Using the Analytic Hierarchy Process to Create a Wildfire Model

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Abstract

Some of the most important questions in wildland fire modeling involve the inclusion or exclusion of anthropogenic factors. Wildfire modeling efforts in the past have focused on fire ignition, fire behavior, and fire spread characteristics with little, if any, effort made to include human values in wildfire prone environments. This lack of integration is due primarily to the difficulty in comparing wildfire variables with human landscape values. This research used the analytic hierarchy process (AHP), combined with a geographic information system (GIS) to manage the integration of stakeholder opinion on spatially based wildfire and landscape value data. AHP allowed stake holders to make pairwise comparisons between competing variables and then calculated a weight for each. These weighted variables were used to produce a strategic decision support system for wildfire management that incorporated both social and natural science data.

Introduction

Strategic management of wildlands for fire is increasingly a mix of traditional fire science, with climatology, and human relations. Not only do managers need to be experts at modeling fuels and fire behavior, they must also understand human behavior, and the effects of climate on landscape. One of the products developed by the Wildfire ALTERnatives (WALTER) project at the University of Arizona is a strategic model that incorporates these three components. FCS-1 (Fire, Climate, and Society – 1) integrates fire behavior, climate projections, and the values humans place on landscapes, aiding the user in setting fire management priorities.

Walter was funded by the Environmental Protection Agency's Science to Achieve Results (STAR) program. FCS-1 is a prototype that focused on 4 venues that represented a spectrum of wildland human interface possibilities in Arizona and New Mexico. The four venues included three in the Coronado National Forest in Arizona (the Catalina Rincon Complex, the Huachuca mountains, and the Chricahua mountains) and one in the Santa Fe National forest in New Mexico (the Jemez mountains).

Figure 1 - Walter study areas (from: http://walter.arizona.edu)

The major challenge in creating FCS-1 was developing a method for integrating fire science with climate and human components in a single model. There were three requirements that needed to be met in order for the model to work. The first was the development of a method for comparing variables that do not have a strong basis for comparison. For example, it is difficult to compare the relative importance of fuel moisture and property value. These two variables have little in common, making the establishment of rankings problematic. The solution to this was to divide FCS-1 into two sub-models, a 'Values at Risk' model that includes variables that capture the importance that people assign to landscape, and a 'Fire Probability' model that uses variables to determine the probability of wildfire occurring in an area. The second requirement was that the system needed to be able to rank and weight variables in a way that was transparent to users. A system called the Analytic Hierarchy Process (AHP) was used to make pairwise comparisons and assign weights to the variables. The final requirement entailed the inclusion of stakeholder input in the model building process. Here again, the AHP was used to collect stakeholders input. This input was used to build models that reflected either an individual's values or the combined values of a group.

Figure 2 – Chiricahua Mountains

This paper looks specifically at the use of AHP with ArcGIS in constructing FCS-1. It begins with an overview of AHP, then examines the development of the variables used in the model, and concludes with a discussion of the modeling process.

AHP: an overview

Decision-making often requires preferential selection among a finite set of alternative objects, events, or courses of action. For a land manager, the list of alternatives might contain possible timber harvest levels, inventory and monitoring activities, watershed analysis, or fire management. In the best situations, there would be a measurement scale that could be used for comparison and the best choice among the available alternatives would be based on that scale. In most real-world situations, however, there is not a single, simple scale for measuring all competing alternatives. More often, there are several scales that must be used and often these scales are related to one another in complex ways. Further, in broad-scale, participatory decision-making, alternative courses of action arise from different stakeholders with different value systems. Integrating this diversity of values can be very difficult. The AHP is intended to help with these types of decisions.

Figure 3 – Huachuca Mountains

Two important components of the AHP that facilitate the analysis of complex problems are: (1) the structuring of a problem into a hierarchy consisting of a goal and subordinate features of the problem and (2) pairwise comparisons between elements at each level. Subordinate features are arranged into different levels of the hierarchy and may include such things as objectives, scenarios, events, actors, outcomes, and alternatives. The alternatives to be considered are placed at the lowest level in the hierarchy. Pairwise comparisons are made among all elements at a particular level with respect to each element in the level above it. Comparisons can be made according to preference, importance, or likelihood-whichever is most appropriate for the elements considered. Saaty (1980) developed the mathematics necessary to combine the results of the pairwise comparisons made at different levels in order to produce a final priority value for each of the alternatives at the bottom of the hierarchy.

