# MAPPING FUELS FOR FIRE MANAGEMENT ON THE GILA NATIONAL FOREST, NEW MEXICO

Robert E. Keane, Scott A. Mincemoyer, Kirsten M. Schmidt, Janice L. Garner
USDA Forest Service, Rocky Mountain Research Station
Fire Sciences Laboratory, Missoula, MT 59807
Phone: (406) 329-4846; FAX: (406) 329-4877
E-mail: bkeane/rmrs_missoula@fs.fed.us

## ABSTRACT

Fuel input layers for the FARSITE fire growth model were created for all lands in and around the Gila National Forest, New Mexico, using satellite imagery, terrain modeling, and biophysical simulation. FARSITE is a spatially explicit fire growth model used to predict the growth of wildland fires in terms of size, intensity, and spread. It requires eight data layers as input; fire behavior fuel model, crown closure, crown base height, stand height, crown bulk density, elevation, aspect, and slope. These input layers were created from a digital terrain model (elevation, aspect, and slope) and from base vegetation layers of biophysical settings, cover type, and structural stage using a methodology designed to be easily replicated by other fire management agencies. Biophysical settings describe long-term environmental conditions and this layer was created from a vegetation-based potential vegetation type classification modeled from hierarchical topographic rulebase terrain models. Cover type and structural stage layers were created from 1993 and 1997 satellite Thematic Mapper (TM) imagery of southwestern New Mexico. Fire behavior fuel models were assigned to each biophysical setting, cover type and structural stage category combination from an analysis of comprehensive field databases created by extensive plot sampling of the entire study area. An extensive accuracy assessment of the layers showed accuracy ranges from 25 to 87 percent for the potential vegetation type, cover type, and structural stage layers. Accuracy for the crown and surface fuels layers is between 40 to 70 percent.

**Keywords:** Fuel mapping, fire modeling, Gila National Forest, terrain modeling, satellite classification



## INTRODUCTION

The prolonged effects of over seventy years of fire exclusion in the western United States has necessitated the use of fire for returning ecosystem health and preventing disastrous wildfires (Boucher and Moody 1998, Covington et al. 1994, Dahms and Geils 1997). Fire managers need a way to quickly evaluate the potential size, rate and intensity of a wildland fire to aid in short- and long-term wildland fire planning and resource allocation. Recent advances in computer software and hardware technology have allowed development of several spatially-explicit fire behavior simulation models that predict the spread and intensity of fire as it progresses across the landscape (Andrews 1989). Some of these computer programs have the ability to project future fire growth and compute possible perimeters of wildland fires for planning applications and for real-time simulations. One of the better spatially-explicit fire growth models is the computer program FARSITE (Fire Area Simulator) available for use on most IBM-compatible personal computers (Finney 1994, 1996, 1998). FARSITE is currently used by many wildland fire managers in the United States and other countries to predict spatial characteristics of prescribed natural fires and wildfires (Finney 1998, Keane et al. 1998b).

Realistic predictions of fire growth greatly depend on the accuracy of the input data layers needed to execute spatially explicit fire growth models (Keane et al. 1998a, Keane et al. 1998b, Finney 1998). FARSITE requires eight data layers for surface and crown fire simulations (Finney 1996). These data layers must be accurate and consistent for all lands and ecosystems across the analysis area, and more importantly, the layers must agree with all other layers in the Geographical Information Systems (GIS) (i.e., spatially congruent). It is also helpful if these layers describe large land areas (e.g., greater than one million acres) so simulated fires will not encounter missing data at layer boundaries (Grupe 1998). Comprehensive development of these input data layers requires a high level of expertise in GIS methods, fire and fuel dynamics, field ecology, and advanced computer technology (Verbyla 1995). It also requires abundant computer resources.

Unfortunately, many land management agencies do not have the computer resources or expertise to develop these complex spatial data layers.

So paradoxically, the FARSITE model, which is available for free to anyone, requires fuels layers that are quite difficult to build (Keane et al. 1998b). Since FARSITE has been selected by many federal land management agencies as the best model for predicting fire growth, many fire managers across the country are currently learning how to use this tool and are desperately trying to obtain the input data layers needed by the model for their respective land areas. Unfortunately, most fire and land managers do not have these fuels maps, or even vegetation base maps from which they could create the FARSITE fuels maps for their area. Most existing vegetation layers and databases do not quantify fuels information to the level of detail or resolution needed by FARSITE. Moreover, some attempts to create FARSITE layers from existing maps have failed because of inexperience with fuels and vegetation modeling and mapping in the context of fire behavior.

