base (Pereira, 1989).

STUDY DESIGN

Given the binary nature of squirrel activity data, logistic regression or discriminant analysis are suitable modeling techniques but, because available data on some of the independent variables (e.g., food productivity, canopy closure, d.b.h.) are qualitative and non-multivariate normal, logistic regression was considered as more appropriate (Press and Wilson, 1978).

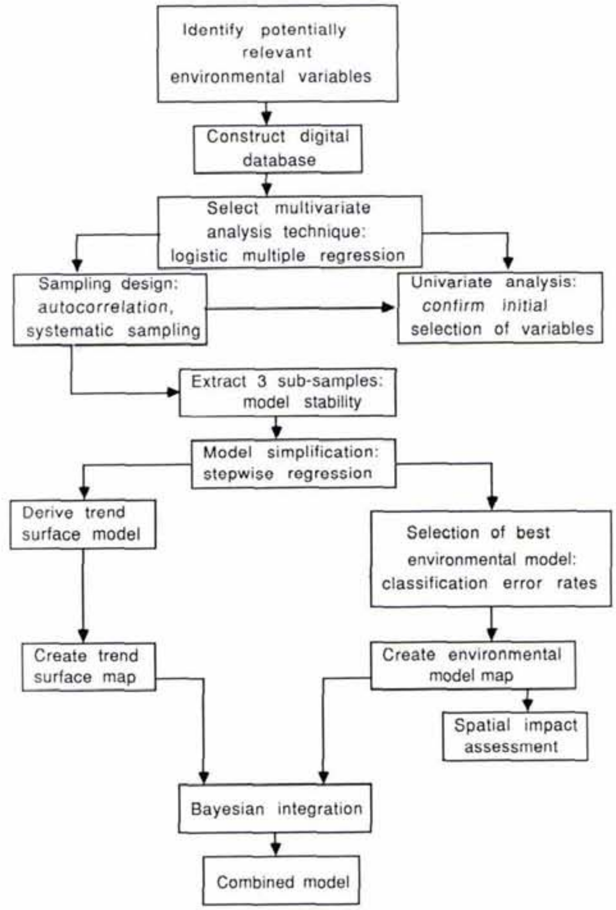

FIG. 2. Flowchart of the study design and data analysis strategy.

Kvamme (1985) used univariate statistical tests to assess the validity of individual model variables and obtained a better understanding of each variable's role before proceeding with global model development and testing, a procedure that is also recommended by Schamberger and O'Neil (1986). It is necessary to find out whether red squirrels actually discriminate among sites based on environmental factors considered relevant on an *a priori* basis. If they do, mean values of environmental variables at locations that squirrels have selected as favorable habitat should differ from mean values obtained from locations taken randomly from the background environment, as well as habitats they avoided. Additionaly, the variance of the data would be smaller for selected locations than for the background environment (Kvamme, 1985).

Identification of such an active, non-randomly patterned habitat selection process requires the establishment of a control group, randomly selected from the population of all available sites avoided by squirrels, against which the data for selected habitat locations can be compared. The sample data for both univariate and multivariate statistical analyses were taken from digital database maps. Henceforth, database grid cells where squirrel activity is present will be refered to as "sites" or "active cells," while those from where squirrels are absent will be called "non-sites" or "inactive" cells. The sample data can be conceptualized as a two-way table or matrix, with observations (grid cells) as rows and cell descriptors as columns. These descriptors include environmental variables of the data base overlays, the