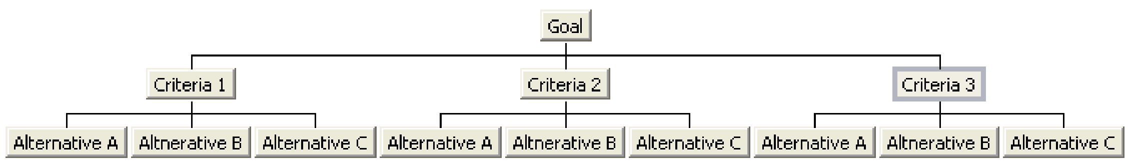

Figure 4 – AHP Hierarchy

The analytic hierarchy process provides a means to elicit priorities when many other options fail. Saaty (1980) outlines six distinct benefits of the AHP in setting priorities.

- It is a systematic methodology that can force stakeholders to make regular judgments, by tracking the logical consistency of judgments used in determining priorities.
- It will lead to an overall estimate of the desirability of each alternative, by enabling people to select the best alternative based on their goals by taking into consideration the relative priorities of factors in a system.

- With the capability of combining group preferences, the AHP does not insist on consensus but synthesizes a representative outcome from diverse judgments.
- By repeating the comparison process, the AHP enables people to refine their definition of a problem and to improve their judgment and understanding through reiteration.
- The AHP can handle complex problems by integrating deductive and systems approaches in solving multifaceted problems.
- By employing a hierarchic structure, the AHP reflects the natural tendency of the mind to sort elements of a system into different levels and to group like elements in each level.

FCS-1 Variables

FCS-1 is a spatial model that uses a variety of variables to model both natural and social factors important to wildfire management. The data were developed in Workstation Arc/INFO 8.2. Processing occurred in a mixed vector/raster environment, with the end products being a regular array of polygons. In this array, each polygon was 1 kilometer by 1 kilometer. This array of polygons was used instead of a raster primarily for reasons of efficiency in the database and for performance in an IMS setting.

As noted above, FCS-1 is divided into sub-models. In the following paragraphs a brief description of the variables that make each sub-model are presented. More complete description of these variables can be found at the project website (http://walter.arizona.edu)

Figure 5 – Fire Climate Society Model - 1

Fire Probability Sub-Model

The fire probability sub-model contains variables that measure the probability a wildfire will occur in a given area. Although there are a multitude of potential variables, the following five were selected at most important.

Fuel Moisture Stress Index

Fuel condition was measured using a fuel moisture stress index (FMSI) that was developed from satellite imagery spanning 1989 to 2003. The FMSI is a relative index of moisture stress based on each pixel's variation from year to year. Positive values of FMSI indicate above average moisture stress; negative values indicate below average moisture stress. By relating each pixel to its own variation over the fifteen year span, the FMSI produces a value that is comparable across pixels that may be populated by very different vegetation types (Taunton 2005).

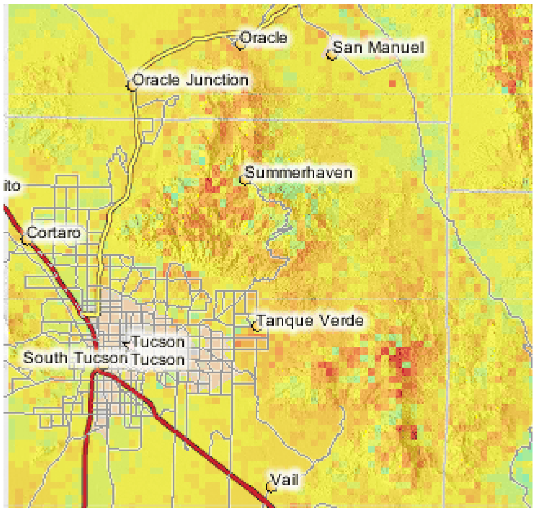

Figure 2 - Fuel Moisture Stress Index

Fire Return Interval Departure (FRID)

FRID is an index of the historical interval between fires for each vegetation type, and the years that have elapsed since the last fire. This technique uses historic fire data to determine areas that have gone longer than normal without a fire and, therefore, more likely to be overloaded with fuels (Caprio, Conover et al. 1997; Keifer, Caprio et al. 1999).