Fire managers from the Gila National Forest and the Southwestern Regional Office of the USDA Forest Service had some unique fire management challenges. Areas in and around the Gila National Forest in southwestern New Mexico have a rich history of frequent fires, especially in the montane dry forests and grassland ecosystems (Abolt 1997, Boucher and Moody 1998). However, effective fire suppression during the last 70 years has increased surface and crown fuels resulting in increased potential for uncontrollable wildfires (Covington et al. 1994, Dahms and Geils 1997). Moreover, intensive grazing in pinyon-juniper woodlands and grasslands had reduced grass competition so conifer encroachment has proceeded unchecked by fires (Dahms and Geils 1997). Fire managers wanted to use the FARSITE computer program to simulate current and future fires for planning and managing fire restoration and wildfire management projects, but they did not have the resources to construct the detailed FARSITE input layers needed for such a large area. Moreover, they wanted to develop spatially explicit, digital fuels maps for other fire management concerns, such as smoke generation and fuel consumption, to include in the fire planning process. We had just completed development of FARSITE input layers for 2.3 million acres in the Selway-Bitterroot Wilderness Complex and had refined several new methods for mapping fuels and vegetation in mountainous terrain (Keane et al. 1998a, 1998b). The Gila National Forest managers asked us to develop FARSITE data layers for their area using these new methods, and they would then take the methods learned for their area to show other Forests in the Region how to map fuels on their areas.

The primary objective of this mapping project was ***to develop all input spatial data layers required by FARSITE to spatially simulate fire behavior on lands in and surrounding the Gila National Forest***. In addition, we agreed to develop several other vegetation and biophysical layers and relational databases useful for other phases of fire and natural resource management. In fact, the vegetation base layers developed from the secondary objectives of this study were essential for the creation of the FARSITE input data layers in the primary objective.

**FARSITE Input Description**

FARSITE requires eight spatial data layers for a comprehensive evaluation of surface and crown fire behavior. The first raster layer needed by FARSITE is called a Digital Elevation Model (DEM) where each pixel is assigned an **elevation**. **Slope and aspect** are also required FARSITE input layers and they are easily derived from the DEM layer using elevation values from surrounding pixels (USGS 1987). The fourth layer is a **Fire Behavior Fuel Model** (FBFM) map. Pixels in this layer are assigned the fire behavior fuel model (Anderson 1982) that best represents the surface fuel complex for the corresponding piece of ground. Surface fuels can be input as either a fire behavior fuel model (Anderson 1982) or customized fuel models (Finney 1994). We used seven of Anderson's (1982) thirteen FBFM and then built two customized fuel models for some unique conditions in the Gila National Forest. Average **canopy cover** is needed to compute hourly fuel moistures and reduce wind under the forest canopy. Canopy cover (percent) is the average vertically-projected tree crown cover in the stand. These are the minimum number of layers needed to simulate surface fire behavior and growth.

FARSITE can compute crown fire behavior if three other vegetation data layers are present. **Average stand height** (m) and **average crown base height** (m) are data layers FARSITE needs to compute crown fire initiation based upon the Van Wagner (1977) crown fire model. Stand height is the average height of the dominant tree layer. Crown base height is the average height to the bottom of tree crowns in the stand. A **crown bulk density** raster layer is used to compute crown fire spread, along with the previously mentioned crown cover map. Crown bulk density (kg $m^{-3}$) is the density of the tree crown biomass above the shrub layer. We used vegetation characteristics to guide our estimations of crown bulk density in the field. A complete discussion of FARSITE algorithms is presented in Finney (1998).

**Study Area**

The FARSITE input layers were developed for all lands in and around the Gila National Forest with boundaries defined by the limits of the satellite imagery and Digital Elevation Model (DEM) coverage (Figure 1) (USGS 1987). This study area will hereafter be referred to as the **Gila National Forest Complex (GNFC)**. Elevations range from 1370 m in the low elevation grasslands to over 3000 m along the Mogollon Rim in the southwestern GNFC. Vegetation in the area ranges from desert grassland and scrub at the lowest elevations to subalpine forest at the highest elevations. Mixed woodlands of pinyon (*Pinus edulis*), juniper (*Juniperus spp.*) and oak (*Quercus spp.*) and forests of ponderosa pine (*Pinus ponderosa*) interspersed with plains-mesa grasslands at mid elevations occupy large expanses of the GNFC. Upper elevations are dominated by montane coniferous forests of white fir (*Abies concolor*), blue spruce (*Picea pungens*), Douglas-fir (*Pseudotsuga menziesii*) and southwestern white pine (*Pinus strobiformis*) with the highest slopes and ridges dominated by subalpine coniferous forests of subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). Broadleaf forests of quaking aspen (*Populus tremuloides*) and Gambel oak (*Quercus gambelii*) also occur interspersed throughout the montane and subalpine forests.

