

# An On-line Interface for Integrated Modeling of Wildfire, Climate, and Society for Strategic Planning for the Sky Islands

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***Abstract**—The demand for strategic planning tools that account for climate and human influences on wildfire hazard is growing. In response, the University of Arizona, through an EPA STAR Grant has undertaken interdisciplinary research to characterize the human and climate dimensions of wildfire. The resulting Fire-Climate-Society (FCS-1) prototype model developed for Sky Islands in southeastern Arizona (Catalina/Rincones, Huachuclas, Chiricahuas) addresses both the biophysical elements of wildfire probability and the human elements of values-at-risk. An online, spatially explicit application will allow users to choose climate-based scenarios, weight model components through a multi-criteria decision process, and then create spatially explicit maps for dynamic strategic planning.*

## Introduction

Natural resources and environmental quality are considered at risk across 190 million acres (77 million ha) of United States forests and rangeland due to wildfire. Altered wildfire regimes jeopardize the sustainability of these ecosystems, particularly in the Southwest. On average, 433,000 acres (175,000 ha) burned annually in Arizona and New Mexico between 1992 and 2003 (Southwest Coordination Center 2004), over seven times the annual rate over most of the past century (Swetnam and Betancourt 1998). The severity of these fires has increased in recent years, posing an increasing threat to human life and property, and to ecosystems more adapted to low severity fires. Climate factors (Swetnam and Betancourt 1998) and human activity (Cardille and others 2001) can be precursors to increased fire activity at a variety of temporal and spatial scales. Increases in tree density and basal area over the past century have led to significantly greater fuel loads indicative of entirely different fire regimes than in the past (Covington and Moore 1994). Ponderosa pine forests have become vegetation- and fuel-dense and are at risk of stand-replacing ecosystem change through historically uncharacteristic high-intensity wildfires (Covington and others 2001). What once were anomalous

crown fires can have radical, long-term impacts on species composition and structure of Madrean oak-pine communities common in Southwestern sky islands (Barton 2002). Severe fires impact the soils—volatilization and mineralization of nutrients, changes in hydrologic functioning, and accelerated erosion and leaching (Neary and others 1999). Population expansion into previously open spaces has exacerbated the problem by placing people and their property at risk, particularly in the Southwestern United States where population increased 1,500% between 1900 and 1990, compared to 225% for the nation as a whole (Choure and Wright 1997).

Demographic trends and changing fire regimes require modifications in fuel management strategies based on spatially explicit and temporally dynamic risk assessments (Conrad and others 2001). Strategic wildfire planning would be improved greatly by a decision support system that incorporates the long-term influences of climate in fire probability analysis and the assessment of values at risk of damage or loss. The importance of different values depend on the perspective of the individual, thus integration with fire probability in an overall risk assessment is difficult if not impracticable (Hardy and others 2001). Addressing these challenges is the focus of Wildfire Alternatives (WALTER; <http://walter.arizona.edu>),

a U.S. EPA Science to Achieve Results (EPA STAR) grant project being conducted by a multidisciplinary research team at the University of Arizona. The objective of WALTER research and development is to enhance the ability of wildfire managers to improve the health and sustainability of fire-prone ecosystems through a web-based, spatially dynamic decision support system that is capable of integrating assessments of fire probability and values at risk (Morehouse and others 2000). WALTER research has culminated in a prototype strategic planning model called Fire-Climate-Society (FCS-1) that will enable decision makers to construct risk assessment maps under alternative climate scenarios and varying perspectives of values at risk for three sky islands in southeastern Arizona (Catalina/Rincones, Huachucas, Chiricahuas) and the Jemez Mountains, New Mexico. FCS-1 risk assessments are constructed with a 1 km<sup>2</sup> minimum mapping unit, the finest resolution at which spatially distributed climate information can be reasonably integrated. This paper reviews the inputs to the FCS-1 fire probability and values at risk sub-models, their integration through a multi-criteria decision method, and the applications logic and architecture behind an interface permitting FCS-1 to be run interactively on-line.