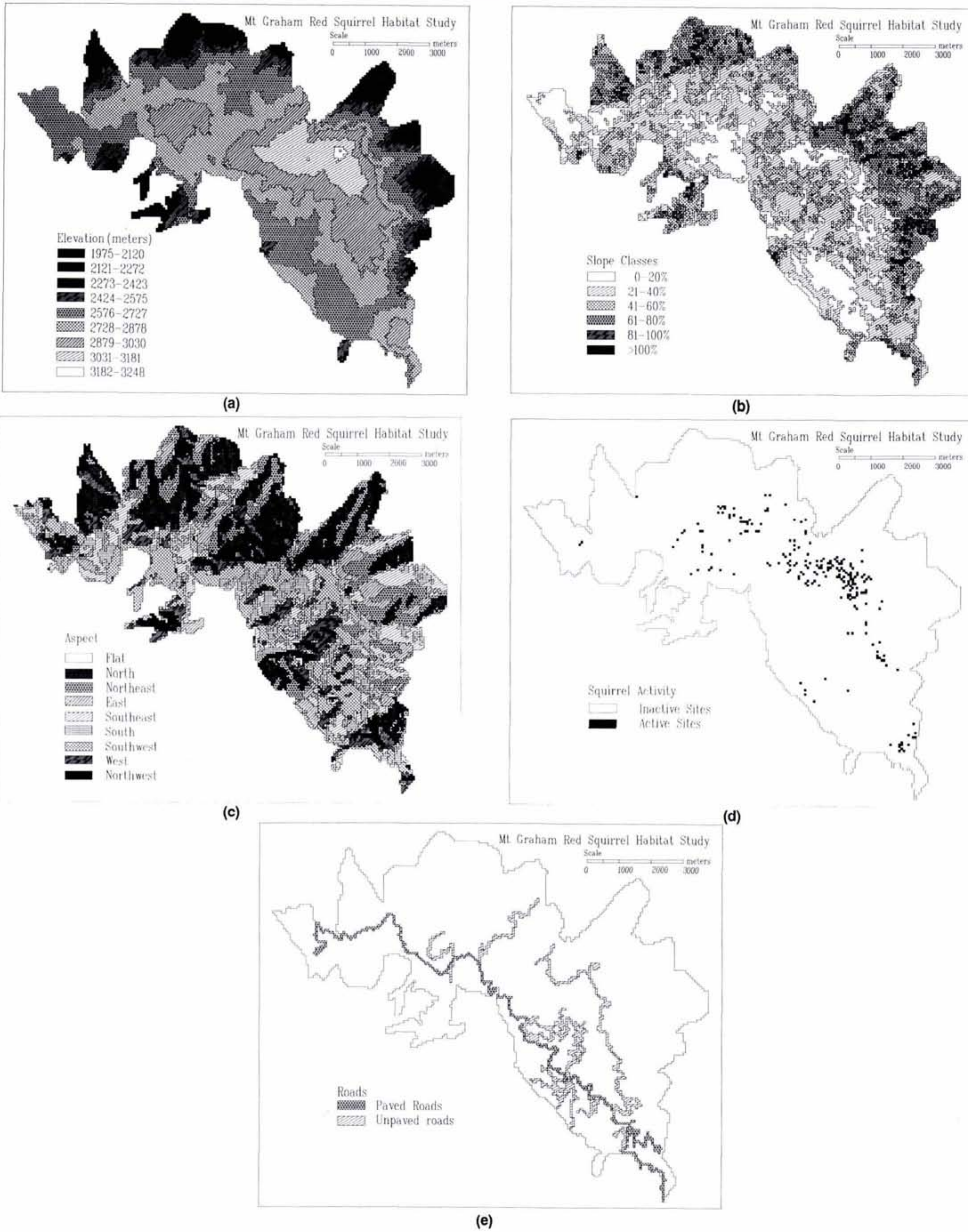

FIG. 3. Database maps of (a) elevation, (b) slope, (c) aspect, (d) squirrel activity, and (e) road network.