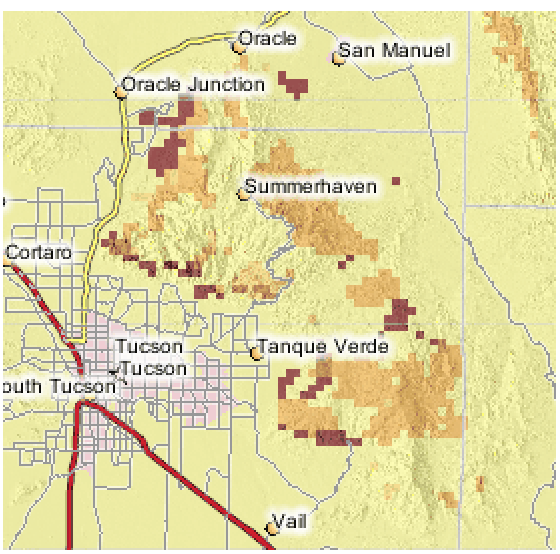

Figure 3 - Fire Return Interval Departure

Large Fire Ignition Probability

Fires that grow to more than 250 acres in size, though few in number, account for most of the acreage burned (95%). In addition, once a fire reaches 250 acres in size, there is a higher likelihood that it will grow much larger. This component of the model uses modified GAP vegetation data, along with Brown, Lowe and Pace vegetation and fire ignition data to create an index of the likelihood a fire will reach the 250 acre threshold. A GAP vegetation type is assigned to each large fire ignition, and then the total ignitions for each vegetation type are standardized into a density based on the total amount of area in each class (Neuenschwander, Menakis et al. 2000).

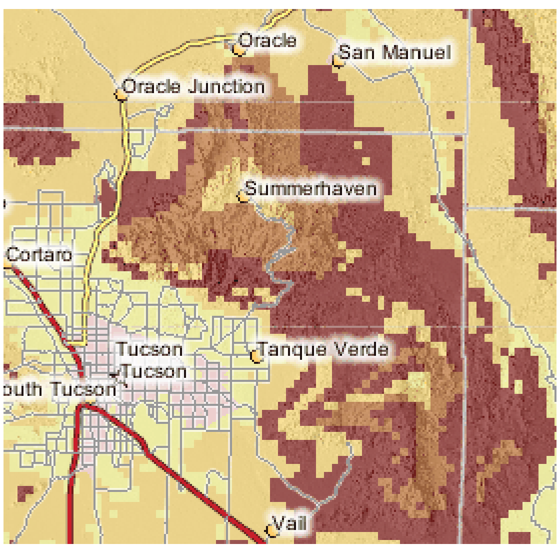

Figure 4 - Large Fire Ignition Probability

Lightning Probability

The major ignition source for non-anthropogenic fires is lightning. To incorporate this factor into the FCS-1 model, lightning occurrence data between 1989 and 1999 was obtained from the National Lightning Detection Network, and the probability of lightning strikes was calculated from the spatially explicit density of lightning strikes per 100 ha per year in each research venue. Each lightning strike was assigned a geographic coordinate and a date, and these data were then converted through several steps to a normalized probability (between 0 and 1) of lightning strikes per 100ha per year (Rollins 2003).

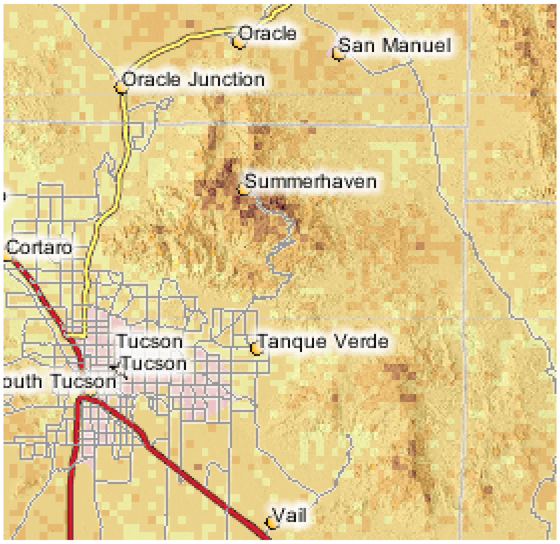

Figure 9 – Lightning Probability

Human Factors of Fire Ignition

As humans increase their interaction with wildlands, the number of human caused wildfires continues to rise (Cardille, Ventura et al. 2001). Through a logistic regression analysis it was revealed that human ignitions were spatially associated with several factors. For example, because people usually access areas by way of roads and spend more time close to them than far away, proximity to roads was a positive factor in human wildfire probability. For similar reasons these kinds of fires also tend to be located near campgrounds and picnic areas. Distance from urban areas was also a positive contributor to the probability of human caused wildfires, as there are more people in urban areas, and less time is spent the further they have to go from where they live. Finally, there was also a positive correlation between the location of non-forested areas and human fire ignitions.

