APPLICATIONS OF REMOTE SENSING AND GIS TO MODELING FIRE
FOR VEGETATIVE RESTORATION IN NORTHERN ARIZONA

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An accurate fire model is a useful tool in predicting the behavior of a prescribed fire. Simulation of fire requires an extensive amount of data and can be accomplished best using GIS applications. This paper demonstrates integrative procedures of using of ArcGIS™, ERDAS Imagine™, GPS, and FARSITE© to predict prescribed fire behavior on the Kaibab-Paiute Reservation. ArcGIS was used to create a database incorporating all variables into a common spatial reference system and format for the FARSITE model. ArcGIS Spatial Analyst was then used to select optimal burn sites for simulation. Our predictions will be implemented in future interagency efforts towards vegetative restoration on the reservation.
ACKNOWLEDGMENTS

I would like to thank the following people for their contributions to various phases of this research: Dr. Thom Alcoze, Mark Anderson, Dr. Dwight Barry, Bethany Bolling, Carla Carr, Steven Earnest, Bruce Hunter, and Dr. Victoria Jackson. Also, many thanks to my committee, Dr. Earl Zimmerman, Dr. Minhe Ji, and Dr. James Kennedy. I especially thank Danny Bulletts and the Kaibab Paiute Tribal Council for allowing us to complete this research on their Reservation. Funding for this research was provided by a grant from the US Department of the Interior through the Ecological Restoration Institute of Northern Arizona University.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACKNOWLEDGMENTS</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>1.</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.</td>
<td>LITERATURE REVIEW</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Prescribed Burning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modeling Fire</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetation and Remote Sensing</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>METHODS</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Study Area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Data Collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetation Classification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ArcGIS Fire Model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Using FARSITE to Model Fire of 2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selecting Suitable Sites for Test-burn Plots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Running Simulations of Test Plots in FARSITE</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>RESULTS</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Vegetation Classification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ArcGIS Fire Model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Using FARSITE to Model Fire of 2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selecting Suitable Sites for Test-burn Plots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Running Simulations of Test Plots in FARSITE</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>DISCUSSION</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Data Collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetation Classification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ArcGIS Fire Model</td>
<td></td>
</tr>
</tbody>
</table>
Using FARSITE to Model Fire of 2000
Selecting Suitable Sites for Test-burn Plots
Running Simulations of Test Plots in FARSITE

APPENDIX .................................................................................................................... 49
REFERENCES.............................................................................................................. 55
LIST OF TABLES

Table

1. Anderson’s (1982) fuel load classes represented on the reservation ............... 15
2. Pathdistance parameters.................................................................................... 20
   Accompanying charts not shown ....................................................................... 23
4. Number of hectares per vegetation class. .......................................................... 33
5. Overall accuracy analysis for vegetation classification. Total Error is calculated
to be 96.57%...................................................................................................... 34
6. Conditional Kappa coefficients for each category............................................. 34
LIST OF FIGURES

Figure

1. Study area location map.......................................................................................... 11
2. Photo of grasslands of reservation......................................................................... 12
3. LANDSAT image is subset to reservation boundary. ........................................... 14
4. Organizational chart of variables and processes for ArcGIS fire model ........... 19
5. A conceptual model representing the process of deciding the location of a burn site.................................................................................................................. 25
6. SAW implementation in ArcGIS Spatial Analyst.................................................. 28
7. Application of Anderson’s (1982) fuel load categories to the vegetation classification done in ERDAS Imagine .......................................................... 32
8. Map of northwest corner of reservation. Shown is the actual fire area in orange diagonal stripes and the output of pathdistance in a stretched spectrum of colors. Only lowest values shown................................................................. 35
10. A hypothetical scenario with adjustments made to wind and the adjustments file......................................................................................................................... 37
11. Map depicting the results of using MCDA and ArcGIS to select suitable testburn sites................................................................................................................. 39
12. Map showing perimeters of FARSITE simulated fires........................................... 40
CHAPTER 1
INTRODUCTION

Ecological restoration has gained increasing recognition for several decades, and use of fire to manage and restore native vegetation is also gaining popularity as a means for restoration. Consequently, the Kaibab Paiute tribal council, in conjunction with the Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), and the Ecological Restoration Institute at Northern Arizona University, have joined forces with the intention of using prescribed fire on the Kaibab Paiute reservation in northern Arizona. Primarily this use of fire will be a means for vegetative restoration, specifically short-grass prairies which have been encroached upon by other native and non-native species of plants. Since this area is federally managed and no burning has been allowed, an excess of the natural fuel-load for fires has put villages located on the reservation in increased danger of catastrophic fire events. Also, the decline of short-grass species has decreased the economic value of the reservation lands for such profitable endeavors as cattle grazing and leases for deer hunting. It was for these reasons that the use of fire has been tentatively prescribed, and that prescription demands the need to accurately predict and model fire behavior using site-specific criteria. The purpose of this research is to provide the land managers of the Kaibab Paiute Reservation an accurate model so fires on the Kaibab Paiute reservation may be simulated and thereby managed. Specifically, the following objectives will be met by this research:

- Collect and create digital geographic data for the Kaibab Paiute Reservation
Assess pre-fire vegetative cover and land use using remotely sensed imagery as well as field techniques

Replicate the boundary of an accidental fire that occurred in the summer of 2000 using ArcGIS™ software (Environmental Systems Research Institute, Redlands, CA)

Simulate the fire of 2000 using FARSITE© fire simulation software (Mark A. Finney, Systems for Environmental Management, Missoula, MT)

Create a map of suitable sites for a test burn using ArcGIS

Model prescribed fires ignited under ideal conditions at those sites using FARSITE

With these specific objectives in mind, the main target of this research is to provide an accurate fire model for the use of predicting the behavior of prescribed fires. This model will provide information on the potential impact of fire on villages and the reservation with the intended outcome being that fires (accidental or purposeful) can be controlled and managed to reduce danger to people and property.

To meet the objectives set forth in this research, it is important to explain through literary review, the main themes of prescribed fire, fire modeling and remote sensing of vegetation. These concepts are covered in Chapter 2. The next chapter discusses, in detail, all methods used to meet the objectives for this project. It is also necessary to include all of the operational components and geographic variables in the models. Geographic Information Systems (GIS) and remotely sensed image analysis were used to create, manage and analyze those variables. GIS plays an integral role in digitally representing the physical features of the reservation while remote sensing, along with field verification using Geographic Positioning Systems (GPS), is used to determine vegetation coverage. Chapter 4 explains the results of the analyses performed for all
levels of the project. Finally, a discussion of successes and difficulties encountered during the course of this project, as well as, recommendations for the Kaibab Paiute Reservation will conclude this report.
CHAPTER 2
LITERATURE REVIEW

Prescribed Burning

As stated earlier, the Kaibab Paiute tribe is involved in an effort to restore reservation vegetation to the native grasses. Prescribed burning is a method that has grown in popularity among restoration ecologists and land managers in recent decades. Parsons, et al. (1986) attribute this management movement to Aldo Leopold who suggested the necessity of preserving “the ecological scene as viewed by the first European visitors”. However, some dispute the goal of restoration through fire management by claiming the use of fire by natives may not be considered a “natural” ecosystem process (Kilgore, 1985).