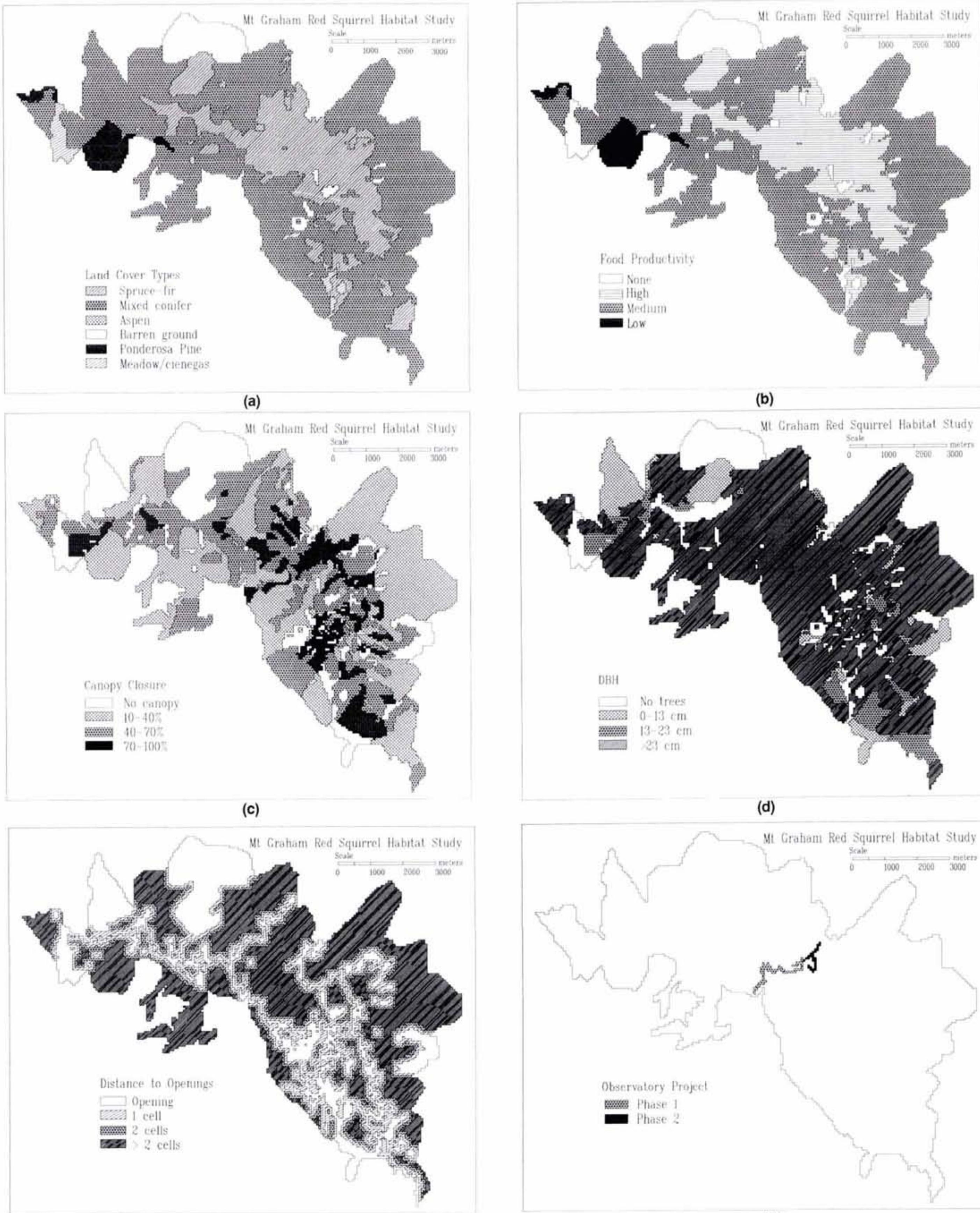

FIG. 4. Database maps of (a) land-cover types, (b) food productivity, (c) canopy cover, (d) tree diameter at breast height (d.b.h.), (e) distance to clearings, and (f) project location.

cells' x and y coordinates, and an indication of presence (1) or absence (0) of squirrel activity.

Two major considerations affected sampling design. Because non-site locations correspond to the vast majority of the study area (Figure 3d), larger variation is expected in environmental attributes for this group. A ratio of non-sites to sites larger than one is therefore desirable (Kvamme, 1985). There are 212 active cells in the database and, therefore, the sample should include a value larger than that for inactive cells. On the other hand, the spatial autocorrelation structure in the independent variables had to be considered in order to assess how to minimize it through systematic sampling (Haining, 1980). Moran's I coefficient (Cliff and Ord, 1981; Upton and Fingleton, 1985), as implemented in the AUTOCORR procedure of the IDRISI GIS package (Eastman, 1987), showed that, for a first-order lag, spatial autocorrelation values for each independent variable were close to unity, but when a seventh order lag was reached, Moran's I had dropped to values between 0.34 for the elevation overlay, down to 0.16 for the slope overlay. A systematic sampling scheme was then followed, where each seventh cell in the database was selected, in both row and column directions. This yielded a sample of 259 non-site cells.

Environmental Model

Two kinds of logistic multiple regression models were developed, one using environmental factors as explanatory variables, and the other a logistic trend surface model, a simple interpolation procedure that uses row and column cell values as independent variables. The categorical nature of the vegetation descriptors (food productivity, canopy closure, and d.b.h.) requires their recoding as dummy variables prior to inclusion in any regression model. Each one of these variables has four categories and must then be recoded to three dichotomous dummy variables (Wrigley, 1985), for a total of nine new variables.

The full environmental model includes these nine variables plus elevation, slope, aspect N-S, aspect E-W, and distance to clearings, for a total of 14 variables. Concern over model stability, which requires a high ratio of number of observations to number of variables, led to the use of three random sub-samples of the original data matrix. Out of each sub-sample, 75 percent of the data were used for training purposes, and 25 percent were left out for independent model validation. Each sub-sample was subjected to stepwise regression in order to simplify the full specification and generate more parsimonious models. Both backward ("p-to-leave" = 0.00) and forward ("p-to-leave" = 1.00) procedures were applied, resulting in a total of six environmental models.

Classification error rates, used to evaluate how well a model fits new samples of data from the same or similar populations, test the percentage of correct predictions on an independent sample. In order to do this, the interval-scaled outputs of the logistic regression model, measuring probability of success (i.e., probability of a sample cell being suitable habitat), are converted to dichotomous 0-1 data through specification of cut-off point. Any cells with values below a given cut-off are considered unsuitable while all above become suitable. This test measures what percentage of cells predicted to be suitable actually contain squirrel activity and, conversely, the percentage of cells predicted to be unsuitable from where squirrels are indeed absent. Moving the cut-off points along the [0,1] probability interval allows estimates of optimal cut-off points to be made by identifying the values for which most successes are correctly classified, while minimizing the number of failures.

Trend Surface Model

The trend surface model (Wrigley, 1976) for habitat suitability analysis is a multiple logistic regression model that uses a fourth-order polynomial of the x (column) and y (row) coordinates of the grid cells as explanatory variables. The polynomial's order determines the complexity (number of "bends") in the resulting probability surface and therefore controls how closely the model will fit the data. A fourth-order polynomial was deemed adequate to describe the general nature of the locational trend in squirrel habitat use, and the trend surface was developed using the same sample of data that yielded the best environmental model.

