Chapter 3

The Scientific Foundation of the LANDFIRE Prototype Project

Robert E. Keane and Matthew Rollins

Introduction

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, originated from a recent mapping project that developed a set of coarse-scale spatial data layers for wildland fire management describing fire hazard and ecological status for the conterminous United States (Hardy and others 2001; Schmidt and others 2002; www.fs.fed.us/fire/fuelman). Schmidt and others (2002) used linear succession transition pathways to estimate vegetation conditions that occurred on historical landscapes represented by combinations of land cover types and structural stages from existing vegetation databases. The comparison of current landscape conditions with these historical successional sequences provided a means for assessing departure and for creating an index, called Fire Regime Condition Class (FRCC), that reflects the magnitude of departure (see Hann 2004 and www.frcc.gov).

Although maps generated from this coarse-scale mapping project provided fire management with a first-ever picture of ecosystem conditions across the lower 48 states or conterminous U.S., they contained problems that limited their use at finer resolutions and for smaller areas. First, the maps were developed with a large grain size (pixel size) of 1 km square. Very few field-referenced data sets are compatible with this large pixel size, making it difficult to develop empirical predictive models to increase or assess accuracy. Second, the project was limited to existing spatial data layers, including the land cover type and stand structure maps, to describe current and historical conditions. The legends of these layers tended to have categories that were broad and therefore difficult to describe uniquely with any degree of accuracy (Schmidt and others 2002). Moreover, the existing map layers used in this project were developed at different map scales and with varied resolution and detail because they were created from various independent efforts that had disparate objectives. As a result, it was often difficult to rectify the broad and sometimes inconsistent map categories between maps. Last, the majority of the data layers were based on models that were parameterized using ecologists' and managers' estimates rather than with data collected in the field. Because of these limitations, the coarse-scale mapping products could be used only for large, regional assessments and were essentially useless for finer-scale applications such as national forest management plan revision and implementation or local wildland fire hazard assessments.

The inability of the coarse-scale mapping project to aid in finer applications spurred the U.S. Department of Agriculture (USDA) Forest Service (FS) Fire and Aviation Management (FAM) to explore the possibility

In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

of developing a set of data layers that could be used at multiple scales, from national planning to local fuel treatment design. To make regional and local comparisons possible, it was essential that each layer be constructed in a manner ensuring that all areas of the country receive the same rigor and detail in the mapping effort.

In December of 1999, FAM met with scientists at the USDA FS Rocky Mountain Research Station (RMRS) Missoula Fire Sciences Laboratory (MFSL) to request the design and implementation of this national, fine-scale mapping project. The MFSL scientists wrote a proposal and study plan for this project and submitted both to FAM in March of 2000. In 2002, the project was funded by the United States Department of Agriculture Forest Service and Department of the Interior, with an annual cost of approximately $2 million. The MSFL scientists started the project in April of 2002 and called it the "LANDFIRE Prototype Project" (Rollins and others, Ch. 2). These methods and tools were tested in two large geographic areas (called prototype areas) during 2003 and 2004 and revisions to the process occurred during 2004 and 2005. The LANDFIRE Prototype Project was completed in April of 2005 and the results are currently being implemented across the nation. Meanwhile, the General Accounting Office (GAO) published two reports on the increasing threat of intense wildland fires across the nation (GAO 2002) and fire management's inability to cope with this emerging threat (GAO 2004), and GAO identified LANDFIRE as a viable project for generating the spatial data needed to plan and implement a national fire program (Rollins and others, Ch. 2).

This chapter documents the history, concepts, theory, and scientific foundation of the development of LANDFIRE products as they were applied to the two prototype areas. First, the background of the project is presented to detail the project's design criteria and guidelines. Then, the theory and development of each integrated LANDFIRE task is discussed in the context of the overall project. This chapter does not describe how each phase of LANDFIRE was accomplished (for this information, see Rollins and others, Ch. 2); rather, it describes the scientific background and concepts behind the design of LANDFIRE and the theory and ideas behind the development of the project's tasks. Although the methods and protocols presented here were implemented and refined for two prototype areas only (Rollins and others, Ch. 2), this report is written with the perspective that these methods will eventually be applied throughout the entire United States.