The use of fire by native Americans for ecosystem health is well documented. Analyzing fire scars on trees can give conclusive evidence to the frequency and intensity of fires in a region (Arno, 1985), but it can be difficult to discern the difference between intentional burns and fires ignited by lightning. Native Americans set low intensity fires in seasons that differed from the seasons most prone to lightning strikes (Kay, 1994). Reasons for native use of burning varied greatly, too. In addition, it is also agreed upon that the use of fire fluctuated between different tribes (Phillips, 1985). A common purpose existed, though, and most accounts given to ethnographers refer to burns as a means of maintaining healthy mosaics of plant diversity and environmental stability (Williams, 1994). This differs greatly from modern uses of fire, such as slash-and-burn, which is often performed to promote the botanical uniformity of monoculture.
Certainly, in current times, multiple reasons for prescribed burns also exist. Prescribed burning is defined by Fischer (1985) for the National Park Service (NPS) as “any fire burning in a predetermined area under predetermined environmental conditions and behaving in a predetermined manner to accomplish a predetermined management object.” NPS management objectives are enumerated by Parsons, et al. (1996) as restoring an ecosystem after misuse or disturbance, protecting a resource, and protecting life and property. All of these objectives apply to this project on the Kaibab Paiute Reservation, However, the Bureau of Indian Affairs has no policy of its own regarding fire management (Tandy, 1985).

As stated earlier, this restorative intervention is desired mainly for grassland areas that have been encroached upon by sagebrush and pinyon-juniper. Maintenance of a grassland ecosystem requires a prescription of low-intensity fires at frequent intervals, which necessitates a reliable, accurate model of fire behavior (Arno, 1985). Also, with obvious emphasis on the keyword “predetermined” in the prescribed burn definition given by Fischer (1985), it is clear that a certainty in predicting fire behavior is vital to this endeavor. Using a GIS fire model is one response to that need.

Modeling Fire

Fire management begins with describing how the characteristics of an area’s ecosystem might be affected by fire (Fischer, 1985). A model is necessary to predict or simulate those affectations (Albini, 1976; Green, et al., 1995; Kilgore, 1985; Kushla and Ripple, 1997; Miller and Urban, 1999, 2000; Ross, 1999). Over time, the concept of this model has changed along with technology. The latest models for fire use GIS-based
data and produce a three-dimensional simulations (Green, et al., 1995; Ross, 1999). This simulation makes it possible to employ prescribed fire techniques more safely and to communicate results easily to managing agencies (Ross, 1999).

Historically, models that predict fire behavior have differed greatly throughout the decades of use. Albini (1976) lists the first documented fire model as being published in 1946. Older models from this time and even some algorithms being published today are completely mathematical, with a calculator as the main processing tool. Unfortunately, a low level of accuracy is inherent with most of these mathematical models, and each model was designed for a specific fuel type without variation, or in some cases, complete heterogeneity of vegetation. Earlier models also were classed under the name of “fire spread” models, giving little attention to the intensity aspect of fire. Later computer-based models, such as FYRCYCL (van Wagendonk, 1985) added more parameters for input, which, in turn, increased accuracy of output data. However, these simulations were still specific to only certain types of fuel loads.

Applications of GIS are taking the lead for simulating prescribed fires because of their unique abilities regarding spatial calculations. Choosing a software package to simulate fire on the Kaibab Paiute Reservation is an important step in meeting the main goal of this research. Two software choices first assessed were FARSITE© (Mark A. Finney, Systems for Environmental Management, Missoula, MT) and FIRE! (Pacific Meridian Resources) which are both stand alone GIS software programs. These two applications have identical input parameters but completely different output displays and user interfaces. Upon further research it was discovered that FARSITE is actually the computational engine of the FIRE! application.
FARSITE, a C++ program, is a raster model versus other GIS models, such as BEHAVE, which use vectors (Green, et al., 1995). Raster models utilize a neighborhood function to create the fire shape and spread (Jensen, 2000). In other words, each cell (raster) uses the constant spatial arrangement of neighboring cells to determine its reaction to the spread of fire. However, BEHAVE is also available for free download and is widely used in the U.S. Forest Service as well as the National Park Service. Further assessment of BEHAVE versus FARSITE revealed that BEHAVE lacked the functions of simulating attack scenarios (planned or unplanned fire fighting field techniques). Therefore, FARSITE was determined to be the premier packaged software choice. This project also explores the use of ArcGIS™ software (Environmental Systems Research Institute, Redlands, CA), alone as a means for modeling fire, although no information was found on this subject.

Vegetation and Remote Sensing

After investigating the use of FARSITE, it became obvious that an important component to the fire model will be constructing a vegetation, or fuel load, classification dataset. Since the purpose of this model is to predict the behavior of an intentional fire, representation of land cover must be accurate. Remote sensing of vegetation in arid regions poses many challenges according to the reviewed literature. Among these problems are difficulties discerning bare land from dried grass, accounting for a shadowing effect from cliffs, and resolution issues. In addition to these classification uncertainties, operational questions arise, such as what imagery should be used and what software will be necessary to compensate for classification difficulties.
All sources reveal remotely sensed imagery to be the best possible source of data for land cover analysis. However the diversity of possible outputs makes the task complicated and often results in variable accuracy due to the subjective nature of vegetation classification (Jensen, 2000). Most sources also agree that LANDSAT7 ETM (30-m resolution) is optimal and easily available. Use of ERDAS Imagine® (Leica Geosystems, www.leica-geosystems.com) software is generally agreed upon as most appropriate for image classification, as well (DeBruin, 2000; Jensen, 2000; Lillesand, 2000; Patterson and Yool, 1998).

More acute problems in classification arise with distinguishing bare land from dead grass. LANDSAT imagery is multispectral, which means that the image has many layers, each representing a different band of spectral reflectivity from the surface of the earth, including three infra-red bands which are valuable in vegetation interpretation. Unfortunately, dead grass and bare sand are very close in their reflectance since neither are photosynthesizing (which reflects brightly in the near-IR). Some researchers address this problem by interpreting satellite imagery with the aid of aerial photographs and hyperspectral imagery, which can be costly (Havstad, et al., 2000; Okin, et al., 2001). Patterson and Yool (1998) attempted to use a linear transform technique to increase accuracy, but they had limited success. Carpenter, et al. (1999) discussed using a neural network, ARTMAP, to process the classification rather than relying on an expert analyst. While this method is designed to be more efficient and reliable, availability and use of this technique was not possible for this project. Using intensive ground survey and GPS could assist and these were the strategies recommended by the U.S. Forest Service in their internet-based Information
System (Burgan et al. 2000) as well as the National Park Service Manual for Prescribed Burning (2000).
CHAPTER 3
METHODS

Study Area

The Kaibab Paiute Reservation in northern Arizona was an ideal study area for this project (Fig. 1). The reservation is 48,737 hec (over 120,000 ac) in size and is unique in its combination of history, geology and vegetation. About 90% of the reservation is undeveloped grazing land or elevated mesas, used for deer hunting. As part of the Arizona strip, this region has a rich history of multi-cultural colonization (Holt, 1992), and, combined with the geology and vegetation types endemic to the Colorado Plateau (Baars, 2000), it serves to make this project a novel case study for prediction of fire behavior.