Bayesian Integrated Model

The environmental and trend surface models were combined using Bayesian statistical inference techniques. This is a technique commonly used in remote sensing where, for example, topographic information provides prior probabilities of a pixel containing a given vegetation type, and then spectral information is used to revise these probabilities, resulting in improved vegetation cover classification accuracy (Strahler *et al.*, 1978; Strahler, 1980). For the Mt. Graham habitat suitability analysis, the trend surface was treated as the generator of prior probabilities and the environmental model as a source of additional information used to revise these probabilities. The mathematical formulation of the procedure is (Maynard, 1981)

$$\text{Pnew} = \frac{1}{1 + e[\log(1 - \text{Penv}/\text{Penv}) - \log(\text{Ptrend}/1 - \text{Ptrend})]}$$

where Pnew is the new, revised probability estimate, and Penv and Ptrend are the probability estimates of the environmental and trend surface models, respectively.

RESULTS AND DISCUSSION

Univariate Analysis

Descriptive statistics for the interval-scaled variables are given in Table 1. Cumulative frequency graphs for the interval variables and the categorical variables are shown in Figure 5. The p-values given in Figure 5 were derived from two-sample t-tests (for the continuous variables) or from chi-square difference in proportion tests (for the categorical variables).

The univariate analysis confirms most expectations regarding the role of individual variables. Active cells are located at significantly higher elevations and gentler slopes. The north-south component of aspect was not a significant discriminator between suitable and unsuitable habitat, but cooler east-facing sites were preferred along the east-west component of aspect. Regarding vegetation characteristics, favorable habitat includes

Table 1 Sample Means, Medians, Variances, and Coeficients of Variation of the Mt Graham Data

	Active Sites (n = 212)			
Variables	Mean	Median	Variance	CV*
Elevation	9954.3	10170.0	269834.0	0.05
Slope	25.6	23.5	214.4	0.57
Aspect (E-W)	97.6	97.0	2605.2	0.52
Aspect (N-S)	94.3	90.0	2419.5	0.52
Distance	2.2	2.0	1.9	0.79
	Inactive Sites (n = 259)			
Variables	Mean	Median	Variance	CV*
Elevation	9020.6	9080.0	583536.0	0.08
Slope	44.0	39.0	884.8	0.68
Aspect (E-W)	85.0	80.0	2411.7	0.58
Aspect (N-S)	88.0	89.0	2431.2	0.56
Distance	4.0	2.0	33.2	1.43