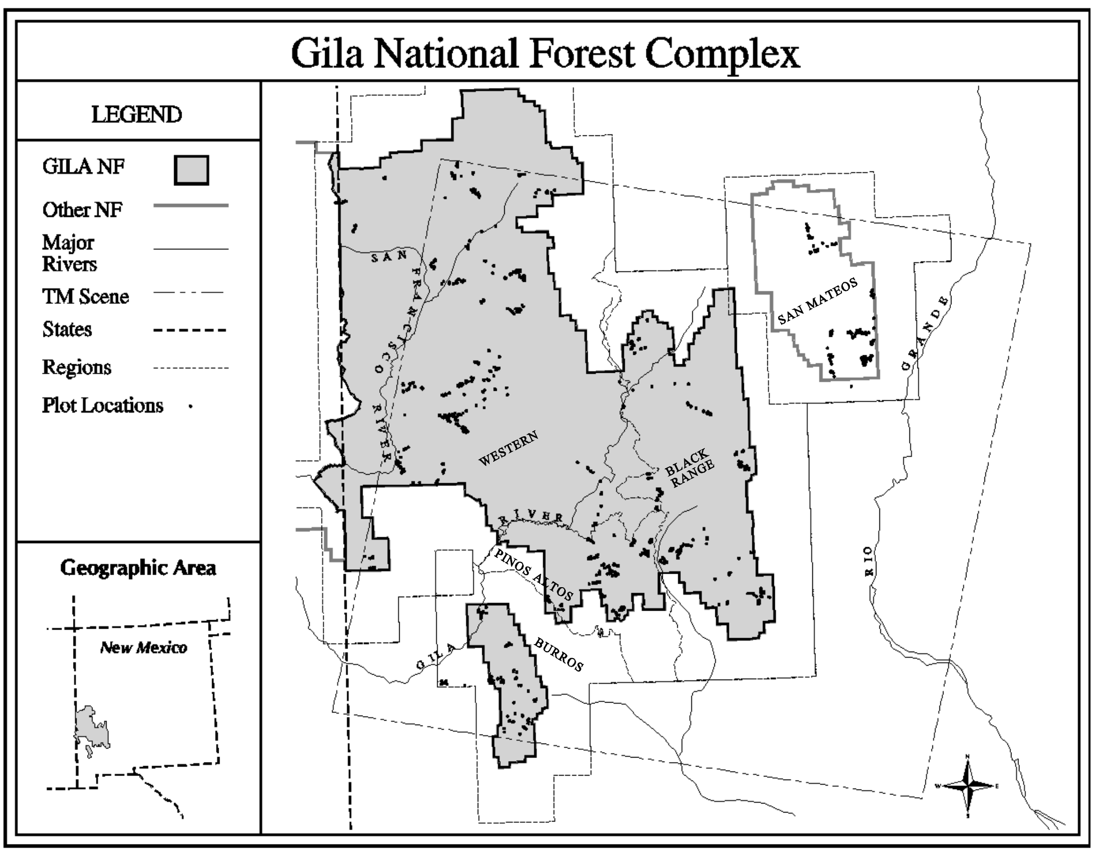


**Figure 1. Map of Gila National Forest Complex (GNFC). Dotted line shows extent of one TM scene. We used another TM scene to map FARSITE inputs for the western portion of GNFC outside main TM scene.**

## METHODS AND RESULTS

There are many reasons why FARSITE input data layers are difficult and costly to build. First and most important, most remotely sensed products used for fuel mapping, such as aerial photos and satellite images, are not particularly useful for discriminating different fuel types because the ground is often obscured by the forest canopy (Lachowski et al. 1995, Verbyla 1995). Second, the most important layer needed by FARSITE, the fire behavior fuel model (FBFM) layer, is not so much a quantitative description of fuel loadings, but rather a quantification of expected fire behavior for the stand (Anderson 1982). Therefore, many people who do not have experience in fire behavior or fuel model classifications are often unable to estimate the FBFM accurately and consistently (Keane et al. 1998b). Next, the characterization of all the types and sizes of fuel in a FBFM is very difficult to discern from remotely sensed imagery. In fact, wildland fire propagates primarily through the fine fuels and the loadings of these small fuels are notoriously difficult to simultaneously classify from imagery for timber environments (Burgan and Rothermal 1984). Fourth, the eight data layers needed to simulate fire growth must be developed and mapped simultaneously so they are spatially congruent. This means the crown base height for a stand must not be taller than the stand height for the same stand, for example. Surface fuel model layer (FBFM) and the four crown fuel layers (closure, bulk density, stand height, and crown height) must be consistently quantified in an ecological context across large land areas (Finney 1998). Last, fuel maps must be developed at fine resolutions (e.g., 30 meter pixels) for the accurate simulation of fire behavior, and many existing stand and vegetation classifications and maps are too coarse for use in FARSITE. So, since fuels are difficult to directly map from imagery, we assumed that there must be a suite of biophysical or biological spatial data layers that are easy to map and yet correlate well with FBFMs and crown characteristics.