This topography is part of a much larger region known as the Colorado Plateau, a geologically defined region in the southwestern United States situated in northern Arizona, southern Utah, southwestern Colorado and northwestern New Mexico. It includes deep canyons, high plateaus, mountains, and flat-topped mesas. Populated areas of the reservation consist of five Paiute villages, and one non-Native American community, Moccasin, in the center of the reservation. A point of interest is Pipe Springs National Monument which contains an old Mormon settlement home and one of the area’s natural springs. Locations of these areas are crucial, as they must be excluded from the prescribed fire plots.

Historical land-use is pertinent to this study as a result of overgrazing in the past. Mormon pioneers settled this harsh environment and brought large numbers of cattle through the Arizona strip. These settlers moved into the area in the 1850’s and
exploited the land with massive cattle operations that left the rangelands completely exhausted. At one time it was noted that the area hosted over a million cattle.

Regarding vegetation, the majority of the reservation is considered a piñyon (Pinus edulis) and juniper (Juniperus spp.) plant community. Other dominant species include rabbit brush (Chrysothamnus spp), sagebrush (Artemisia spp.), many grasses including introduced cheat grass (Bromus tectorum), and a large number of herbaceous species. Extreme use as grazing land rendered the natural grasses unable to compete with the invasion of such native species as piñyon pine, juniper and sagebrush and exotics like cheat grass (National Park Service, 2001). Not only do these invasions change the ecology and geology of the land, but they also degrade the land’s economic value for further ranching and deer browsing (Alcoze, 2001; Holt, 1992). A typical
scene of the vegetative state of the grasslands on the southern half of the reservation is shown in Fig. 2.

![Figure 2. Photo of grasslands of the reservation.](image)

Another relevant factor is the history of fire suppression in this area. As part of traditional Paiute land management, burning was integrated with a nomadic existence involving the gathering of piñyon nuts and a few cultivated crops (Alcoze, 2001; Holt, 1992). After Mormon occupation of the region this method came to an end, thus creating a build-up of fuels for fires, a process known as fire suppression (Fischer, 1985). Fire suppression continued after the land became the Kaibab Paiute Reservation in the 1930’s.

Dangers associated with such suppression can be documented following an accidental fire that took place on Moccasin Mesa in the summer of 2000. Several acres near the community of Moccasin burned with only morphology of the land saving the
homes of the Moccasin residents from destruction. Consequently, this fire could be used as a means of validating our fire model.

Data Collection

To meet the main goal of creating a reliable and accurate fire model for the Kaibab Paiute Reservation, the first objective was to gather and/or create digital data representing this unique and remote area to apply the fire model. Data collection was both in situ and remote and was a continuous process throughout the fulfillment of the other objectives. Therefore, this topic will be discussed in each of the following sections of this chapter.

Vegetation Classification

The second objective of this research was to classify the reservation vegetation for input into the fire model as the fuel load component. As vegetative coverage is not homogeneous, it was necessary to use GIS to distinguish these classes spatially. I originally considered using existing vegetation maps such as the GAP vegetation analysis completed by the U.S. Geological Survey (USGS), but the resolution was found to be too coarse for application in a fire model. Also, citations of inaccuracies for this dataset were frequent in literature. Therefore, I acquired satellite imagery to complete the task of classifying vegetation.

Due to cost and availability constraints, two LANDSAT7 Enhanced Thematic Mapper images (ETMs) of the study area were purchased from USGS, a pre-fire (12May2000) and a post-fire (17Sep2000) image. LANDSAT7 ETMs are already
projected to the UTM coordinate system using WGS-84 datum. However, these images are not evenly projected due to inherent inconsistencies with photographic images and usually require further georectification. However, precise points for rectification were not available as the area is remote from the urban environment and is devoid of features easily distinguishable from space. We attempted to use the Digital Ortho Quarter Quads (DOQQs) we received from the BLM office in St. George, Utah, but found that they, too, required rectification. Upon visually assessing the degree of inaccuracy, it was deemed that the best possible step was to omit georectification altogether.

Working with the pre-fire image, I clipped the scene to the area of the reservation. Sub-setting reduces the size of the image in disk storage and subsequently the amount of processing time required for each data set. A digital file of the reservation boundary was downloaded from GIS Data Depot (www.geocomm.com). Then, a subset was performed in ERDAS Imagine® (Leica Geosystems, www.leica-geosystems.com) to include only the area of interest. This transformation is shown in Fig. 3.
The image subset then was classified using a supervised classification technique that assigns individual pixels into a number of user-specified, predetermined categories based on spectral reflectance. These categories were reclassified into land cover classes which were based on fuel load parameters necessary for the FARSITE© model (Mark A. Finney, Systems for Environmental Management, Missoula, MT). Anderson (1982) has defined 13 classes of vegetation coverage which FARSITE documentation recommends using. Only five of those classes are represented within the reservation landscape (Table 1).

<table>
<thead>
<tr>
<th>Vegetation Category</th>
<th>Description</th>
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<tr>
<td>1</td>
<td>Continuous herbaceous coverage with &lt; 1/3 shrub</td>
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<tr>
<td>2</td>
<td>Herbacious material, litter, open shrublands 1/3 to 2/3 shrub, some Pinyon/Juniper</td>
</tr>
<tr>
<td>4</td>
<td>Nearly continuous second overstory, mature shrubs, &gt; 6 feet tall, deep litter, thick Pinyon/Juniper</td>
</tr>
<tr>
<td>5</td>
<td>Young, short, green shrubs, little dead material</td>
</tr>
<tr>
<td>6</td>
<td>Older shrub, &lt; 6 feet tall</td>
</tr>
<tr>
<td>99*</td>
<td>Bare (non-fuel)</td>
</tr>
</tbody>
</table>

* not in Anderson’s categories but necessary for FARSITE

Consultation of the documentation for the input parameters for FARSITE was important in determining the selection of variables for the model. Data necessary for the model include vegetation (or fuel), terrain, location data for villages, and roads. Other variables such as meteorological conditions and soil moisture were also input as raster datasets.

The remainder of the classification procedure was as follows:
• GPS points were collected by Earl Zimmerman in June of 2001; digital photos were taken as well as detailed notes on vegetation cover.

• GPS points were taken personally in June 2002 along with digital photos (all south-facing for consistency) with notes of plant composition and percent of coverage.

• All GPS points were imported into a shapefile and imported into ArcMap™ GIS software (Environmental Systems Research Institute, Redlands, CA). Hotlinks to the digital photos were added, and vegetation descriptions were included as attributes to the points for easier reference during classification.

• Points in the shapefile were then assigned to the designated fuel load categories described by Anderson (1982) and labels were created according to these categories. (Photos of each vegetation type are shown in Appendix B.)

• In ERDAS Imagine, the points were laid over the clipped Landsat image, and, with assistance of Anderson’s (1982) categorical information, photos and DOQQs as a visual aid, a region based on similar spectral values was grown (“region grow” function of ERDAS Imagine) on the image and saved as signatures in the signature editor.

• The signatures were then input into a supervised classification performed by Imagine, and a classified image was the resultant output.

• The output classification was grouped by category. Classes that appeared suspect to inaccuracy (or those that lay in shadows) were masked and
reclassified. This masked classification was mosaiced to the original output to create the final product.