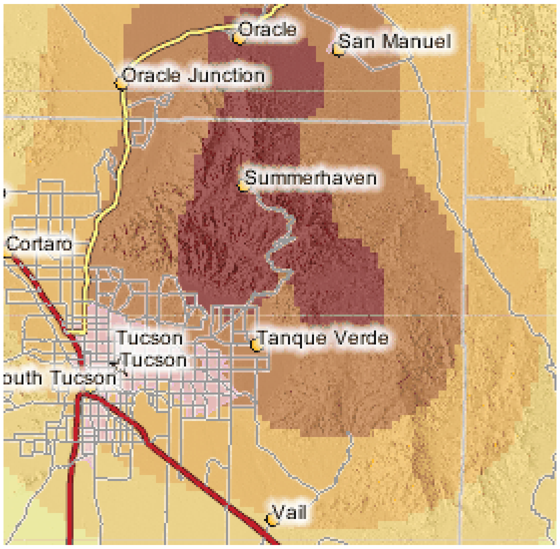

Figure 10 – Human Factors of Fire Ignition

Values at Risk Sub-Model

The values at risk sub-model contains variables that measure the values that humans place on particular landscapes. Although these variables are less concrete than the fire probability variables, values at risk to wildfire are often what drive discussions about fire management.

Recreation Value

In historical perspective, wildlands have often been viewed as places to conquer in the name of King and country, a source of untapped riches, or as large science experiments. This view has changed radically in the American Southwest and wildlands are now most likely to be viewed in terms of recreation. In order to capture this shift, a variable that maps recreation and recreation value was created.

This variable was constructed from maps of known recreation areas and an understanding of the types of recreation most likely to occur in each venue. A Forest Service recreation survey provided the proportion of people participating in each recreation type (Kocis, English et al. 2002). From this list, the top 10 recreation types in each venue were selected for the model. Spatially explicit features representing locations for each of these recreation types were identified. For example hiking trails were selected as the features to represent hiking.

Once the features representing each recreation type were identified, distance and visibility were used to model recreation value. Studies have demonstrated that both distance and visibility are important factors in how humans value wildlands (Irland 1991; Miller 2001; Wing and Johnson 2001). To model distance, Euclidean distance rasters were created from each object representing recreation. Inverse distances from 0 – 2000 meters were used to represent the relative importance of each cell in the raster. For example, a cell 30 meters from a trail was considered more important than one 1000 meters from that same trail, and a cell more than 2000 meters was considered unimportant. To model visibility importance, cumulative viewsheds were created from the representative features. Cells in the resulting rasters that were visible 6 times were considered more important than those visible 2 times. The Euclidean distance and cumulative visibility rasters were scaled between 0 and 1, and summed to create a model for each recreation type. These rasters were then scaled between 0 and 1, and weighted by the proportion of individuals participating in each recreation type. The sum of these weighted rasters represented the relative value of each cell in the study region for recreation.