The methodology we used to develop the GNFC FARSITE input layers is based on the premise that most ecological characteristics, especially fuels, can be described from three commonly-used ecological classifications of **1) biophysical environment, 2) species composition, and 3) stand structure**, called the vegetation triplet. The biophysical environment is important because site-related ecological processes such as productivity, decomposition, and fire regime often govern fuel loadings and fuel characteristics (Brown and Bevins 1986). Species composition is important because branchfall and leaffall rates are unique to many forest and range communities and their accumulation rates coupled with varied woody morphology can create unique fuelbed characteristics (Brown and See 1981, Brown and Bevins 1986). Stand structure is critical because it describes the vertical arrangement of live and dead biomass above the ground surface (O'Hara et al. 1996). It is the arrangement of this biomass, both on the ground and in the air, that dictates the subsequent intensity and severity of fires over time (Anderson 1982). The problem then is to select the set of three classifications that best describe environment, composition, and structure. For the GNFC project, we selected the classifications of **potential vegetation type** to describe biophysical environment; **cover type** to describe species composition, and **structural stage** to describe the vertical stand structure. Hereafter these three classifications will be referred to as the **base vegetation classifications** and maps.

Ideally, the biophysical environment layer should integrate important ecosystem processes, such as climate, hydrology, evapotranspiration, vegetation, and soils processes, to spatially predict the changes in GNFC environment important to fuels mapping (Milner et al. 1996). But, biophysical settings are inherently difficult to map because they represent the complex integration of long-term climatic interactions with vegetation, soils, fauna, and disturbance (Keane et al. 1997, Milner et al. 1996). Moreover, biophysical setting categories are difficult to identify in the field because of their temporal aspect. So, a vegetation-based site classification is needed to easily identify biophysical settings on the ground from a plant key. Therefore, a **Potential Vegetation Type (PVT) classification** was used to identify biophysical settings in the field (Keane et al. 1998b). A PVT describes the composition of near-climax communities at the endpoint of succession (Daubenmire 1966). Theoretically, a PVT supports a stable, self-perpetuating plant community in the absence of disturbance (Pfister et al. 1977). This community exists within a unique set of environmental conditions that serves as a surrogate for classifying environmental site conditions (Daubenmire 1966, Deitschman 1973). Habitat types and habitat type phases (Pfister et al. 1977, Steuver and Hayden 1996)) are equivalent to PVT's at fine spatial scales, while habitat type groups, fire groups, or topographic settings (Keane et al. 1997, 1998a) can be used as PVT's at mid scales, which is the scale of reference for most fuel mapping studies (Keane et al. 1998b).

Species composition is broadly described by **cover types** with categories that generally characterize dominant plant species based on a plurality of basal area and canopy cover for forest types or based on vertically projected plant cover for rangelands. Examples of coarse and mid scale cover type categories are presented in Shiflet (1994) for range types and Eyre (1980) for forest types. Differences in cover types can be successfully discriminated from satellite imagery and remote sensing but with a limited accuracy (Lachowski et al. 1995, Shao et al. 1996). Cover type maps can also be created from aerial photo interpretation, digitized stand maps, videography, and gradient models

(Lachowski et al. 1995, Keane et al. 1997, Kessell 1979). Both cover type and structural stage maps for the GNFC project were created from satellite imagery using standard image processing techniques. Plant community structure is the vertical arrangement of dead and live plant biomass above the ground and mostly describes the vertical characteristics of canopy layers and stem material. Stand structure was described by Keane et al. (1998a) by a process-based classification of **structural stage** which describes the vertical succession of tree and rangeland structures during stand development (O'Hara et al. 1996). However, preliminary field investigations on the GNFC revealed many process-based structural stages could not be accurately and consistently assessed in the field or adequately discriminated with satellite imagery. Therefore, we simplified our structural stages categories by relating them to tree diameter size-classes for forested types.

There are many advantages of using this vegetation triplet approach to mapping fuels. First, the concept can be used across many spatial scales because the categories in each of the three classifications are easily scaled to the appropriate level of application. Second, many land management agencies already use some form of these classifications in their every day management activities, and these classifications can be easily developed if they do not exist for some areas. Resource professionals already use similar classifications to formally or informally describe stands or watersheds (Pfister et al. 1977). There is a large body of research available on these types of classifications and their mapping. Many National Forests have existing classifications for these three attributes and many of their databases contain fields for these classifications, but very few have accurate maps of these attributes across large land areas as yet. Fourth, this vegetation triplet provides a context in which to interpret fuels maps. Many types of georeferenced field data can be used to identify categories of these classifications in the field. Next, these layers can easily be updated and refined, and new categories can be added, as additional field data become available. Lastly, and probably most importantly, these layers can be used to map not only the FARSITE input data layers, but also could be used to map many other ecosystem characteristics such as hiding cover, coarse woody debris, and erosion potential useful to wildlife, fuels, and hydrology issues.