Since the fuel load layer was crucial to the validity of the fire model, and, therefore prediction of fire behavior, it was important to have an accurate classification. This required a means for testing accuracy. One may test for classification accuracy by taking a sample of classified cells and field verifying their accuracy (Jensen, 2001). Based on the binomial probability theory, a common determination of sample size (N) can be computed by the following equation:

\[ N = \frac{Z^2(p)(q)}{E^2} \]

where \( p \) is percent accuracy expected, \( q \) is 100-\( p \), \( E \) is the error term (100 – confidence level) and \( Z = 2 \) based on the standard normal deviate 1.96 for 95% confidence level.

Vegetation classification based on satellite imagery is generally acceptable if the accuracy is above 85%. To determine the minimum number of points for acceptable accuracy testing results, I applied the following equation:

\[ N = \frac{Z^2(85)(15)}{E^2} \]

This yields a sample size of 204. Using ERDAS Imagine, I generated 204 points, output as UTM coordinates, to be field verified for accuracy assessment of the classification using stratified random sampling as the method of generation. A problem with accessibility to those points on the ground was encountered. Access to scattered sites throughout the reservation was impossible due to limited time and resources, making a new sample regime a necessity. As areas with roads (paved or unpaved) were most accessible, the sample sites needed to occur within close proximity to the
roads. A buffer of 30 m (one cell) was created around all features of the roads shapefile. Again the stratified random sample was executed for that buffered area, and the resultant points were used for field verification.

Using a GPS unit, I visited all 204 coordinate destinations and recorded the vegetation class for each location. This information was used to create an error matrix in ERDAS Imagine and to obtain the percentage of overall accuracy. Determining overall accuracy as derived from the diagonal of the error matrix ignores errors of omission and commission. Consequently, I ran another measure of accuracy using the $K_{nat}$ statistic, an estimation of KAPPA. The $K_{nat}$ computation additionally considers the off-diagonal elements by taking the product of the row and column marginals.

ArcGIS Fire Model

The third objective of this research was to explore the possibility of creating a fire model using basic ArcGIS™ Environmental Systems Research Institute, Redlands, CA) tools and extensions. Variables for input were determined by examining earlier models, specifically FARSITE. Data necessary for the model included fuel load, terrain, ignition point and wind direction. The conceptual movement of data through the GIS model is illustrated in Fig.4. Input parameters are shown on the left followed by the source of the data, as well as, the format of the input type. The processing stage is shown in green.

Data collection was a significant portion of this phase of research. All data received was projected to UTM, zone 12, WGS 1984 datum to match the vegetation classification. After being appropriately transformed, if necessary, data were clipped to the boundary shapefile of the Kaibab-Paiute Reservation. USGS was the source for all
digital elevation models (DEMs). DEM’s were downloaded, converted to GRID files, and mosaiced. Elevation GRID datasets created from USGS DEMs have an 83.3-m cell size. The elevation dataset was resampled to a 30-m cell size so that it would match the vegetation classification. Once this was accomplished, the elevation grid was clipped.

Figure 4: Organizational Chart of variables and processes for ArcGIS fire model.

Locating meteorological conditions data, such as the wind direction, proved to be a difficult task. Due to the remoteness of the study area, weather data are not collected on the reservation, or in close proximity. Research online of the National Oceanic & Atmospheric Administration (NOAA) historical data showed St. George, Utah, to be the closest weather station but the data were incomplete and difficult to understand. Weather Underground (www.wunderground.com) was the most efficient provider of these data. However, the important factor of wind direction was missing from their collection. Following personal contact, a representative of Weather Underground
located the data needed within the archives of NOAA historical weather data for Page, Arizona. Page is approximately the same distance from the reservation as St. George and more similar in elevation. Therefore, Page became the operative locality for which to obtain meteorological data.

The last parameter listed in Fig. 4 is the source of the 2000 fire, or the ignition point. For this model the ignition point of the fire on 22 July 2000 was input. This was a GPS point taken based on personal communication from an official of the reservation (D. Bulletts). This point was converted first to a shapefile then a raster source file.

The final obligatory dataset is the perimeter of the fire in 2000. The post-fire satellite image of the study area was used to digitize the burned area in ArcMap. When compared to a surveyed map of the burn area from the BLM, they were nearly identical.

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<th>Table 2. Pathdistance parameters.</th>
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<td>elevation grid dataset</td>
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</tr>
<tr>
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<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>o_allocate_grid</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>max_distance</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>value_grid</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

To create the fire model, I used ArcGIS Spatial Analyst tools which encompass most of the functionality of Arc/Info GRID™ GIS software (Environmental Systems Research Institute, Redlands, CA). GRID has the capability of processing an operation called pathdistance. The pathdistance command calculates the least accumulative-cost
distance over a cost surface from a source cell, while accounting for surface distance and horizontal and vertical cost factors. As with most functions that ESRI software provides, this is a general operation with an array of applications, one of which could be modeling fire.

In other words, theoretically, one should be able to input a number of raster datasets into the algorithm provided in the pathdistance function and output a grid of values quantifying the likelihood of being burned. How these arguments were answered in ArcGIS Spatial Analyst Raster Calculator is shown in Table 2.

Using FARSITE to Model Fire of 2000

FARSITE fire modeling software was also used to simulate the behavior of the fire in the summer of 2000. All the data used in the ArcGIS pathdistance model were used in this model. Additional data were necessary as well as run-time user input. A complete list of all data and their sources can be found in Appendix A.

Again, the meteorological data from NOAA and Weather Underground was used. For this model, I used hourly observations of wind speed, wind direction, temperature, and relative humidity. Fuel moisture was determined based on relative humidity by using Rothermel’s (1983) guide. The calculations for Rothermel’s model, shown in Table 3, are based on such variables as relative humidity, elevation, shade and time of day. The result of these calculations was a constant number, representing fine dead fuel moisture which can then be used to derive 1 hr, 10 hr and 100 hr dead fuel moistures by adding 1, 2, and 4 respectively. Live fuel moisture is estimated by stage of vegetative development. According to Rothermel (1983), vegetation slightly cured or entering dormancy is 50% moisture content, while mature with new growth is at 100%.
All of the live fuel on the reservation was estimated to be in between those two values at 80%. All fuel moisture values are entered in FARSITE based on fuel load.

Vector data were also an important component for a fire model. Vector data such as roads can be an existing barrier to fire, while a village would be an existing feature in need of a barrier for fire protection. All roads on the reservation were digitized to shapefile format from the DOQQs. This shapefile was helpful as a fire model input, and as a mapping component in the field. Finally, slope and aspect were derived from the DEMs using ArcGIS Spatial Analyst.

Upon experimenting with the use of FARSITE, it became clear that using ArcGIS (or Arc/Info) was a necessity to even begin the process. Before simulation can begin, it is necessary to input several spatial and temporal variables for analysis. All inputs, except for run-time user inputs, must be in a precise ASCII format and saved as specific file structures within FARSITE.