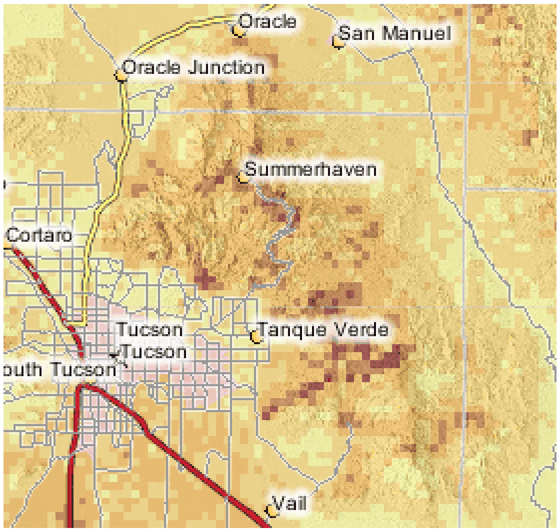

Figure 11 – Recreation Values

Personal Landscape Values

While GIS models of environmental risk and value have long taken into account "hard" data such as precipitation levels and property values, they have historically not included less tangible values placed on natural areas by concerned groups and individuals (Johnson, Perin et al. 2003). In an effort to redress this imbalance in the FCS-1 model, project researchers conducted map-based interviews in each of the four study areas. Interviewees answered a series of questions from a 5 page questionnaire. The key questions involved having the interviewees mark on a map the locations of perceived fire risk, areas of personal recreation use, travel routes, areas that they valued but had never traveled to and the area that they valued the most and believed should be protected from wildfire (Perin, Morehouse et al. 2003).

The polygons marked on the maps were digitized, digitized, and summed to create rasters of varying value. Cells with higher values were in areas selected more often by the interviewees as important, those with low values were selected less often, or not at all.

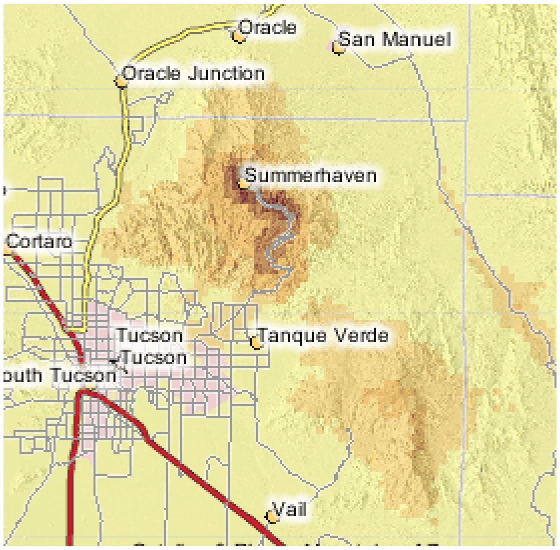

Figure 12 – Personal Landscape Values

Property Value

Nothing spices up a wildfire more than threat to private property. This variable sought to identify property value across a landscape (Fried, Winter et al. 1999; Winter and Fried 2001; Perin, Morehouse et al. 2003). Although this sounds straightforward, it turned out to be the most problematic of the variables. Determining property value in urban settings is easily determined, but on public lands it is always difficult and sometimes impossible. Traditionally land value on Forest Service lands was a function of the value of the timber. Since no logging takes place in any of the venues for this project, land values could not be determined in this way. Over the course of the project, a number of different approaches were tried, but in the end housing value from the 2000 Census was used. Although not perfect, it was available across all four venues, and does give a limited idea of property value.

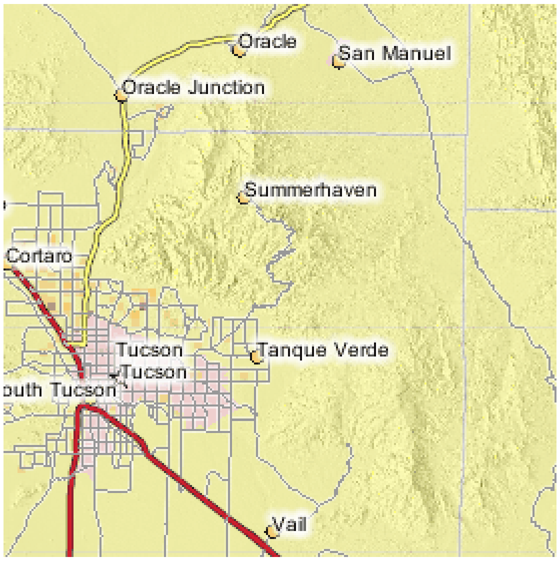

Figure 13 – Property Values

Species Habitat Richness

This variable mapped species habitat diversity as a proxy for species diversity in an attempt to determine those areas with potentially large wild animal populations and therefore a high environmental value (Bengtsson, Jones et al. 1997; Pimentel, Wilson et al. 1997; Bulte and Van Kooten 2000; Fromm 2000; Gatto and De Leo 2000; Vivien 2000). This variable was based on Arizona and New Mexico GAP data. Information on habitat for birds, mammals, reptiles and amphibians was obtained and combined to form a single map that details species habitat diversity for each of these four classes.