**Field Sampling**

The collection of field data is especially important in the mapping of fuels, even though it is often the most costly and time-consuming part of any mapping effort. As mentioned, it is nearly impossible to accurately describe the fuels characteristics from remotely sensed imagery because the canopy obscures fuels and the important fine fuels are too small to detect. Therefore, plot data with georeferenced coordinates are the only source available to accurately describe fuelbed characteristics for mapping and relating these characteristics to other mappable entities that correlate closely with fuels. Field sampling is literally the only way as yet to adequately describe fuel characteristics for fire modeling and this field description of fuel data provides the critical reference for map creation.

We used a fixed-area plot sampling approach to describe ecological characteristics within each map unit (i.e., polygon). Each plot was circular in shape and 405 $m^2$ (1/10th acre) in size. Plot centers were subjectively located in a representative portion of a selected polygon without preconceived bias (Mueller-Dombois and Ellenburg 1974). Representativeness was determined from disturbance history, plant species composition, and site environment (Pfister et al. 1977). Each plot was georeferenced using a Global Positioning System (GPS) and its coordinates were entered into a database that was later imported into a GIS. We gathered data on 2,000 field plots during the spring and summers of 1997 and 1998. Information collected at each plot was measured using modified ECODATA methodology where FARSITE input values were directly measured in the field (Hann et al. 1988, Jensen et al. 1993). We also designed a hierarchical sampling approach where plot data were recorded using one of three intensities to ensure all ecosystem components are sampled and adequate sampling was obtained across all site, vegetation, and structure types (Keane et al. 1998a, Keane et al. 2000).

A preliminary map of GNFC polygons was created from an unsupervised classification of satellite imagery data obtained for this study to temporarily stratify the landscape for field sampling (Jensen 1986, Lachowski et al. 1995). Paper maps of these preliminary polygons, made at the same scale as a USGS 7.5 minute quadrangle map, were brought into the field for navigation to polygons selected for sampling. Polygons were selected for sampling based on a geographic and topographic hierarchical sampling stratification where the GNFC was divided into ecological zones, then important environmental gradients within each region dictated the sampling locations (Dicke-Peddie 1993). We used ecological zones, not only to stratify plot sampling, but also to refine and constrain the cover type and PVT base layers needed to map fuels. This zonation allowed us to key certain cover type and PVT categories to those areas where they occurred, and it allowed us to stratify the imagery classification by broad ecosystem types so that we could constrain the unique list of possible cover types and structural stages to each zone and minimize image classification categories by geographical region. Polygons were selected for sampling based on important environmental gradients within each zone to ensure all combinations of vegetation and environments are present in the field data (Keane et al. 1997). We tried to sample all cover type and structural stage combinations within a topographic gradient, but this was also difficult because the combinations were not known prior to going into the field.

We established exactly one thousand plots across more than two million ha of the Gila National Forest Complex in 1997. Intensive ecological measurements were taken on all plots but 190 of these plots had detailed measurements of fuels, trees, and plants. All plot locations were georeferenced to within a 5 meter accuracy using Global Positioning Systems (GPS). Most plots were located adjacent to roads or trails because of time and cost constraints. All sampled data were entered into several databases that were linked to the GIS point layer of plot locations created from the GPS coordinates. We again sampled exactly 1,000 polygons in 1998 using a methodology where ocular estimates of all vegetation classification categories and FARSITE input parameters were obtained. These data were also entered into a database and linked to the polygon layer. These data were only used to assess accuracy of the data layers and to refine the PVT terrain model.

**Vegetation Classification and Mapping**

We created robust, comprehensive, and flexible vegetation classifications of PVT, cover type, and structural stage from the data collected in the field and entered into the database. This proved to be one of the most demanding tasks of the project because the classifications for the vegetation triplet are the heart of the image classification and fuel mapping procedure, so the resolution of the categories of each vegetation map needed to match the resolution of FARSITE input layer categories and the resolution of the digital maps. For example, cover type categories needed to be fine enough to identify major changes in surface FBFMs and crown fuel characteristics at a 30 meter pixel resolution, but broad enough to minimize classification and sampling complexity. Broad categories could “smooth” the spatial distribution of fuels, while many fine categories could overwhelm the satellite image classification process and require inordinately large field data sets (Jensen 1986, Schowengerdt 1983, Verbyla 1995). And most importantly, we needed to design vegetation classification categories so that they would be useful to other facets of land management, and not only fire management (Keane et al. 1998b). This was difficult since most cover types and structural stages commonly used in land management are difficult to accurately discriminate using satellite imagery (Keane et al. 1998b, Lachowski et al. 1995).