First, a landscape file was created. This file represented all of the terrain variables of the study area, including elevation, slope, aspect, and several characteristics about the fuel loads including the vegetation coverage created earlier and fuel moisture. These files were converted using the ArcToolbox™ (Environmental Systems Research Institute, Redlands, CA) function of “GRID to ASCII.” Second, after calculating the dead fuel moisture at the time of ignition, it is converted to ASCII format and saved in the FARSITE inputs. Then, a weather file was created using ambient temperature and relative humidity. A wind file was similarly created with wind speed, direction and time.
Lastly an adjustment file was generated. According to the FARSITE documentation, a first run through a simulation does not work perfectly due to input inaccuracies and a variety of factors that could not be input at all. The purpose of the adjustment file is to calibrate the model for these unknown factors and the adjustment levels were set for each of the fuel load categories. All settings were set to 0.25, except for fuel class 6, which ran more effectively at 0.15. Of course, these values are subjective for the user and are meant to change depending on the results obtained from multiple trials.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ambient temperature</td>
<td>105</td>
</tr>
<tr>
<td>2 Relative Humidity</td>
<td>10</td>
</tr>
<tr>
<td>3 Reference number for fuel moisture (Rothermel, 1983, p.17)</td>
<td>2</td>
</tr>
<tr>
<td>4 Month</td>
<td>July</td>
</tr>
<tr>
<td>5 Table to be used (Rothermel, 1983, p.18)</td>
<td>B</td>
</tr>
<tr>
<td>6 Exposed or shaded</td>
<td>Exposed</td>
</tr>
<tr>
<td>7 Time of day</td>
<td>0900</td>
</tr>
<tr>
<td>8 Elevation change from weather station</td>
<td>Above</td>
</tr>
<tr>
<td>9 Aspect</td>
<td>North</td>
</tr>
<tr>
<td>10 Slope (0-30% or &gt;30%)</td>
<td>0-30%</td>
</tr>
<tr>
<td>11 Fuel moisture correction%- using Month table</td>
<td>1</td>
</tr>
<tr>
<td>12 Initial fine dead fuel moisture (line 3 + line 11)</td>
<td>3</td>
</tr>
</tbody>
</table>

After all inputs were entered, the next step was to run the model. The simulation was initiated by inputting the landscape, weather, wind, fuel moisture, and adjustment files. The user must then set the time and duration of the fire. The fire I was recreating began on 21 July 2000 at 0920 hr. The end time was set to July 25 at 1200 hr, although the precise end time of the fire is uncertain. Roads, the existing barriers to fire, were introduced to the model as a shapefile.
Output parameters were set according to suggestions in FARSITE documentation. Resolution of the perimeter and distance of calculation were set to 30 m to match the input data. This allows for optimum accuracy with the given inputs. The time steps variable was set to 30 min which means that the calculation will process the data in 30 min (real time, not processing time) increments. Finally, the visible steps were set for every 6 hr. Every 6 hr of the fire will produce a line showing the fire perimeter. This feature allows visualization of the fire growth as it proceeds through the simulation.

The last input before initiating the simulation was to load the ignition point. A shapefile was added to the onscreen map depicting this point. This location may also be added manually. Finally, the simulation commenced and processed calculations.

Selecting Suitable Sites for Test-burn Plots

Deliverables of this research project to the agencies managing the reservation, besides the fire model itself, should include scenarios run in the model as test plots. I used ArcGIS Spatial Analyst™ (Environmental Systems Research Institute) and the simple additive weighting (SAW) method of multi-criteria decision analysis (MCDA) to determine the location of sites best suited for the purpose of simple experimental burn plots. The SAW method was chosen from Malczewski (1999) on the incorporation of GIS and MCDA. No new data were necessary for this phase of the project, so the SAW procedure was followed by simply manipulating the existing data using the raster calculator function of Spatial Analyst. A general overview of the plan is presented in Fig. 5.
Since vegetation is homogeneous, in that no type is preferable over another for ability to burn, I simply classified it for vegetation coverage or bare. Fire literature maintains that fire management may be simpler on level land, so it was determined that an experimental test burn would be better with less sloping topography. Access to the burn site would also be necessary, so a roads dataset was an important inclusion. The previously-burned area was also an input variable, as it would not benefit from being burned a second time. Other exclusion zones from the fire were considered, such as locations of villages, the National Monument, the town of Moccasin, and the boundaries of the reservation.

Figure 5. A conceptual model representing the process of deciding the location of a burn site.

Preparation of these datasets could not begin until a plot grid was determined. As stated earlier, most of the land is undeveloped, leaving no actual boundaries within the reservation that could be used as plots for this spatial determination. In other
words, no smaller parcels could be compared against each other regarding their relative values as test sites. Therefore, I opted that the land be measured off in grid cells; the question was what size?

The fire on the reservation in the summer of 2000 burned for 4 days, consuming 655 hec (1,618 ac). Since prescribed burns are best managed in a 1-day period, the test plot size was determined by taking the area of the fire of 2000 and dividing by four. Thus, the area of each cell was 169 hec. Calculating out to 330 plots contained within the study boundary, this was considered to be a manageable number of plots for analysis and comparison.

After the grid size was determined, resampling, and, in some cases, constructing the grids were the next processes to be performed. Some grids simply needed to be resampled to change the cell size. Other layers, however, needed reclassification or even more complex functions performed on them so they would be helpful to this analysis. Following is a list of all layers and the steps that were taken to prepare them to be used in the SAW process. (See also, Fig. 6 for a detailed diagram of the SAW procedure.)

1. Vegetation – Reclassified to either vegetated or bare (0 or 1), then resampled to 1300-m cell size
2. Slope – Cell size resampled to match vegetation
3. Burned area – Feature to raster function of Spatial Analyst used, masked to slope and reclassified to 0 or 1 (not-burned, burned)
4. Points to not burn – Point feature to raster, masked to slope and reclassified to 0 or 1
5. Boundary – Line feature to raster, masked to slope and reclassified to 0 or 1 (cell contains boundary or not)

6. Highway – Separated from roads shapefile and line feature to raster, masked to slope and reclassified to 0 or 1

7. Distance from highway – Costdistance function run in raster calculator 
   (temporary grid with fixed value of one created for cost grid, and highway grid was source) Equation reads: “costdistance (highway, tempgrid, #, #, #, #)

8. Distance from other roads – Roads shapefile (without the highway) converted from feature to raster and masked to slope and reclassified to 0 or 1.
   Costdistance function was run (same process as for Distance to highway)

After the data were ready to analyze, I implemented the SAW method in Spatial Analyst. This process was almost entirely accomplished using the raster calculator. Once the layers were resampled, the values had to be standardized using the score range method. This method is particularly appropriate for determining the lowest cost alternative. Equation A, below, was interpreted to equation B for implementation in the raster calculator.

\[ x_{ij} = \frac{x_{ij} - x_i^{min}}{x_i^{max} - x_i^{min}} \]

\[ (<grid\_layer> - minimum\ value) / (Maximum\ value - minimum\ value) \]
Using this equation sets all the data layers on a scale of 0 to 1, or in some cases 0 or 1. In all instances, 0 would be considered beneficial, as it is the least cost plot for that particular criterion.

Figure 6. SAW implementation in ArcGIS Spatial Analyst

Define evaluation criteria

Choose layers, resample, reclassify, costdistance

Standardize values among layers

Score range procedure in raster calculator

Weights

Multiply each standardized layer by its weight in raster calc.

Overall score

Add all weighted layers in raster calc.