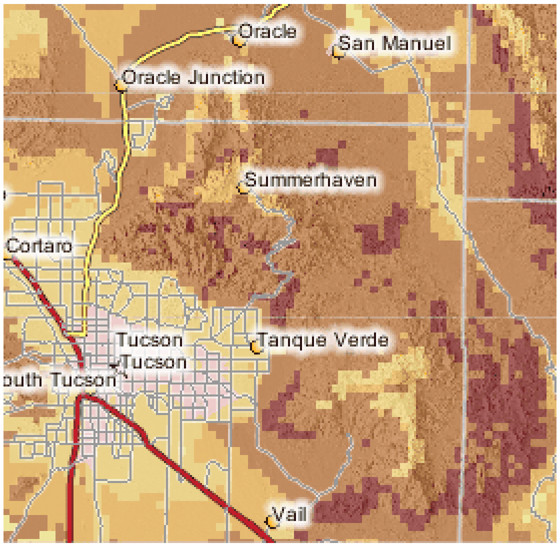

Figure 14 – Species Habitat Richness

Creating the Model

The model was built in a series of steps summarized here.

- Each variable was normalized by scaling it between 0 and 1.
- Pairwise comparisons of each variable and the two sub-models were made.
- Eigenvectors were calculated for each variable and for the two sub-models.
- The normalized variables were weighted by the eigenvectors.
- The weighted variables were summed to create the sub-models.
- The sub-models were normalized and weighted by their corresponding eigenvectors.
- The weighted sub-models were summed and normalized to create the final, combined model.

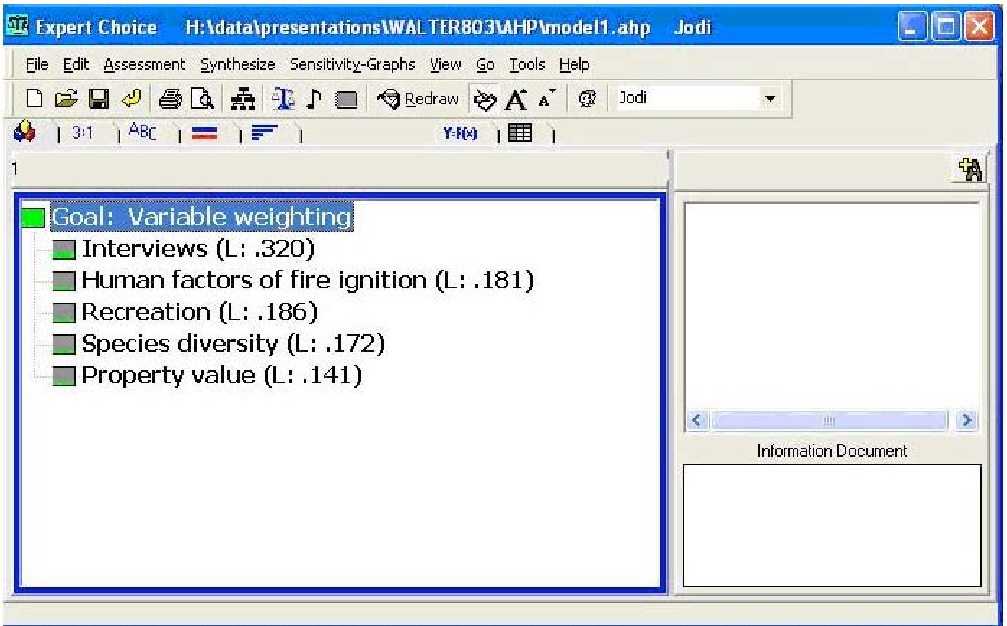

Figure 15 – Variable weights

Once these processing steps for creating the model were established and tested, meetings were held in each of the venues. At these meetings, experts and lay-people were involved in creating models specific to their area and to their values. At each meeting, in-depth descriptions of the model's structure variables were given to the participants. Stakeholders were then asked to make pairwise comparisons among the variables within each sub-model and then between the sub-models themselves. For example, "Which do you think is more important to fire probability, lightning or human ignitions?" Or, "With regards to setting management priorities, which is more important, fire probability or values at risk?" These comparisons were recorded using wireless keypads that transmitted each individual's choices to a laptop running Expert Choice software. These comparisons were combined using the geometric mean to produce group based comparisons and eigenvectors were calculated for each variable and sub-model.