**PVT** - The existing habitat type classification for the GNFC (USDA Forest Service 1997) was not useful for this study for several reasons. First, the level of classification was too fine for fuel mapping, and it was difficult to aggregate habitat types to the coarser categories needed for this mapping effort. This was partially because many habitat types were not true PVT’s but rather plant associations which integrate disturbance processes and therefore make it difficult to consistently determine site conditions. In addition, it was difficult to hierarchically aggregate types with the existing classification system and relate the composite types to dynamic site descriptors such as climate or soils (USDA Forest Service 1997). So instead, we created our own PVT classification based on the synecology of existing tree species in the GNFC. First, the field data were analyzed using database queries to identify similar groups that describe biophysical conditions appropriate for mapping fuels. We used the existing habitat type classification as a starting point, and then refined, deleted, and added classified types according to our project objectives. We then created a working list of draft PVTs and an associated key to their classification. The draft PVT key was refined by reclassifying the field data and also by soliciting help from regional experts. In the end, our PVT categories tended to describe vegetation life zones on the Gila National Forest as defined by Carleton et al. (1991).

The PVT map was created from a terrain model developed from hierarchically structured topographic combinations of elevation, aspect, and slope rules (Keane et al. 1998a, Brown et al. 1994). First, field data were summarized to determine plausible ranges in elevation, aspect, and slope that would consistently and accurately identify PVT categories. This is a time-consuming process of querying the field database and comparing results with those found in the literature (Shao et al. 1996, Steuver and Hayden 1996, USDA Forest Service 1997). Topographical ranges (i.e., terrain model) were spatially input into the GNFC GIS using interactive software we designed especially for this project. Each PVT is instantly mapped in the GIS and displayed so that topographic criteria can be immediately refined to match ecological expectations and user experience. Some PVT categories, such as rock, water, and urban development, cannot be mapped using only terrain modeling, so we used the classification of satellite imagery mentioned below to delineate these areas. The final PVT map was used to constrain the image classification of cover type and structural stages to eliminate illogical combinations.

**Cover Type -** The cover type classification key was constructed by first specifying the target number of cover types we wanted to include in the mapping effort. This number could not be so great that many plots would be needed for their description, or so few that fuels weren't adequately differentiated. We decided that there should be between 10 to 30 cover types based on a review of the literature and discussions with National Forest personnel (USDA Forest Service 1997). The first year's field data, coupled with our knowledge of the area and its ecosystems were used as guides in revising this list (Anderson et al. 1998, Grossman et al. 1998, USDA Forest Service 1997). We then tried to rectify the number in the cover type list to the target number by aggregating similar cover types or eliminating cover types that had small aerial extents.

A combined unsupervised-supervised satellite image classification was performed using four LANDSAT (TM) scenes for two areas at two time periods (1993 and 1997). We obtained this imagery from the Southwestern Region Engineering Office in Albuquerque, New Mexico. We used the PCI image processing software to perform the image classifications on a series of IBM UNIX workstations. We first used a segment program that created landscape polygons (minimum of 2 ha) based on textural information contained in TM bands 3, 4, 5, and 7 and the previously mentioned unsupervised classification. We then performed a supervised classification of the imagery using the 1,000 polygons sampled in 1997 as training sites and constraining the classification to delineated polygons and PVT categories. We then assigned the spectrally determined cover type category to each delineated polygon based on modal values. We used another 1,000 plots sampled in 1998 to assess the accuracy of the cover type layer, and then used the results to refine spectral classification assignments to polygons. This process was repeated for each PVT and ecological zone to achieve the highest accuracy.

**Structural Stage** - The initial structural stage classes used during the 1997 field season were based on stand developmental processes and included seven forested types and eight rangeland types as described by O'Hara et al. (1996). We then added six woodland classes to describe structure of pinyon, juniper and oak. After the 1998 field season, it was determined that this fine level of structural differentiation was not needed to describe the changes in fuels as related to vegetation structure. We found very few stands dominated by seedlings, saplings or large trees within the GNFC so we lumped the seven forested structure types were into 3 broad classes based on tree diameter at breast height (DBH). Woodland, shrub and herbaceous communities were grouped into two structural stages based on projected canopy cover. These seven structural stages plus two more for non-vegetated types were used as the final set of categories for the key to stand structure. We simultaneously mapped structural stage with cover type using the four TM scenes and the image processing procedure mentioned above.

**Fuels** - FARSITE has options that allow over 80 user-defined or "custom" FBFMs in a spatial fire simulation. Since it is necessary to match fuel characteristics with observed fire behavior (Burgan and Rothermal 1984), the creation of new, custom FBFMs can be a demanding and complex process. We developed two new FBFMs for the GNFC project by following procedures detailed in Burgan and Rothermal (1984). The first FBFM was for surface fires in pinyon-juniper understory. We estimated fuel loadings in the standard size classes for this ecosystem based on measured fuel data and ocular estimates and used these fuel loadings in a custom fuel model option in the fire behavior program BEHAVE (Andrews 1986). We varied these loadings in BEHAVE to obtain fire behavior estimates similar to those observed in the field under constant weather conditions (Burgan and Rothermal 1984). The other new FBFM was for rock, bare soil, and water where fuel loadings were set to zero so no fire could spread on this area.