Slope, boundary, villages, distance to roads and highway, burned area, veg. cover

GRID – MINIMUM

Max – min (sets all layers on 0-1 scale)

Villages * .30
Boundary * .13
Dist. to roads * .18
Veg. cover * .10
Past fire * .10
Slope * .07
Dist to hwy * .05

Rank grid into classes from good to bad test sites
Once the data layers are standardized, weights can be determined and applied. These weights (Fig. 8) are chosen by the decision maker. Obviously, the villages would be the most costly alternatives to burn, and so these were given the highest weight. Access to the plot also ranked high in the weights, while slope and distance to the highway ranked relatively low. Multiplication of the standardized grid layers and their assigned weights were performed one at a time in the raster calculator. Finally, the weighted layers were added together in the raster calculator to achieve the objective. Output from this calculation was a grid that had values from 0 to 1, representing the cost of burning a given plot. The closer the value was to zero, the more suitable that plot would be for an initial test burn on the reservation. Upon studying the data, it was determined that ranking the 330 cells would be confusing to the observer. Therefore, a classification of those values was made. Five classes were named: Best plots, Adequate plots, Acceptable plots, Questionable plots and Unacceptable plots. The classification method was based on natural breaks, and the last class was manually widened to encompass the entire lower half of the ranked values. Also, the upper class was restricted to the six highest ranking plots which all tied for the lowest value.

Running Simulations of Test Plots in FARSITE model

Once the best test plots were identified, the last phase of this research was to simulate prescribed burns in those plots. Here, it should be indicated that it is beyond the scope of this project to actually prescribe the burn, itself. However, to meet this objective, it is necessary to enter the appropriate input parameters and simulate a fire’s behavior in that given area. Given that input parameters for a prescribed burn require
data such as ideal wind, weather, and fuel moisture conditions, those variables were researched so that the input would be as accurate as possible for how an actual prescribed burn would perform.

With this in mind, assumptions were made regarding how the actual prescription would be administered based on general research of prescribed fires. The first assumption is that there would be a barrier around the plot created at the time of or prior to the burn. For the purposes of the simulation model, the boundary of the burn plot was entered as though it were a barrier, as were the roads data.

It can be assumed that the prescription would call for a certain range of ideal conditions for a safe, manageable fire to occur. Upon reviewing the work of Scifres (1993) this range was decided upon being 24 km/hr (15 mph) for wind speed and 32°C (90° F) for temperature. Personal communication with residents of the reservation informed me that the predominant wind direction in the summer is from the southwest. Therefore, wind direction was set to a constant 225 degrees. Initial fuel moistures were recalculated, again using Rothermel’s guide, based on the ideal of 20% relative humidity.

The following other changes from the initial simulation were made to the input data:

- Adjustments were reset to 1, since these test models were only run once and with no way of checking for accuracy.
- Ignition points for each of the plots were placed arbitrarily within the plot. Three of the plots were burned using the concept of a headfire, while the remaining three were ignited with a backfire concept in mind.
To simplify and maintain consistency, 4 hr was entered as the duration for each of the test burns. Common sense dictates that the duration would be of a manageable period of time, i.e. less than a day. Since this variable is entered at run time, if it is deemed by the prescribed burn crew that the time should be longer or shorter, this variable is easily altered.

Also, the visible increments of fire growth were set to 30 min.

No changes were necessary for the landscape file. It is assumed that no changes to the actual landscape have occurred since the time of the fire of 2000, except for the burn itself. While the post-fire image was available to classify and use as input, it was an unnecessary step, due to the fact that the test plots were not in close proximity to the burn site.
Vegetation Classification

From the representation of classified vegetation (Fig. 7), it is clear that the predominant vegetation type in the southern portion of the reservation is the grassland with sagebrush (classes 1 and 2), while in the more northern regions larger fuels such as piñyon and juniper dominate (classes 4 and 6). Class 5 is seemingly absent from the map as it mainly represents riparian vegetation. Bare ground or rock is seen scattered throughout, mainly cliff faces and , in the southern
portion, bare soil. Since the vegetation in Fig. 7 has been laid over the elevation model, it can also be seen that the piñyon and juniper habitat correspond with the higher elevation areas.

Counts for the area covered by each class of vegetation are shown in Table 4. These areas were calculated by multiplying the total number of cells for each class by 900 which represents the 30-m resolution. Clearly the largest area is covered by class 1 and 2 which are sparse sagebrush dominant rangelands.

<table>
<thead>
<tr>
<th>Fuel Load Class</th>
<th>Total Hectares Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19,519.65</td>
</tr>
<tr>
<td>2</td>
<td>14,432.49</td>
</tr>
<tr>
<td>4</td>
<td>1,931.13</td>
</tr>
<tr>
<td>5</td>
<td>63.45</td>
</tr>
<tr>
<td>6</td>
<td>12,482.91</td>
</tr>
<tr>
<td>99</td>
<td>643.41</td>
</tr>
</tbody>
</table>

When I calculated overall accuracy for the classification by using an error matrix I got 96.57% correct (Table 5). Accuracy is split into two categories; producer’s accuracy and user accuracy. Producers accuracy shows the percentage of correctly classified cells divided by the reference cells for that category, while users accuracy is a term reserved for the number of correct cells divided by the total number of elements classified. Another standard assessment of accuracy is the Kappa Coefficient of Agreement. Results for the Kappa Analysis showed almost 95% accuracy and are shown in Table 6. Kappa coefficient compares the observed agreement to agreement expected by chance. Kappa coefficient is considered to be the more valid assessment of accuracy of the two methods, as the values present in the error matrix have not been
standardized. Kappa analysis corrects this by using the marginals as well as the diagonals.

Table 5. Overall accuracy analysis for vegetation classification. Total error is calculated to be 96.57%.

<table>
<thead>
<tr>
<th>Class</th>
<th>Reference Totals</th>
<th>Classification Totals</th>
<th>Number Correct</th>
<th>Producers Accuracy</th>
<th>User Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>89</td>
<td>85</td>
<td>85</td>
<td>95.51%</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>57</td>
<td>53</td>
<td>98.15%</td>
<td>92.98%</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>100%</td>
<td>85.71%</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>52</td>
<td>51</td>
<td>96.23%</td>
<td>98.08%</td>
</tr>
<tr>
<td>99</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>100%</td>
<td>66.67%</td>
</tr>
<tr>
<td>TOTALS</td>
<td>204</td>
<td>204</td>
<td>197</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Conditional Kappa coefficients for each category.

<table>
<thead>
<tr>
<th>Class</th>
<th>Kappa Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.9046</td>
</tr>
<tr>
<td>4</td>
<td>0.8528</td>
</tr>
<tr>
<td>5</td>
<td>0.0000</td>
</tr>
<tr>
<td>6</td>
<td>0.9740</td>
</tr>
<tr>
<td>99</td>
<td>0.6634</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.9493</td>
</tr>
</tbody>
</table>

ArcGIS Fire Model

Results from using the pathdistance function in ArcGIS Spatial Analyst Raster Calculator™ (Environmental Systems Research Institute, Redlands, CA) provide an output GRID with continuous values that were classified into categories (Fig. 8). On the map in Fig. 8, red indicates the category of cells most likely to have burned in the fire. As the spectrum spans out the blue (not shown on map) those areas are less likely to burn. Categorization was performed to show that, indeed, the lowest category does appear to show similarity, at least in size, to the actual area of the fire of 2000. I used
20 classes based on natural breaks to achieve what can be considered to be only an aesthetically correct result (seen in deep red).

While the map shows similarity in size, the area of the pathdistance output shown in red is actually 1,022 hec while the area of the actual burn was 655 hec. It may also be seen that roads are absent therefore barriers to fire are non-existent. If this model were to be used, it could be assumed that, were this a real fire, it would not have an end in time or space but would suddenly stop at the reservation boundaries where the data input ceased.