Background

Project Objectives

The primary objective of the LANDFIRE Prototype Project was to develop a fine-scale (30 meter) digital map (spatial data layer) of Fire Regime Condition Class (FRCC). FRCC is an ordinal index with three categories indicating how far the current landscape has departed from historical conditions (Hann 2004) (see www.frcc.gov for complete details). This data layer can be used to identify those areas that are in need of treatment to reduce wildland fire hazard and protect homes and lives. Fire management can then use this information to allocate funding, fire fighting resources, and personnel to these areas for implementation of restoration activities and fuel reduction treatments (Laverty and Williams 2000) (see www.fireplan.gov for details).

The FRCC layer's primary use lies in fire management planning and resource allocation, with limited use in designing and implementing possible treatments. We therefore identified several secondary objectives of the LANDFIRE Prototype Project aimed at creating spatial and software products to aid fire management in implementing the National Fire Plan's Cohesive Strategy (Laverty and Williams 2000). For example, we specified the development digital maps of wildland fuel (surface and canopy) and of vegetation composition and structure as important data for designing fuel treatments. We eventually identified 24 core data layers to be developed as LANDFIRE Prototype products (see table 1 in Rollins and others, Ch. 2).

Design Specifications

A set of design criteria was developed during the initial LANDFIRE organizational meetings with USDA FS MSFL scientists and FAM. Most of these criteria resulted from the abbreviated timelines and solid deadlines imposed by FAM and other fire management agencies. Other criteria were imposed as a result of FAM's condition that LANDFIRE be based on a strong scientific foundation and be scalable to local applications with minimal modification.

The design criteria for the LANDFIRE Prototype are listed below and are detailed in the following paragraphs. According to the design criteria, the LANDFIRE Prototype Project must be:

- based on the best available science,
- able to be implemented consistently across the nation,

- mapped at a 30-meter pixel size,
- reliant on no new field data collection,
- repeatable in time and space,
- scalable in application,
- developed within a three-year development timeline, and
- tested for accuracy.

Fire and Aviation Management's overriding design specification was that the products generated from LANDFIRE must be based on *the best available science*. This meant that the many tools, methods, programs, models, and protocols used in LANDFIRE to produce the FRCC maps needed to have a publication record, preferably in peer-reviewed journals, or in some way demonstrate acceptance by the scientific community. This limited the methods and procedures, especially those involving spatial analyses, to those that are citable in the literature. This specification implied that LANDFIRE development should have a minimal amount of subjectivity. We interpreted this to mean that each data layer and model should be developed using methods that are *repeatable* and objective. Some tasks in LANDFIRE required the creation of new methods that are not in the literature. In these cases, we developed the new methods from scientifically credible sources and prepared manuscripts for publication describing these methods.

To build LANDFIRE on a scientifically credible foundation, we based the development of all products in LANDFIRE on an extensive, plot-level database, called the LANDFIRE reference database (LFRDB) (fig. 1) (Caratti, Ch. 4). Every product generated by LANDFIRE was developed from legacy field data collected by resource professionals and screened for quality and consistency (the *LANDFIRE Prototype Design* section below gives additional detail on the database). This data compilation process ensured that each data layer could be easily recreated (*repeatable*), an especially important feature when additional data become available in the future. In addition, this process allowed for *accuracy assessment,* and the reference plot data could be used to *scale* LANDFIRE products for local applications by facilitating the development of additional, more detailed classifications of cover types, structural stages, and fuel models. A major complication arose from the design specification that, to reduce the costs of and time for project development, *no additional data be collected*. This meant no new data could be added to the database to supplement the ecosystems or geographic areas where data were lacking. This criterion was relaxed, however, when we found significant gaps in data coverage for the mapping of current vegetation conditions.