*CV = Variance ½ × 100/Mean

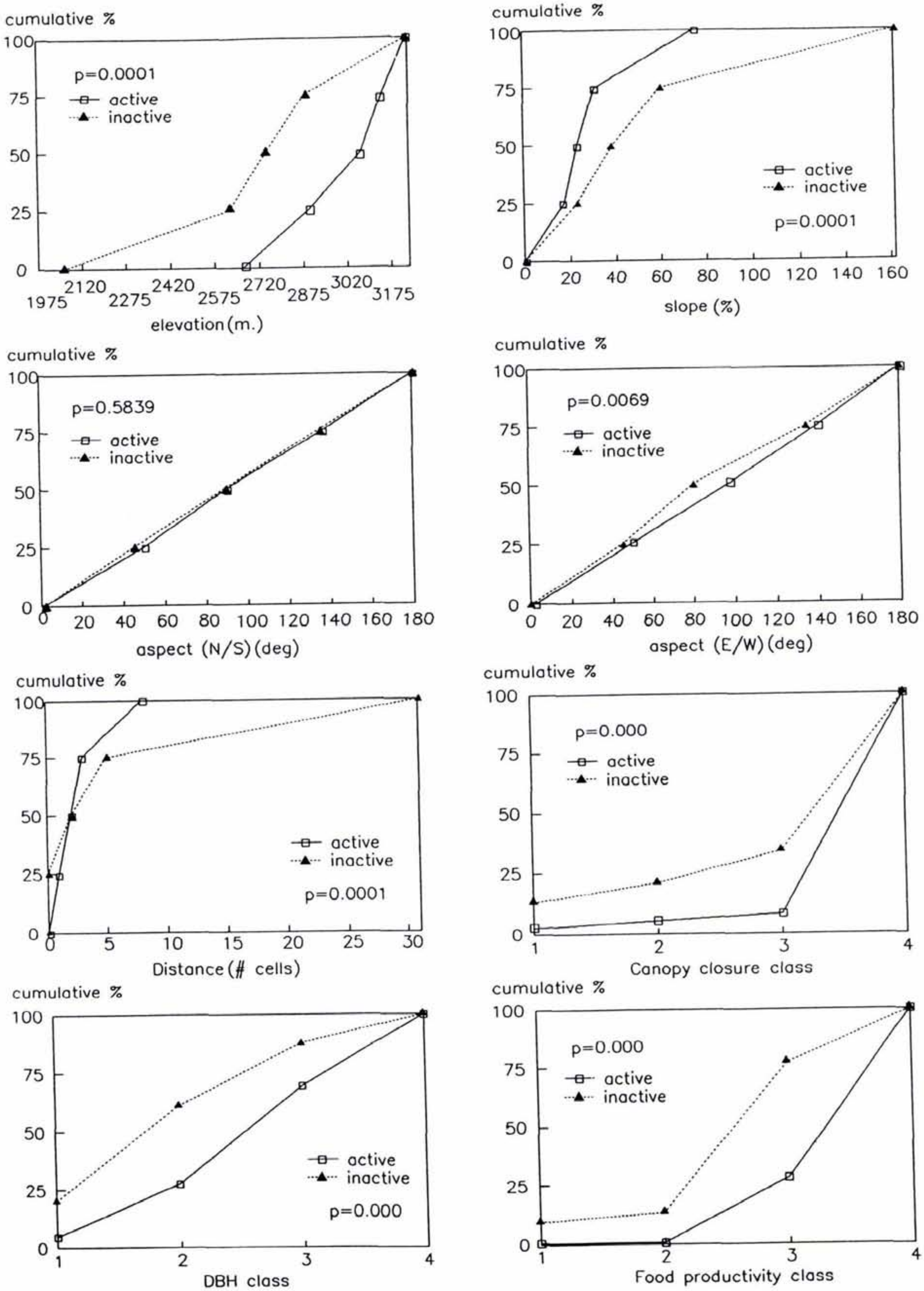

FIG. 5. Cumulative frequency graphs for model variables. For interval-scaled variables (elevation, slope, aspect (E-W), aspect (N-S), and distance to clearings) p-values are significance levels for t-tests of differences between mean values of site (active) and non-site (inactive) cells. For ordinal-scaled variables, p-values are significance levels for chi-square tests.

the more productive conifer cone vegetation types, as well as high d.b.h. and canopy closure classes (Figure 5).

Distance to openings was also a significant discriminator, but in the opposite direction to what was expected, i.e., the active cells are located closer to openings in the forest canopy than the overall environment. Because proximity to openings means more solar radiation and wind affecting the forest ground floor, creating dry, unfavorable conditions for cone storage, this result was apparently paradoxical.

Two explanations were plausible for this effect. It was possible that the negative impact of clearings decays so fast with distance that a cell size of 70.7 m on the side fails to capture it, but then this variable should not show up as an effective discriminator. The other likely explanation involves considering inter-variable correlations: the gentle slopes and high elevations favored by red squirrels were associated with the presence of roads that were built to provide access to the higher parts of the mountain and follow preferentially flat terrain. Most forest clearings in the areas of denser squirrel activity are road corridors and, therefore, the apparent preference of squirrels for clearings simply reflects the co-occurrence of squirrels and road corridors at high elevations on gentle slopes.

Environmental Model

Three models converged on formulations including elevation, slope, aspect E-W, and canopy closure as the statistically significant variables. The best of these models, at an optimum probability cut-off level of 0.4, correctly identifies 90 percent of the squirrel activity; at the same time only about 27 percent of the inactive areas are misclassified (Figures 6a and 6b), resulting in a model that would cover approximately 27 percent of the study area if it were mapped cell by cell. This represents a 63 percent improvement of predictive power over chance, because a worthless model that covers 27 percent of the landscape should only predict 27 percent of the sites correctly by chance; the fact that 90 percent are correctly predicted yields the 63 percent improvement over chance figure. The logistic model was represented by the equations

$$\begin{aligned} Y = {} & 0.002 \times \text{elevation} - 0.228 \times \text{slope} \\ & + 0.685 \times \text{canopy1} + 0.443 \times \text{canopy2} \\ & + 0.481 \times \text{canopy3} + 0.009\ \text{aspectE-W} \end{aligned} \quad (1)$$

and

$$p = 1/(1 + \exp(-Y)) \quad (2)$$

is the estimated probability of success, i.e., the probability of squirrel presence at a given cell. A habitat suitability map for the red squirrel was created by applying Equations 1 and 2 to the map overlays representing model variables. The result is a map of continuous probability values that was discretized into five categories and overlaid with the activity areas map to facilitate comparisons between observed spatial patterns of squirrel activity and model predicted suitability (Figure 7a).

The agreement between observations and predictions was very good, especially at the largest concentration of middens, on the highest part of the study area, around High, Hawk, and Emerald peaks (see Figure 1), and along the ridge extending south from High Peak. It was also very good around Heliograph Peak, in the southeastern edge of the study area, and at the headwaters of the northern branch of Marijilda Creek, north of Heliograph Peak and west of the main north-south ridge. Much moderate quality, and also some high quality habitat, was identified northeast of Webb Peak and around the headwaters of Ash Creek, but the agreement with habitat use was not as good as for the areas mentioned above. Besides these major clusters, the model also identified good quality habitat in the Grant Hill/Hospital Flat area and near Grand View Peak, where there is an isolated squirrel midden.

One of the most obvious differences between model predictions and observed activity can be seen at the northwest edge of the study area, near Riggs Lake, where two isolated activity areas are present in what the model predicts to be poor quality habitat. However, one of these areas corresponds to an inactive (temporarily or permanently abandoned) midden and the location is actually believed to provide poor habitat conditions (Randall Smith, pers. comm.).