Figure 8. Map of northwest corner of reservation. Shown is the actual fire area in orange diagonal stripes and the output of pathdistance in a stretched spectrum of colors. Only lowest values shown.
Using FARSITE to Model Fire of 2000

Given the available data, the most accurate simulation of the fire of 2000 was only achieved after several trial runs in FARSITE© (Mark A. Finney, Systems for Environmental Management, Missoula, MT) fire simulation software (Fig.9). Several attempts were necessary as wind/weather data came available. Strikingly, when viewed against the area of the actual burn, clearly one can see there is no match in perimeter. In fact, with the actual burn area measuring 655 hec, the simulation area more than doubles that calculation at 1,462 hec. The simulated perimeter is shown in orange and can be seen at 6-hr intervals of the fire’s growth. On day two of the simulated burn, one measurement of area came close to reaching that of the actual burn when, at 1600 hr, it measured 667 hec.

When faced with such a drastic difference in fire perimeter, I attempted to hypothesize on the cause of the inaccuracy. Wind is one of the most powerful forces
behind the movement of fire, as well as one of the most predictable. This combination of characteristics made wind a likely source of the inaccuracy in the burned area of the simulated fire. While fully aware that changing the data to suit the model would not prove, one way or another, the accuracy of the model, I, at least wanted to attempt to pinpoint some cause of the discrepancy.

Manually, I changed all of the wind direction data over 270 degrees to be exactly 270. My prediction was that with a slight change in the wind variable, I could “push” the simulated fire out in the direction of the actual fire. To account for the areal difference, I modified the adjustment factor, lower, still to 0.15 for all classes except class 6 which I changed to 0.10. The results of these changes can be seen in Fig. 10.

Figure 10. A hypothetical scenario with adjustments made to wind and the adjustment file.

Surprisingly, the shape of the perimeter (shown now in green) changed very little from these changes. As compared to the simulated perimeter in Fig. 9, one can see that the size of the fire has been reduced. The area of this simulated fire was 920 hec.
However, it is impossible to know whether the changes in size were brought about by changing the adjustment, the wind direction, or a combination of those variables based on the given terrain data.

While creating this hypothetical scenario, it became clear that there are too many variables, many seemingly accurate that could be the cause of the miscalculations of the model. With this in mind, I attempted, again to recreate the fire of 2000 with hypothetical data, this time changing all wind direction data to 230 degrees, which is said to be the predominant wind direction on the reservation.

![Figure 11. Trial run with wind direction set to 230 degrees.](image)

Maintaining its consistent fan-shape, the simulated fire outline (depicted in blue in Fig. 11) for this wind direction results in a model that is still unable to predict accurately the actual fire. The cause for this remains unknown.
Suitable Sites Using ArcGIS and MCDA

Test plots selected and their suitability for a test burn using ArcGIS™ software (Environmental Systems Research Institute, Redlands, CA) are shown in Fig. 12. Areas least recommended for burning (blue) are located, as predicted, mostly at the reservation boundary. A minor issue is the shift in the grid during resampling. This problem was noted and quickly disregarded, since burning near the reservation boundaries would not be recommended because of the risk of escaped fire. Also, completely within the least recommended areas for burning, as predicted, were the occupied villages and NPS and reservation facilities (seen as points). Categorized as “Questionable Plots” are roadless areas with a higher slope value (light blue). “Acceptable” and “Adequate” plots are depicted in yellow and tan, respectively. These areas appear to be flatter and/or with access to roads. The six cells that were calculated to be the best test-burn plots are near the highway for easy access and have little slope (not shown). They are also a sufficient distance from human-occupied areas and the National Monument. Based on personal knowledge of the reservation features, I conclude that these areas are appropriate sites on which to run simulation test-burns. A quick calculation indicates that, of the total area of the reservation, approximately 50% can be managed with fire.
Modeling the Results of MCDA with FARSITE

Taking into the consideration the difficulties resulting from the initial simulation, there was no way to assess the accuracy of the results of the Multicriteria Decision Analysis. After making appropriate alterations to the methods of the first FARSITE simulation, I ran the model on the Best Test Burn Plots and mapped the resultant shapefiles in ArcMap. The simulated perimeters (Fig. 13) are depicted with each line representing a 30-min interval of the simulation. Upon analyzing the number of intervals for each test burn, it is apparent that the ignition points set for a headfire burn the entire plot quickly, sometimes in less than an hour. As could be predicted the backfires burn more slowly, as can be evidenced by multiple lines of perimeter.
For each of the scenarios run, the entire plot (169 hec) was burned, unless there was a barrier such as a road within the perimeter of the plot, in which case the fire stopped at the road. All three headfires grew at almost the same rate, extinguishing between 0.5 hr and 1.5 hr. Backfires took significantly longer, but also moved at rates comparable to each other. Each took nearly 3 hr to burn.
CHAPTER 5
DISCUSSION

Data Collection

To acquire data, I used the traditional methods of search and download, purchase, creating with a GPS and digitizing from borrowed photography. This allowed me to meet the objective of attaining all the necessary data, even the elusive wind and weather data. Certainly the most valuable data collection came from going in the field with the GPS unit and collecting points. For the ignition point of the fire, this was the only way to get the information. Fortunately, the char from the burning vehicle, which was the origin of the fire of 2000, remains on the road and vegetation at that site. Field verification for the fuel load classification was vital, as well, and best suited to using a GPS as the method of choice. Digitizing features from satellite imagery and aerial photography also proved to be a successful method.

Little data needed to be purchased. As stated earlier two LANDSAT7 images were purchased, but only the pre-fire image was necessary. While the post-fire image was used for digitizing the burned area, that information could have been obtained from the BLM.

Vegetation Classification

I knew from the literature that classification of vegetation in arid environments can be problematic. While originally I tried using an unsupervised classification, the method of using a supervised classification in ERDAS Imagine® software (Leica Geosystems, www.leica-geosystems.com) using field reference points and aerial
photography was successful. However, there is some question left from this research about the validity of using Anderson’s (1982) fuel load model for arid-land vegetation types. The question remains; can all the factors of fuel load be captured in 13 categories? Also, can those factors be measured accurately using 30-m resolution satellite imagery? To answer these questions, I recommend expanding the 13 categories to be more specific and all-encompassing. It may also be useful to purchase and classify higher resolution imagery. For this project, I felt that the geographic extent of the data as well as cost, prohibited such a choice.

ArcGIS Fire Model

Since ESRI’s ArcGIS™ software (Environmental Systems Research Institute, Redlands, CA) was already installed in our research facility, and I wanted to use all our existing resources before implementing other approaches, I applied it to its full “out-of-the-box” potential by using the pathdistance command to model fire. Pathdistance was the closest function possible for weighing so many variables. ESRI has reported its capability to use its extensions to analyze the risk of fire but not yet the prediction of its behavior.