## FCS-1 Model Components

FCS-1 is made up of both a fire probability and values at risk sub-models (figure 1).

### Fire Probability

FCS-1's fire probability sub-model is made up of five components: Fuel Moisture Stress Index, Fire Return Interval Departure, Large Fire Ignition Probability, Lightning Probability, and Human Factors of Fire Ignitions. The Fuel Moisture Stress Index (FMSI) is central to how climate

scenarios are built into FCS-1 (e.g., fuel moisture conditions that result after a wet winter followed by a dry spring and summer). FMSI is a measure of moisture stress in vegetation relative to a given time of year. It is predicated on a correlation analysis of the interactions between antecedent climate and wildfire variability (Crimmins and Comrie 2004) and the relationship between chlorophyll content, live fuel moisture condition, and a time-series analysis of bi-weekly fire season Normalized Difference Vegetation Index (NDVI) (e.g., Nemani and Running 1989) derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery between 1989 and 2004. In order to measure the temporally relative stress that is distinctive to a given pixel, "raw" NDVI values are transformed into negative z scores (Yool 2001). The negative z score is calculated by:

$$-(x_i - \mu) / \sigma$$

where  $x_i$  is the NDVI value of a pixel for a given date,  $\mu$  is the mean value for the pixel's NDVI time series, and  $\sigma$  is the standard deviation for the pixel's NDVI time series. This standardization of the current pixel relative to the time series provides us with a value for relative fuel moisture stress that is comparable between pixels (Taunton and Yool 2004). Climate measures showing strongest correlation with FMSI were air temperatures coincident with the fire season and precipitation the winter prior to the fire season. This study has employed an extensive investigation of climate correlations to determine the inception and length of fire season (highly variable in complex sky island terrain) so that FMSI can be averaged over the fire season for each pixel for each year to produce a fire season summary FMSI for each year.

Fire Return Interval Departure (FRID) is a measure of how long it has been since this area has experienced a fire in relation to how frequently it would be expected to burn in a natural state (Keifer and others 2000). From maps of where and when fires have occurred in the past, average fire return intervals for each