The second most important design standard was that LANDFIRE products must have the potential for *national implementation*. This meant that all ecosystems had to be mapped and modeled with the same degree of complexity and detail, ensuring that the FRCC categories would have the same meaning across the entire conterminous U.S. In other words, a "red" pixel in Maine would mean the same as a "red" pixel in Arizona. For LANDFIRE, we used the terms "consistent" and "comprehensive" to define this national implementation. *Consistent* means that we used the same methods of mapping and modeling for every pixel in the conterminous U.S., and *comprehensive* means that we used the same rigor (a thorough and wide-ranging approach) for all LANDFIRE tasks, regardless of ecosystem or geographic area.

The *30-meter pixel size* condition specified by FAM was an important criterion because they wanted fine-scale applications to be possible for all LANDFIRE map products. This posed a significant scale problem because it is difficult to match map category and simulation model resolution for national implementation to the small spatial resolution of 30 meters; however, this pixel size matched the grain of the satellite imagery and digital elevation models that were used to map current vegetation conditions.

Another important criterion was that the project had to be developed so that it could be *repeated* every five to ten years to assess and monitor the efficacy of the National Fire Plan and the Cohesive Strategy (www.fireplan.gov) across the U.S. in a standardized format. By repeating the LANDFIRE process every five to ten years, fire management would have a vehicle by which to monitor the success of the National Fire Plan and Cohesive Strategy across multiple spatial scales. Subjective and arbitrary methods and protocols had no place in the creation of any LANDFIRE product because they are difficult to consistently replicate.

The specification that LANDFIRE include tools and methods to *scale* maps and models both upwards (coarser) and downwards (finer) presented a major challenge in the creation of many LANDFIRE products. Although important, this turned out to be a time-consuming design requirement because it required that all products have the ability to be scaled both in geospatial and management applications. For example, the vegetation data layers needed to be developed so that refinement and additional detail in the vegetation classification categories could be remapped on smaller landscapes with relative ease. This stipulation also meant that tools were needed that integrate the LANDFIRE products into value-added