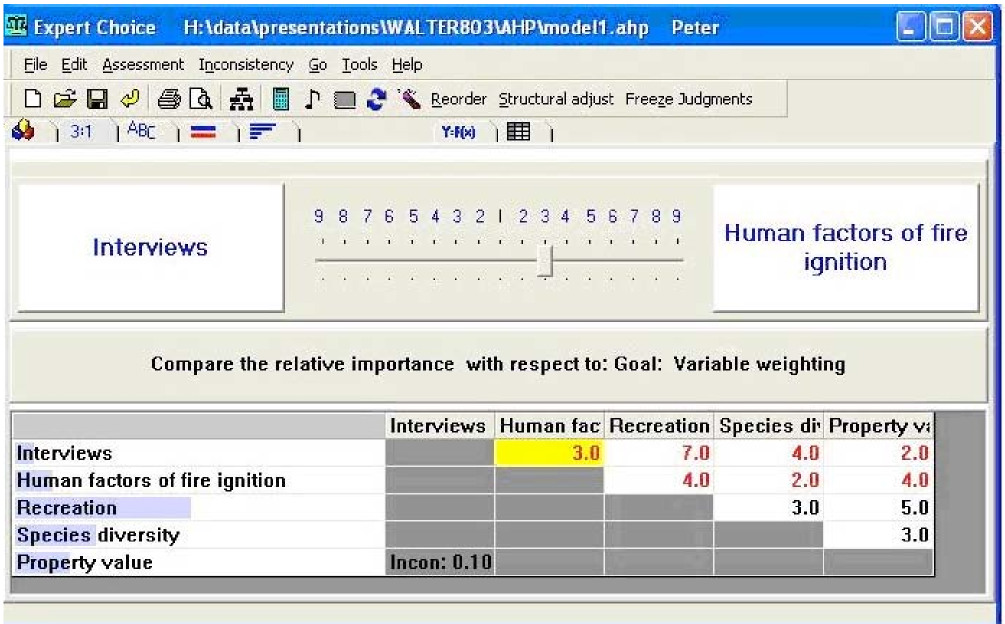

Figure 5 - Making pairwise comparisons

These eigenvectors were then used as input in an AML that did the calculations to create three models: a Fire Probability sub-model, a Values at Risk sub-model, and the combined Fire Climate Society model. The Fire Probability model highlights areas with a high probability for wildfire. The Values at Risk model captures those areas most valued by humans. The combined model provides the manager with a map of higher and lower priority areas, with the priority established by a combination of both fire probability and values at risk.

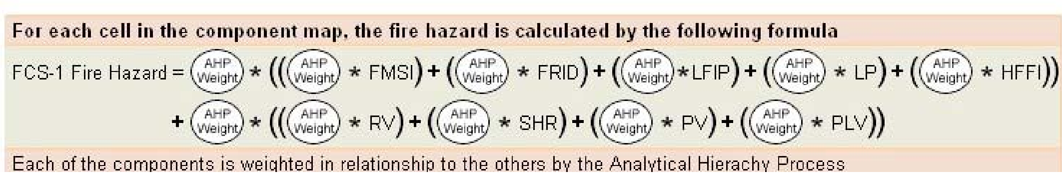

Figure 6 - Model Process (from http://walter.arizona.edu)

An important feature of AHP and FCS-1 is the ability to produce unique models for either groups or individuals. Users of FCS-1 come with a set of values and a range of understanding on wildfires in the Western United States. The result of these different backgrounds and values was seen in the models created at each venue. To highlight this point, it is interesting to compare the models made by a Fire Management Officer (FMO) from a National Forest and a Ranger from a National Park. The FMO produced a map where heavily forested areas with ideal conditions for wildfire were his top priority. Using the same data, but different values, the park ranger's map highlighted areas of historic and recreational value as her top priority. These results reflect the mandates that these two individuals have for the lands that they manage. In this case FCS-1 was able to reflect the different priorities of these land managers had in a spatially explicit map.

Conclusions

FCS-1 was developed for the WALTER project to improve our ability to integrate traditional fire science with, climate and human factors in a strategic model. Built using the Analytic Hierarchy Process, it is a tool that allows decision makers to set priorities in landscape management for wildfires. The methodology involves the development of a spatial decision support system that utilizes the analytic hierarchy process and a geographic information system. The resulting tool allows for either individual or group based model, and allows the creation of models that reflect either group or individual values.

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