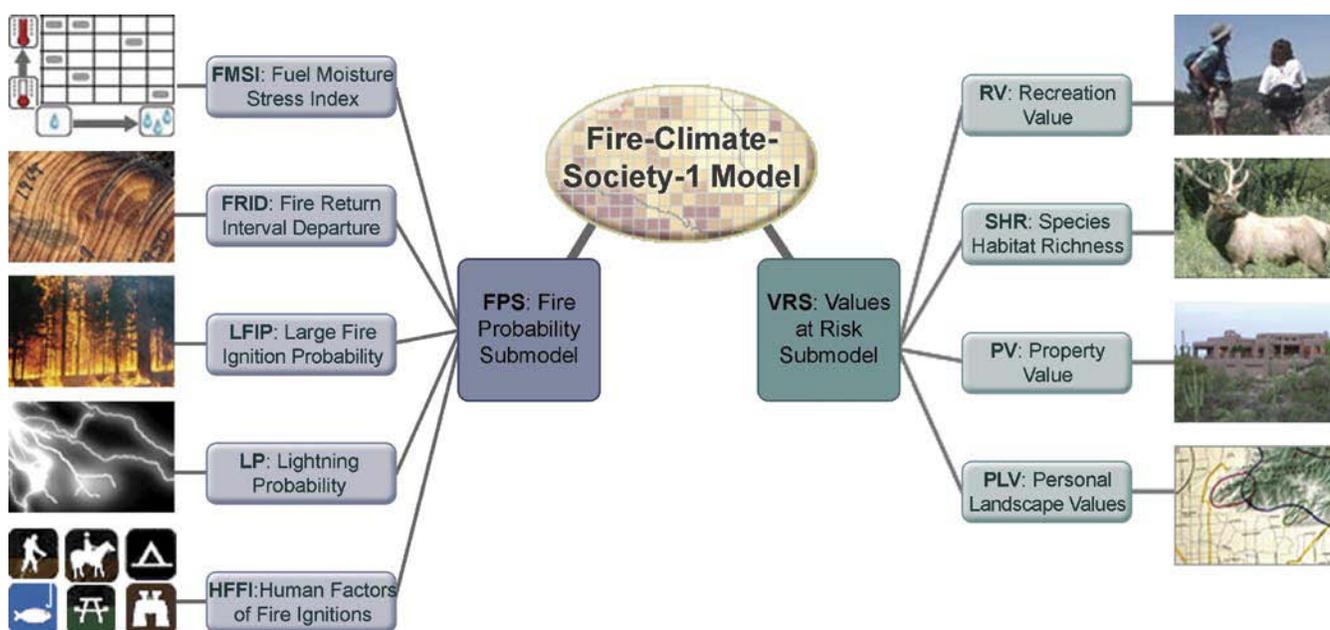


Figure 1—FCS-1 model components.

vegetation type class can be determined. Using the time that has elapsed since the last fire, a derived index can be calculated for each map pixel to quantify the departure of an area from its average fire return interval. The equation for FRID is:

$$\text{FRID index} = (\text{Years since last fire} - \text{Natural Fire Return Interval}) / \text{Natural Fire Return Interval}.$$

Large Fire Ignition Probability (LFIP) represents the chance an ignition will grow into a “project” fire. Based on a cumulative fire size probability analysis, fires that reach 250 acres (101 ha) in size have a 45% chance of expanding to 1,000 acres (404 ha), and once achieved, a 30% chance of growing into a major wildfire of 5,000 acres (2,023 ha) or more increases substantially once a fire reaches 250 acres in size (Neuenschwander and others 2000). Only 5% of all fires on the Coronado National Forest, for example, reached 250 acres between 1986 and 1999, but they account for 95% of the total area burned. Because different vegetation types produce different fire behavior, a vegetation type is assigned to each fire ignition in FCS-1. The vegetation types were obtained from gap analysis vegetation maps (Halvorson and others 2001).

The total ignitions for each vegetation type are then standardized into a density map based on the total area in each class. Lightning Probability (LP) is based on the density of lightning strikes per 247 acres (100 ha) per year in each research venue data acquired between 1989 and 1999 from the National Lightning Detection Network™ (Cummins and others 1998). Annual data proved sufficient because the relative probabilities of a lightning strike in one location versus another remained consistent year to year. Human Factors of Fire Ignitions (HFFI) is based on the spatial relationship between human activities and the location of human caused ignition. A logistic regression analysis revealed human ignitions were spatially associated with proximity to roads, location of campgrounds and picnic areas, and proximity to urban areas. Human ignitions also tended to occur more frequently in non-forested vegetation types.

## **Values at Risk**

The FCS-1 values at risk sub-model is composed of four components: Recreation Value, Species Habitat Richness, Property Value, and Personal Landscape Value (Johnson and others 2003). Recreation Value (RV) is based on a proximity analysis of major recreation activities in each venue as determined through data obtained from public land agencies such as the Forest Service’s National Visitor Use Monitoring Program (English and others 2002). Maps were created for the top ten recreation activities in each venue (i.e., campgrounds, hiking trails, roads, picnic areas, lakes, historical sites, and visitor centers). Viewsheds were created by calculating Euclidean distance grids and visibility surface grids from features of interest based on the assumption that visual amenity makes up part of recreation value. These were then weighted by the proportion of visitors who participated in each activity and then summed for an overall assessment of recreation values at risk. Species Habitat Richness (SHR) was designed to be a proxy for the diversity of fauna since landscape-scale species diversity

maps are not available for the WALTER study sites. SHR is a spatially explicit sum of the GAP-model habitats (Halvorson and others 2001) for mammals, amphibians, reptiles, and birds. Property Value (PV) uses maps of property value created from tabular housing data joined to census block-level data, and total housing value was assigned proportionally based on area of intersection with the 1 km<sup>2</sup> project grid. Personal Landscape Value (PLV) addresses the personal perceptions of risk that concerned groups and individuals assign to areas at risk of wildfire (Johnson and others 2003). This model component is based on participatory map-based interviews at each of the WALTER venues. A purposive sample of 30 stakeholders was chosen to capture the breadth of viewpoints including representatives from agency personnel, home associations, and environmental advocacy groups.