Two fire behavior fuel model (FBFM) GIS layers were developed for this project. Apparently, some plant communities can exhibit drastically different fire behavior after prolonged drought or under severe winds, and the standard fire behavior fuel models do not account for the contribution of deciduous shrubs to subsequent fire behavior. For example, montane shrub communities are often assigned the live shrub fuel model (FBFM 5) because of their high summer moisture contents (Anderson 1982). However, these same communities can exhibit severe fire behavior typical of the xeric shrub model (FBFM 6) under extreme drought conditions because of their very low live fuel moisture contents. The **normal FBFM** map describes the most common distribution of fuel models on the landscape and will probably be used for many prescribed fire planning and real time wildfire simulations. The **extreme FBFM** map describes the spatial arrangement of fuel models under the most severe conditions (e.g., extreme drought or highest fuel loadings). This map can be used to simulate wildfires for worst-case scenarios.

**FARSITE Input Layer Development**

The FARSITE input layers were created by summarizing the field database by all possible combinations of the categories for all three vegetation base layers — PVT, cover type, and structural stage. We intersected the final PVT, cover type, and structural stage layers to determine all possible combinations for any polygon. We then created an ASCII database called the **base layer combination lookup table** where each line in the file defines a unique combination of PVT-cover type-structural stage. Field data are then summarized by combination to the myriad of ecological characteristics used to create FARSITE input maps and to develop other maps useful for land management. These summaries are then entered into the lookup table. The final FARSITE input maps were created by relating the combination lookup table to the polygon layer based on the polygon assignment of PVT, cover type, and structural stages.

The summary analysis used modal values to assign FBFMs (i.e. normal and severe fuel models) to each combination. Stand height, crown height, crown bulk density, and canopy closure were computed as averages across every plot in the unique triplets. Assignment of average canopy closure from the lookup table was compared to directly classifying closure from the satellite imagery and was found inferior so we used the direct image classification to assign canopy closure to polygons. Some PVT-cover type-structural stage combinations were not represented in the field data so we conducted a two-day workshop attended by all fire managers on the Gila National Forest where they assigned FBFMs and crown heights to each combination based on their experience.

**Accuracy Assessment**

We performed an intensive assessment of the accuracy and precision of all field data, workshop assignments, vegetation classifications, ancillary data layers, base vegetation layers, and the FARSITE fuel layers using a multitude of ground-truth sources and accuracy assessment methodologies (see Congalton and Green 1999, Mowrer et al. 1996). First, we tested and evaluated the eight key FARSITE assessments made in the field with detailed plot information taken on a fraction of the plots. Ocular estimates of PVT, cover type, structural stage, stand and crown heights, crown closure, crown bulk density, and fire behavior fuel models made on detailed sampled plots were compared with an analysis of the detailed ecological data measured on each of these plots (Congalton and Green 1999). Measured fuel characteristics from fuel transects were compared to the loadings in the ocularly estimated FBFM. Accuracy and consistency of developed vegetation classifications were estimated from queries of the field database on plant species cover information gathered on the detailed plots. All plots were keyed to PVT, cover type, and structural stage category using database queries on the field data. About 1,000 plots were used to test, validate, and refine the existing and developed map layers using standard contingency table techniques (Congalton and Green 1999).

We assessed the accuracy of all categorical GNFC maps using methodologies presented in Congalton (1991) and Congalton and Green (1999) where contingency tables are constructed comparing the reference (ground-truth) data values to the classified (map) values. Omission and commission errors were computed for each map category, and a final accuracy was estimated using the KHAT statistic (Congalton 1991, Mowrer et al. 1996). The accuracy of continuous GNFC maps such as elevation, aspect, and slope was computed using a regression approach similar that used by Keane et al. (1998b). The observed values at each polygon (plot data) were regressed with the predicted values from the maps using a linear, least-squares regression where three regression statistics were recorded ($R^2$, standard error, and slope of regression line) as estimates of accuracy (Keane et al. 1998a). Accuracy of the some categorical maps and vegetation classifications data are presented in Table 1.

## DISCUSSION AND CONCLUSIONS

Mapping fuels from vegetation and biophysical settings proved successful but accuracies of resultant fuel maps are somewhat low. Accuracies of cover type and structural stage layers increased by 10 percent when the spectral classification was constrained by PVT. Accuracies of cover types increased by over 40 percent when cover types were aggregated to life forms, and structural stage map accuracies increased when aggregated. FARSITE crown and surface fuel attributes were consistently and comprehensively mapped across the entire 1.5 million ha GNFC, but accuracies were well below our 70 percent target. This mapping methodology has a proven application in mapping ecological

| Map | Accuracy (Percent) | KHAT Accuracy (Percent) | Adjusted Accuracy (percent) | Fuzzy Accuracy (Percent) |
|---|---|---|---|---|
| **PVT** | 63 | 50 | 83 | 89 |
| **Cover Type** | 43 | 39 | 63 | 65 |
| **Structural Stage** | 52 | 42 | 77 | 64 |
| **FBFM Normal** | 36 | 26 | 65 | 62 |
| **FBFM Severe** | 38 | 28 | 66 | 58 |
| **Crown Closure** | 41 | 28 | -- | -- |

**Table 1. Accuracy assessment of base vegetation and fuels categorical layers. Adjusted accuracy resolves the under-representation of some cover types and adjusts accuracies based on their frequency on the landscape.**

entities other than fuels for many land management needs.