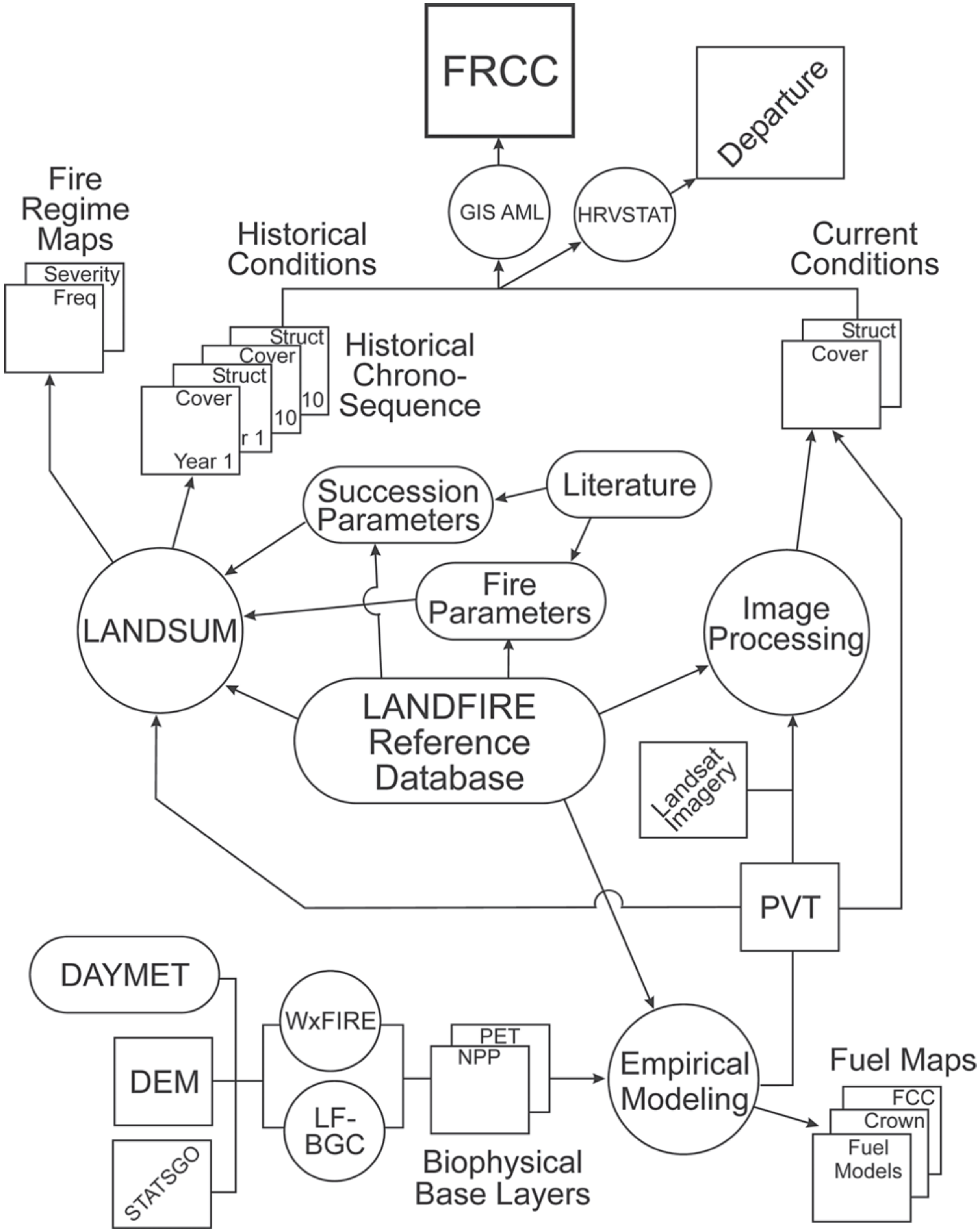

Figure 1—Flow chart of all LANDFIRE software and products culminating in the creation of the FRCC layers. All squares in the figure are digital maps, circles are analysis tasks involving software, and ovals are data sources. The acronyms are defined as follows: DEM - digital elevation model, PVT - potential vegetation type, PET - potential evapotranspiration, NPP - net primary productivity, and GIS AML - geographic information systems macro language. All other acronyms are program names that are detailed in this report.

products that have more specific meaning and utility for fire management, especially at local scales. For example, the LANDFIRE fuel layers can be used in the Fire Hazard Rating Model (FIREHARM), to create spatial data layers of expected fire behavior and effects. Moreover, all of LANDFIRE analysis programs and models are open source so that they can be modified for local situations and applications.

As specified by FAM, the entire LANDFIRE Prototype Project needed to be completed in *three years*. This included the final 24 map layers, the analysis software, and the final draft manuscripts of all chapters presented in this report. This timeline required that the entire process had to be developed within the first 18 months and implemented within the first prototype mapping zone during the following six months. Revisions and refinements needed to be made, and the second prototype area had to be mapped during the following six months. The chapters in this report were written during the last six months. This accelerated timeline dictated the detail of analysis for many LANDFIRE tasks and prevented a more thorough investigation of a few aspects of the project.

The last design requirement specified that every data layer be *assessed for accuracy* to ensure and document the quality and precision of LANDFIRE products. As mentioned, we created the LFRDB to serve as a foundation for meeting the accuracy assessment requirement. There is, however, a wide range of accuracy assessments: from thematic accuracy (Is this pixel mapped correctly?) to classification accuracy (How often does this classification fit real field data?) to model accuracy (How often does the statistical mapping model predict the correct answer?). FAM identified thematic accuracy as the primary target. The estimation of this measure has many problems, however, including the possibility of field data having 1) inaccurately georeferenced plot coordinates, 2) errors in data measurement and entry, and 3) inexperience and inconsistency within field crews (Vogelmann and others, Ch. 13). We therefore attempted to report as many types of accuracy measures as possible, using the reference database and data from other modeled sources, to provide a more complete assessment of accuracy. The main three measures of accuracy that we calculated for most LANDFIRE products were 1) thematic accuracy or the accuracy of a pixel being mapped correctly, 2) landscape accuracy or the accuracy of pixel summaries across large areas, and 3) model accuracy or the accuracy of the statistical models used to build the maps (Vogelmann and others, Ch. 13).