## **Weighting and Integration**

Each of the components of FCS-1 provides information on either fire probability or values at risk, and yet none can stand alone as an integrated risk assessment. Stakeholder feedback from the outset of FCS-1 development emphasized the need for an operational model that could integrate risk assessment elements through expert knowledge of local conditions. Of concern was the reality that stakeholders with different priorities would place differing levels of importance on the FCS-1 model components and sub-models. This is evident particularly when trying to integrate human and biophysical characteristics of the model.

One method for addressing this is assignment of weights through expert opinion. Where there are multiple criteria and interrelated choices, however, weighting decisions become complex. Saaty (1980) developed a method to decompose and synthesize this complexity through the Analytical Hierarchy Process (AHP), reducing decisions into a series of one-on-one comparisons. The problem FCS-1 is trying to address—strategic fire planning—is structured first into a hierarchy with criteria (the sub-model components) and alternatives (the 1-km<sup>2</sup> map cells) (Johnson and others 2003). Next, the relative importance of each sub-model component versus the next component is scored on an integer scale of 1-9 by each individual stakeholder. These same steps are used to compare the relative importance of the two sub-models. These comparisons are essentially a ratio of relative importance or preference. The set of preference scores are then synthesized through a matrix averaging (eigenvector) method (Saaty 1980) in order to assign weights to the criteria. Linear combination of the weighted sub-model components creates the “fire probability” map and a “values at risk” map. A linear combination of the sub-models creates the final FCS-1 risk assessment. Figure 2 provides an example of the model output.

This modeling approach integrates the preferences of a group of people in order to visualize their combined preferences. Feedback from the stakeholders who evaluated FCS-1 emphasized how the combination of AHP and interactive maps illustrated the complex relationships inherent to wildfire risk assessment.