It is interesting to notice how the environmental suitability map (Figure 7a) shows tight clustering of activity, with squirrels inhabiting contiguous cells in some high density areas that are, however, surrounded by unused regions of predicted high quality habitat. This may reveal the influence of factors undetectable at the present spatial scale of analysis, but that let squirrels discriminate within what the model considers equally suitable areas. According to Vahle and Patton (1983), d.b.h. may be such a variable but this could only be confirmed by higher resolution mapping and measurement of d.b.h. at higher precision.

Trend Surface Model

Results of the trend surface model are shown in Figure 7c. Classification error rates (Figures 6c and 6d) show a maximum improvement over chance in predictive power of 57 percent at the 0.4 cut-off point, represented in the binary map of Figure 7d.

The high predictive power of the trend surface model may be due to the squirrel's tendency to form clusters in relatively well defined areas of good habitat. If intraspecific behavioral interactions account even partially for this clustering, then the trend surface captures an aspect of squirrel habitat use that is ignored by the environmental model.

Bayesian Model

Model performance statistics (Figures 6e and 6f) show that a probability level of 0.5 is the optimal cut-off point for a binary model, capable of correctly classifying 87 percent of the sites while covering only 24 percent of the study area, for a predictive improvement over chance of 63 percent. Although the Bayesian integration model has exactly the same predictive power as the environmental model alone, there are some differences among the two that are made clearer by comparing Figures 7a and 7b with Figures 7e and 7f. A Bayesian binary model defined at the optimum cut-off point captured a slightly smaller number of sites than an optimum binary environmental model, but also covers a proportionately smaller part of the study area. The shape of the Bayesian model revealed the influences of component models, with a clear smoothing of the higher probability areas of the central part of the study area due to the trend surface model. Transitions between lower suitability classes remain jagged and complex, primarily under control of the environmental model.

Spatial Impact Assessment

One of the goals of this study was to assess the amount and quality of red squirrel habitat that will be lost due to development of the astronomical observatory, with the underlying assumption that habitat losses can be used as a proxy measure for impact on long-term survival of the population. Squirrel habitat equivalents (U.S. Forest Service, 1988) is the concept that translates measurements of affected area into population impacts. Squirrel habitat equivalents equal the number of red squirrels that could be supported by a given habitat acreage, and are calculated by overlaying the project location areas (Figure 4f) on the environmental habitat suitability map (Figure 7a).

This determines the number of cells, or acreage lost in each suitability class.

Density of squirrel activity areas by suitability class was calculated by overlaying the squirrel activity map (Figure 3d) on the habitat suitability map and dividing the number of activity areas in each suitability class by the number of cells in that class. The number of squirrel habitat equivalents lost in each suitability class was given by the product of density of activity times acreage lost. Summation over all suitability classes determines the overall losses.