Guiding Principles

Given these design specifications, we then developed a set of principles that we used to guide the development of all LANDFIRE data layers. These principles were a direct outgrowth of the design specifications, and they allowed us to set boundaries for the development of every LANDFIRE product. These guidelines were as follows:

- Development should be targeted at mid-scale map classifications.
- All themes must be identifiable, scalable, mappable, and model-able.
- Mapping applications must incorporate the biophysical gradients that determine the distribution of vegetation and disturbance regimes across landscapes.
- The primary development tool should be simulation modeling.
- The timespan for historical reference conditions would be 1600 AD to 1900 AD.

Development should be targeted at mid-scale – The mid-scale development target was chosen because of the national implementation design specification. It was unrealistic to develop and map classifications of vegetation at finer scales for several reasons. First, national vegetation classifications that are scalable to local applications are nonexistent or, at best, incomplete, especially for mapping purposes (Anderson and others 1998; Grossman and others 1998). Next, most existing classifications do not provide for the shared dominance of two or more species in a consistent manner for the entire nation (Long and others, Ch. 6). In addition, many rare vegetation types that are important to management have not been sampled in the field and were therefore under-represented in the LANDFIRE reference database, making it difficult to map rare vegetation types at a national scale. Last, there was not enough time to develop the detail in our simulation models required for fine-scale mapping. For these reasons, we decided to aim for a mid-scale target in the development of all LANDFIRE intermediate and final products, including map categories, model elements, and fuel classes.

In keeping with this mid-scale development, we chose to use the USGS Center for Earth Resources Observation and Science (EROS) mapping zones (Rollins and others, Ch. 2) to define the spatial extent which guided the design of all vegetation classifications and simulation models. To that end, we decided that a vegetation class must occur in at least five percent of the mapping zone to warrant its mapping. This restriction eliminated from consideration many vegetation types which, although important for local applications, are uncommon across an entire mapping zone. It is doubtful that we could have mapped these types anyway as there were so few representative data for these in the LFRDB. It is important to note that the mid-scale development target concerned mainly the vegetation and fuel classifications that were mapped across the nation, not the spatial and temporal resolution of the maps; we still had to meet the fine-scale design specification of a 30-meter spatial resolution.

All themes must be identifiable, scalable, mappable, and model-able — The categories within the vegetation map unit classification mapped by the LANDFIRE Prototype team served as the building blocks used to construct all LANDFIRE Prototype maps and models. It was essential that the design of the classification match the detail provided by the 1) imagery used to map existing conditions, 2) empirical models used to assign attributes to vegetation categories, and 3) simulation models used to determine historical conditions (Long and others, Ch. 6; Zhu and others, Ch. 8; Pratt and others, Ch. 10). For LANDFIRE, we specified that classification categories must meet four criteria to warrant their mapping. First, the classification categories had to be *identifiable* on the ground and in the LFRDB, meaning that we had to be able to construct a key that would uniquely identify the classes from commonly sampled vegetation characteristics, especially those present in the reference database. Moreover, field crews needed to be able to use the LANDFIRE key to accurately identify the vegetation classification type on the ground. Second, the classifications had to be *scalable;* similar categories needed to have the ability to "collapse" to form a coarser classification, or the ability to expand so that additional, finer-scale categories could be added with little effort. Third, map categories had to be *mappable,* meaning that the methods used to map entities had to be able to detect this classification category. For example, we did not map upland willow shrubland types if the Landsat imagery (EOSAT 1992; http://landsat.gsfc.nasa.gov/) could not distinguish them from other shrubland types. Lastly, the vegetation categories needed to be consistent in scale and detail with the simulation model entities used to estimate historical conditions (*model-able*). Categories that included both shade-tolerant and shade-intolerant tree species, for example, were not included in the classification because they could not be used to simulate seral states in models of vegetation succession (Long and others, Ch. 6; Long and others, Ch. 9).