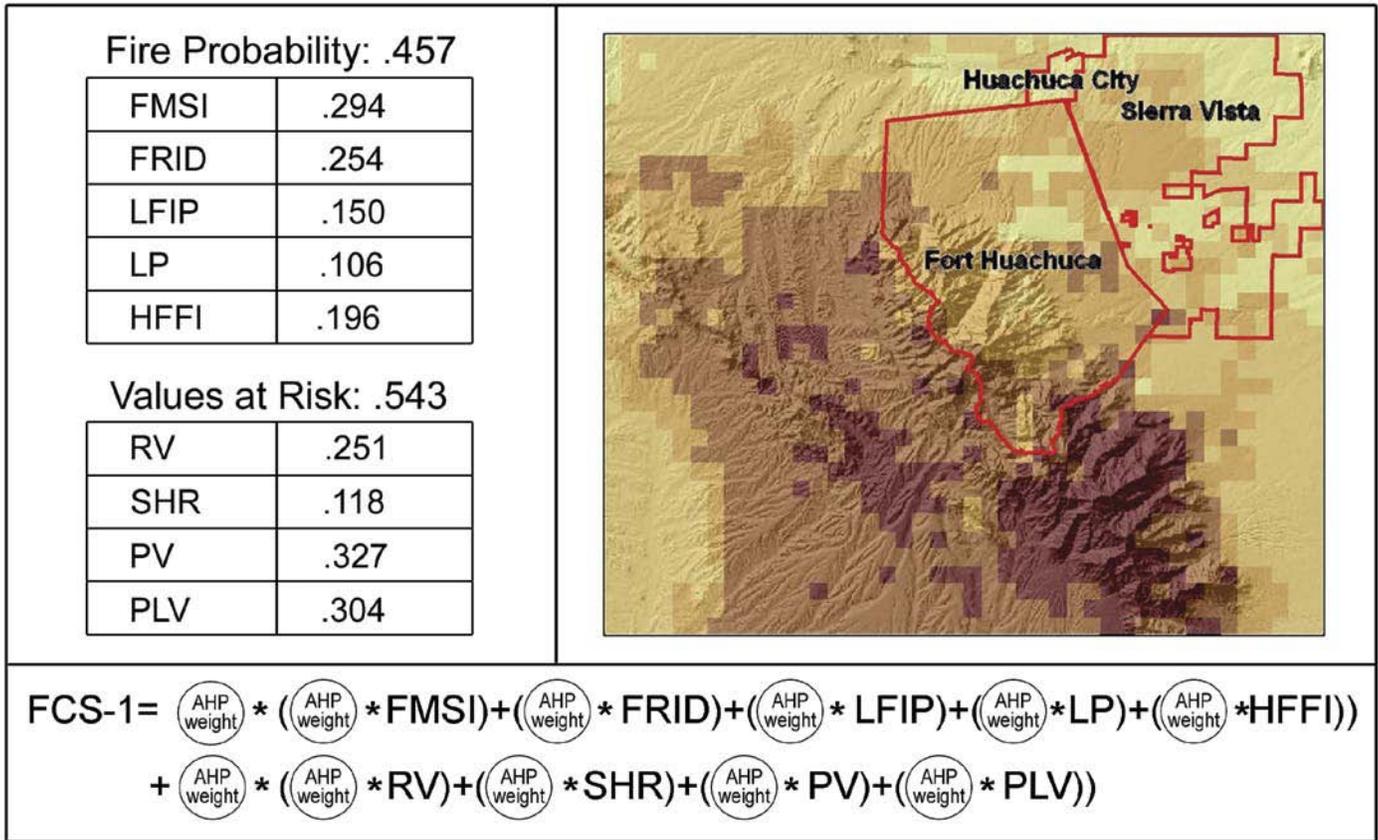


Figure 2—Example AHP output, where darker areas have higher risk.

## FCS-1 On-line Application

We designed the WALTER Web site to serve a wide range of stakeholders interested in the climate and human dimensions of wildfire. Our objective has been to create a Web-based decision support tool that will enable decision makers to construct fire risk maps under a selected set of alternative climate scenarios (e.g., a wet winter followed by a dry spring). Transferring FCS-1 from the desktop to the web involves the use of relational database and Internet map server technology. Web programming will feature map algebra to calculate cell attributes on-the-fly so user-specified parameters can be passed on and used in the FCS-1 model. In keeping with the WALTER objectives of technology transfer geared to a wide range of stakeholder interests and backgrounds, the web-based version of FCS-1 is being framed in a decision flow structure, ensuring comprehension at each decision step to guide users, much the way a “wizard” guides users of desktop software.

The first decision step involves a FCS-1 model overview as visualized in figure 1. Explanations of each model component and the science behind their creation will be linked to each respective graphic. Next, users will be able to select one of the four WALTER study sites from a map or a list. All FCS-1 model components will then be displayed as interactive maps (zoom, query, etc., available) for that site (again, with links to the underlying science). The third step is generation of the

climate scenario based on FMSI fire season summaries grouped in a matrix based on the temperature coincident with that season and precipitation from the season before. This matrix, the underlying FMSI maps, and graphical representations of the climate summaries will guide the user in choosing a scenario that match climate-influenced fuel moisture conditions of interest. This choice then initializes the AHP—either through the selection of a set of weights obtained by experts who have stored their results in the database, or the execution of a personal model (following the steps detailed in the previous section).

Pairwise comparisons will be facilitated by graphic representation (interactive maps of each combination of variables) and a series of radio buttons (1-9 for both criteria) to record user preferences. The final step, AHP synthesis, will result in a report page that will include a fully interactive map of the final risk assessment, spatially linked maps of the sub-models along with all nine input variables and their corresponding weights. Our ultimate plans are to develop a query tool that will deliver the relative importance each input map value and corresponding AHP weight contributes to each map cell.

Though the WALTER project databases are currently only available for the four study sites under investigation, we intend to develop regional databases that apply the tool applicable over larger areas. We will then distribute the model components to those groups who wish to develop their own databases.

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