The inherent error in each step of this mapping procedure could be explained by the continuous behavior of fuels and vegetation dynamics across the GNFC landscape (Table 1). Errors exist in the field data because it is often difficult to estimate continuous variables into the required discrete units for mapping. For example, stand height is hard to estimate in the context of crown fire spread when many trees have different heights and crown characteristics. Vegetation communities consist of many plant species that vary in abundance, stature, and dominance across fine scale environmental continua (Anderson et al. 1998, Grossman et al. 1998). Therefore, since fuel dynamics vary by environment and fine-scale stand processes across a landscape, mapping fuel loadings into discrete units will always be inherently difficult.

Our hierarchical accuracy assessment showed classification of potential and existing vegetation types has a high degree of error because indicator plant species vary in abundance and dominance across complex environments. Vegetation classifications contain inherent error because effects of past disturbance history, integrated environment, and genetic differences within indicator species complicate precise identification. For example, a ponderosa pine PVT may not be identifiable on the ground because a previous stand-replacement wildfire killed every ponderosa pine tree (Deitschman 1973, Steuver and Hayden 1996). And, our classification category combinations often did not uniquely identify a fuel model. And lastly, there are errors in mapping fuels and vegetation because of the compounding errors mentioned above, and also because fuels and vegetation are not constantly arrayed in space (i.e., vary across a continuum). But, while the accuracies seem low (40 to 80 percent), they are comparable to accuracies of other vegetation maps generated from remotely sensed imagery (Deitschman 1973, Grupe 1998). Therefore, it is doubtful this method of mapping fuels will ever produce highly accurate GIS fuels layers.

Another reason for low accuracies in the vegetation layers can be explained by the under-representation of ground truth data in common cover types such as rock, herblands and barren. We only established 25 plots in these types when we should have established over 300. We did not extensively sample these areas because we were concerned with describing forest communities. These cover types are easily identified by image processing because of their unique spectral signature (Verbyla 1995). If we had established ground-truth plots in these cover types at the same level as their occurrence on the landscape, the overall accuracies would have increased to 83 percent for the PVT map, 63 percent for the cover type map, 77 percent for the structural stage map, and 65 percent for the normal fuel map (Table 1). Other satellite-based cover type mapping efforts with higher accuracies than this study (Gonzales and Maus 1992) have a proportionately higher percentage of ground-truth plots in the cover types that are most clearly distinguished by satellite imagery such as rock, barren, or water (Verbyla 1995).

One way to improve accuracy is to create a FBFM, cover type, and structural stage map with classification categories that describe what the satellite sensor is sensing rather than categories that comprehensively describe the vegetation and fuels. However, when this is done, the resultant vegetation categories are rarely useful to common land management applications (Verbyla 1995). Another way is to use remotely sensed products, such as the promising Lidar and SAR, that can penetrate the canopy and uniquely discriminate stand structure and forest floor characteristics. This would seem to have the highest potential to accurately map fuel characteristics useful to fire management.

Products from this fuels mapping study are currently being packaged for transfer to the Gila National Forest and Southwestern Regional fire management staff. We are creating a CD that contains the appropriately formatted FARSITE input files along with other GIS and weather data needed for model execution. We have also organized all field data, lookup tables, and GIS layers into a directory on the CD. A report detailing the study (Keane et al. 2000) will be included along with all public domain software programs used in this project or useful for fire management analyses.

## ACKNOWLEDGMENTS

This project was a cooperative effort between the USDA Forest Service Rocky Mountain Research Station Fire Sciences Laboratory, the Gila National Forest, and the Fire Management and Engineering staffs of Region 3. We thank Lindon Weibe, Gary Benavidez, Abel Camarena, Paul Boucher, and Bruce Williams of the Gila National Forest; Bill Krausmann, Martin Martinez, Dan Winter and Ron Moody of Southwestern Regional Office; Wayne Cook, Cameron Johnston, Kevin Ryan, Dennis Lemond, and Dennis Simmerman of Fire Sciences Laboratory, Missoula, MT; and Mark Finney, Systems for Environmental Management, Missoula, MT. We would especially like to acknowledge the superior efforts of Owen Williams and Lawrence Garcia of the Gila National Forest for their help in field sampling and logistics.

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