Obtaining an accurate model was dubious, since the algorithms that other models employed in this task were absent from the ArcGIS functions. Problems with applying this method to fire modeling are inherent and abundant. First and foremost, fire “accumulation,” which is the growth of the intensity, is a complicated calculation, one for which this procedure may not necessarily be well suited. Second, there was no standardization of the input data. One would think that, with elevation ranges in
thousands of meters and vegetation nominally ranging from one to fourteen, the computation would not produce results with a high level of accuracy. Another area of uncertainty is the use of “least” cost. Intuitively, it makes more sense to determine the “most” desirable cells for the fire to be used as a management tool. While this may cause some confusion, a possible resolution of this problem might be to reclassify data into lower discrete values to make more desirable circumstances. Finally, the most complicated aspect of using this method may be the weights of the actual variables themselves. For instance, how does elevation effect the movement of fire? What if the wind is pushing it uphill? As it was not possible to include these important scenarios, I conclude this method is not effective for modeling fire at this time.

Using FARSITE to Model Fire of 2000

While it may seem that the modeling of fire using FARSITE© software (Mark A. Finney, Systems for Environmental Management, Missoula, MT) on the Kaibab-Paiute Reservation, was not accurate, given the probable causes for that failure, the application of FARSITE may still be a helpful tool for predicting the behavior of prescribed burns in the area. It would seem that the location which made this case study for fire modeling unique, also made data collection, particularly historic weather data, a difficult task to accomplish. For prescribed fires, this will not be an issue, since with controlled burns the weather is taken at various points on site during the planning and operation phases.

Any number of variables could have played a role in the inability to recreate the fire of 2000. A first estimation was that the wind/weather component of the model was
incorrect for the location on the dates of the fire. In the data collection phase of the research, it was difficult to locate historic data from a site on or near the reservation. The closest weather station in Fredonia, Arizona, closed in 1976 (NOAA). As previously stated, meteorological information for Page, Arizona was used. One can assume there are immeasurable differences between these two areas, since there are at least 200 km between them. Perhaps at a later date, a comparison of historic data to that of Fredonia prior to 1976 may be made. For now, though, my conclusion is that in order to have simulated the fire as it actually occurred, records of the weather conditions would have had to exist closer to, if not on, the reservation itself.

Other possible inaccuracies involving the input variables must include resolution of raster data. Terrain data were available at 83.3-m resolution. At this scale, slope of cliff faces which are frequent in this southwest topography may be vastly underestimated or even spatially inaccurate. Another resolution issue might be the vegetation classification. Even with a high level of accuracy, the 30-meter cell size cannot take into account discontinuity within a given cell. Imagine can only interpolate the average vegetation coverage for the entire cell.

Vegetation type itself may play some part in the problems faced in the results of the FARSITE model. While the fuel load categories set forth by Anderson (1982) appeared to be all-inclusive for vegetation types, it was necessary to use less stringency in interpretation in order to make the sagebrush grasslands and piñyon-juniper mesa-tops fit into the categories as they were written. It appears that fuel load capacities for these vegetation types, need to be investigated and determined more precisely.
Any one of these reasons or a combination including the unknown may be the cause of our inability to exactly recreate the fire of 2000. These problems do not, however, reflect the validity of the model’s ability to predict the behavior of a prescribed fire. During a prescribed fire many data are collected in the field, such as wind, temperature and fuel moisture. Perhaps if these variables are correctly input, the model would accurately simulate the behavior of the fire. At this time, there is no way to know.

These specific issues taken into consideration, applications of the FARSITE model exemplify the need for numerous variables, many of which are spatial in nature. GIS can provide the means of creating and managing those data. I have also demonstrated a need for further advancements in the field of modeling the complexities of fire. As our skills and knowledge of this phenomenon move forward, so, too, should our ability to capture it digitally in GIS.

Selecting Suitable Sites for Test-burns

The resulting output from the multicriteria decision analysis was a second attempt. After the first attempt, weights were altered, and the highway itself was added as a separate cost criteria. Upon making these changes, it was realized that this is a subjective process, and there is low probability that someone else could repeat this project and get the same results unless the decision made by the original user are applied. Under these constraints, there is a high level of reproducibility.

Another important issue in the MCDA is selection process for the grid cell size. From general research of fire behavior, it is known that a fire does not grow at a steady rate, but expands almost exponentially. Since this cell size is approximately ¼ that of
the area burned in 2000, simply dividing that area by four would yield a much larger area than would probably burn in one day. This problem is of minimal importance, however, since the majority of planning and managing a prescribed burn is done in situ, and such issues as plot size could be changed easily in the decision-making process of the fire planning.

Aside from these minor difficulties, overall the resulting grid and map resulting from the MCDA appear to have been successful in determining those areas best suitable for management using controlled burns. As for this phase of the project, I conclude that this method was a successful approach in meeting the objective and will serve as a practical aid in the actual fire planning on the reservation.

Running the FARSITE Model on the Test-burn Plots

An obvious problem with this phase of the project is the inability to test the results for accuracy. In other words, since I could not determine the precise cause of inadequacy for the model to predict fire behavior when recreating the fire of 2000, knowing which variables might need to be altered for the simulated test-burns must be determined.

Another issue which came to my attention after researching the ideal values of inputs for simulated test-burns, is whether or not fire is an appropriate restoration tool for this type of environment. Fire prescriptions are specific to the purpose and goal of the fire. For example, if the goal is to kill all the sage on a rangeland you would need an extremely intense fire capable of producing temperatures that will heat the sub-soil sufficiently so that the roots do not re-sprout (Scifres, 1993). Obtaining that fire intensity
will be difficult on the rangeland of the reservation due to the spatial distribution of the herbaceous vegetation and the shrubs themselves. Strong wind may promote such intensity, although creating a burn that might have a higher level of risk from the standpoint of management.

Based on the research presented here, I conclude that the methods applied to modeling fire on the Kaibab-Paiute Reservation did not yield a reliable system for predicting fire behavior. My recommendations for proceeding with plans for prescribed burning are to create careful fire prescriptions with stringent wind and weather requirements and that all variables entered into the planning process be field verified. As safety is a premium requirement for this type of endeavor, this can be the only plan of action.
APPENDIX A

DATA AND SOURCES
<table>
<thead>
<tr>
<th>Data</th>
<th>GIS Data type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
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<td>Imagine Image (.img)</td>
<td>Classified from Landsat 7-TM</td>
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<tr>
<td>Elevation</td>
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<td>USGS Online</td>
</tr>
<tr>
<td>Slope and Aspect</td>
<td>Calculated in ArcGIS</td>
<td>Elevation GRID</td>
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<tr>
<td>Burned area from 2000</td>
<td>Polygon shapefile</td>
<td>Digitized from Landsat 7-TM</td>
</tr>
<tr>
<td>Reservation Boundary</td>
<td>Polygon shapefile</td>
<td>GIS Data Depot online</td>
</tr>
<tr>
<td>Highway and roads</td>
<td>Line shapefile</td>
<td>Digitized from DOQQs</td>
</tr>
<tr>
<td>Ignition point</td>
<td>Point shapefile and GRID Format</td>
<td>GPS converted to shapefile</td>
</tr>
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<td>Reference points for image classification</td>
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<td>Colorado Plateau Boundary</td>
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<tr>
<td>Major Cities</td>
<td>Point Shapefile</td>
<td>ArcView Sample Data</td>
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<tr>
<td>Points of Interest</td>
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<tr>
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<td>Weather Underground online</td>
</tr>
<tr>
<td>Wind Speed and Direction</td>
<td>Text Data</td>
<td>NOAA online</td>
</tr>
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</table>
APPENDIX B

PICTURE SERIES DEPICTING

VEGETATION TYPES OF THE RESERVATION
REFERENCES


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