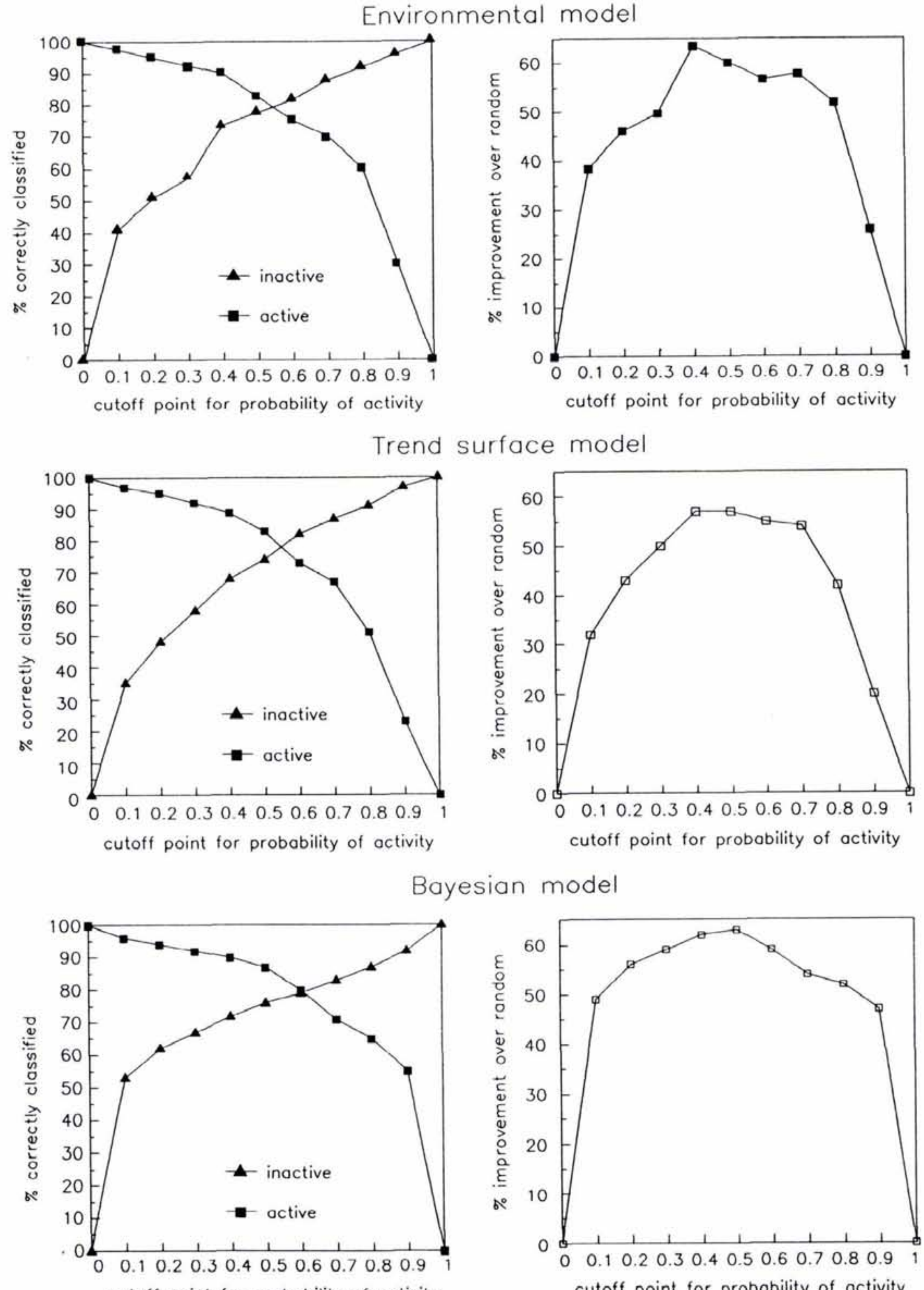

Fig. 6. Classification error rates and predictive improvement over random habitat classification for environmental, trend surface, and Bayesian combined models.

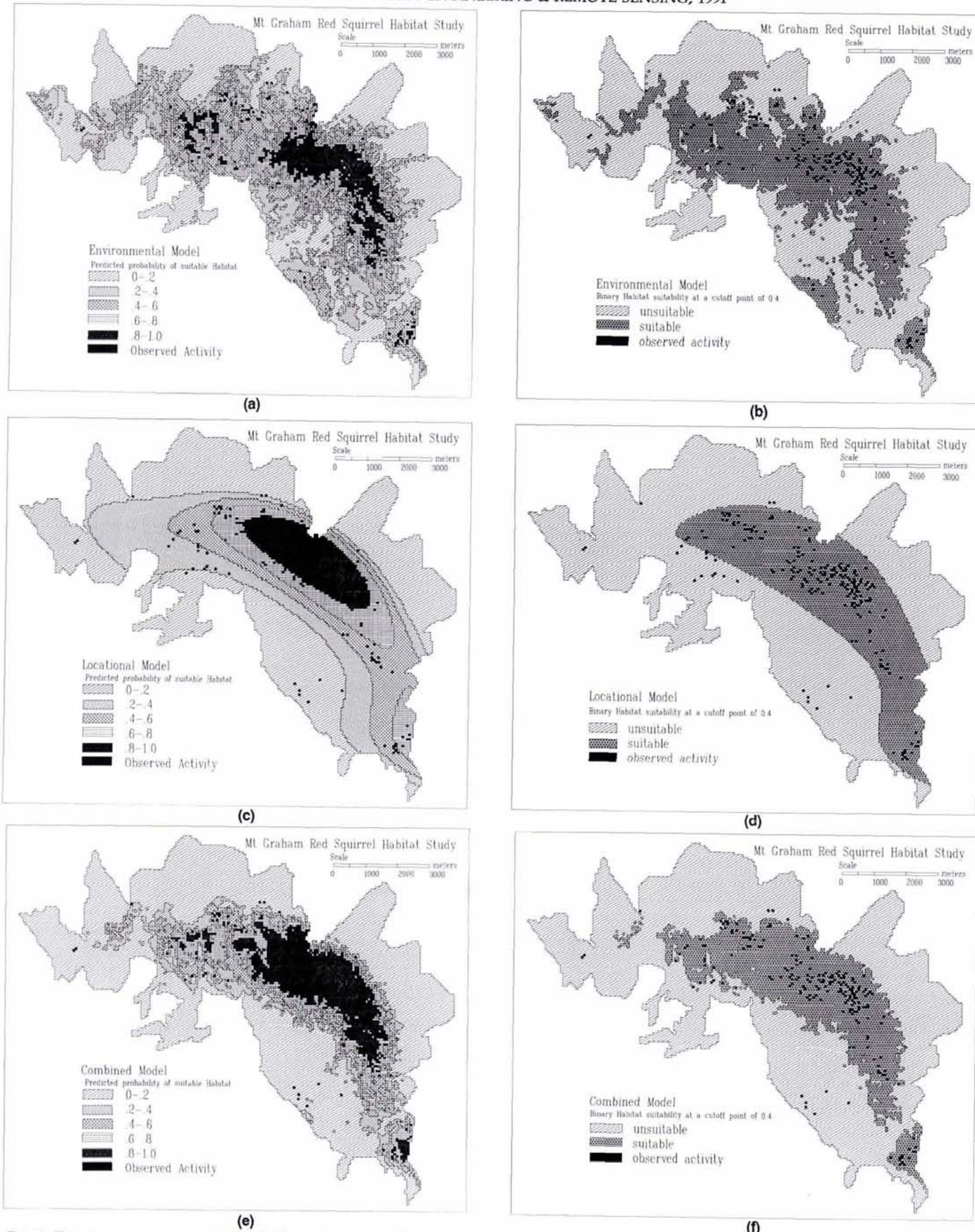

FIG. 7. Five class map representation of (a) environmental, (c) trend surface, and (e) Bayesian models, and binary habitat classification at optimal cut-off points for (b) environmental, (d) trend surface, and (f) Bayesian models.

Squirrel habitat equivalents lost to development were calculated using the data in Table 2. Phase 1 of the observatory project will cause the most impact, leading to the loss of 3.5 units while phase 2 is estimated to impact 3.2 habitat equivalents. A fully developed observatory would have an impact of 6.7 squirrel habitat equivalents, or approximately 3 percent of the 212 activity areas identified in the 1986-87 census and taken as a base population level for this study. These impact magnitude estimates assume that all habitat will be lost in a 70.7-m wide corridor, which is the best approximation to the true impact permitted by the grid-cell resolution. This value may overestimate the direct spatial impact of developing the observatory but it should be a better estimate of overall impact that includes clearcutting, paving, construction, and other negative effects of human presence, such as noise, smells, and movement.

It should be emphasized that habitat area lost is a proxy measure of the project impact on population size. The Mt. Graham red squirrel is in danger of extinction, and preservation of its habitat is a necessary, if not sufficient, condition for long-term survival. However, even though impact magnitude can be estimated, it is much harder to determine what will be the importance of a given impact, that is, how will it influence the attainment of the desired goal of maintaining a viable red squirrel population. Continued monitoring of population dynamics and habitat status will be needed in order to make sure that the various uses sought for the mountain can be reconciled and are not ultimately incompatible.

Table 2. Spatial Impact Assessment

Suitability Class	Activity Density	Number of cells Lost		Number of Habitat Equivalents Lost	
		Phase 1	Phase 2	Phase 1	Phase 2
0-0.1	0.000	0	0	0	0
0.1-0.2	0.004	0	0	0	0
0.2-0.3	0.005	0	0	0	0
0.3-0.4	0.009	0	0	0	0
0.4-0.5	0.017	2	1	0.034	0.017
0.5-0.6	0.025	8	1	0.200	0.025
0.6-0.7	0.019	19	1	0.361	0.019
0.7-0.8	0.028	11	4	0.308	0.028
0.8-0.9	0.089	12	5	1.068	0.445
0.9-1.0	0.150	10	18	1.500	2.700
Total	-	62	31	3.471	3.234

SUMMARY AND CONCLUSIONS

A GIS-based statistical habitat suitability model for the Mt. Graham red squirrel was developed, and impact assessment of the observatory project was accomplished. Selection of cell size, a critical decision in database development (Laymon and Reid, 1986), was successful because most of the original data were preserved and species-habitat relationships were clearly identified.

The univariate analysis was very informative and effectively demonstrated the role of different environmental variables as dimensions of habitat selection, and facilitated comparisons with previous expectations. Good results were also obtained in the development of predictive multivariate models. The visual impression of acceptable agreement between model predictions and field observations conveyed by the environmental, trend surface, and combined maps is confirmed by model performance statistics. Predominance of terrain variables in the model selected for impact assessment should not be attributed to biological irrelevance of vegetation factors, but probably stems from the coarse character of categorical information and to correlations with variables measured in higher resolution interval scales. This seems to explain the selection of elevation instead of food productivity, whose inter-correlation is quite clear (Figures 3a and 4b). Data coarseness alone may be responsible for the ineffectiveness of d.b.h., obviously too homogeneous throughout the entire study area to be a good discriminator (Figure 4d).

It is possible that different sets of variables dominate the habitat selection procedure of Mt. Graham red squirrels at different spatial scales: terrain variables would be more important at the overall landscape level, while vegetation characteristics dominate at a finer resolution. This hypothesis could be tested by developing habitat suitability models for smaller areas of more homogeneous terrain and using higher resolution mapping and more discriminating scales for the measurement of vegetation factors.

Finally, it is important to recall that the habitat use data from which the model was developed correspond to a single year, and may be insufficient for long-term management purposes, especially when the species of concern is an endangered one. This limitation can be removed by linking the static suitability model presented in this paper with a forest succession model capable of simulating habitat suitability changes as a function of landscape dynamics. Several examples of this type of work are given in the *Proceedings of the Wildlife 2000 Symposium* (see Section V: "Linking wildlife models with models of vegetation succession"). Validation of such an integrated system would require continued monitoring of the population and re-testing of the models on a longer time-series of data, considering also the need to develop distinct habitat suitability models for "boom" and for "bust" years, typical of rodent population dynamics in general and also, it is believed, of Mt. Graham red squirrels. Further research should also consider developing quantitative measures of squirrel habitat use, based on variables such as midden diameter or midden biomass.

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