Methods must stress those ecosystem processes that govern mapped entities — LANDFIRE National ultimately depends on a set of core data layers that are consistent and comprehensive across the entire nation. We employed these layers as the raw material to construct other data layers used to create the LANDFIRE mapping products. It was especially important that these core layers represent those fundamental biophysical processes that govern vegetation, fuel, and fire dynamics. In addition, we wanted to incorporate all possible existing national 30-meter scale layers into the LANDFIRE Project to ensure that our GIS library had the latest mapping technology; however, upon researching the availability, extent, and quality of possible core data layers, we found very few that had national coverage and fine-scale resolution (30-meter). The only two sets of nationally consistent data layers that fit LANDFIRE's needs were the USGS National Elevation Database (ned.usgs.gov/), which served as the LANDFIRE Digital Elevation Model (DEM), and the extensive catalog of Landsat data from the USGS Multi-Resolution Land Characteristics (MRLC) 2001 project (landcover.usgs.gov/index.asp).

Given the lack of comprehensive, nation-wide GIS data layers, we decided to create our own set of base layers, called *the biophysical gradient layers,* because we wanted these layers to be consistent in design, extent, and detail so that we could use them in complex analyses and minimize error resulting from independent and sometimes incompatible sources. Creating our own layers also allowed us the opportunity to build a GIS library of consistent data layers describing those fundamental processes that govern vegetation, fuel, and fire dynamics. The LANDFIRE Prototype's *core* layers were data we obtained from elsewhere and the *base* layers were those we built to describe basic ecosystem processes.

The biophysical gradient layers were developed using a *process-based approach* that emphasized the creation of layers describing the fundamental biophysical drivers influencing the vegetation, fuel, and fire characteristics that we were to map. Having previously used this approach to map vegetation and fuel characteristics on the Kootenai National Forest, we found that it increased map accuracies from 10 to 30 percent (Keane and others 2002a; Rollins and others 2004). In this approach, we used spatially explicit biophysical gradients to augment the mapping of vegetation and fuel composition and structure. Incorporating these gradients in our mapping process allowed for increased discrimination between mapped categories because the gradients represent the causal mechanisms that physically determine the distribution of vegetation and fuel across landscapes. For example, average annual soil water availability is often a better indicator of growing conditions than average annual precipitation, especially for fine-scale applications.

Several databases were needed to build this biophysical gradient base layer library. First, we needed the DEM (ned.usgs.gov/) to represent topography across the nation. Next, we needed a daily weather database for the entire nation with a temporally deep record. The DAYMET national weather database (www.daymet.org) was selected because of its national coverage at 1-km^2 resolution and 18-year daily resolution weather record (Running and Thornton 1996; Thornton and others 1997; Thornton and White 1996). The STATSGO layer was used to represent soil because of its national scope; however, because it was developed at very coarse scales, we performed several procedures to compile the layers for LANDFIRE analyses (Holsinger and others, Ch. 11). Lastly, we needed a set of simulation models that could take the DEM, DAYMET weather data, and STATSGO information and produce mechanistic maps that best discriminate vegetation dynamics. We used the LANDFIRE Biogeochemical Cycles (LFBGC) model (Thornton and others 2002; Thornton and White 1996; White and others 2000) to simulate ecosystem processes, the WXFIRE model to simulate weather and climatic processes (Keane and Holsinger 2006), and a landscape succession model called LANDSUMv4 to generate historical chronosequences (Keane and others 2006*;* Pratt and others, Ch.10; Keane and others 2002b). We found no other existing layers that met our design criteria and development guidelines.

The primary development tool should be simulation modeling — The use of simulation modeling as the primary development tool was an important guiding principle in LANDFIRE because it was used to create the biophysical layers, as previously discussed, and also to quantify historical landscape conditions. Simulation modeling provides a comprehensive and consistent method to create fine-scale data layers across large domains such as the conterminous U.S. The LFBGC and WXFIRE models were used to map basic ecosystem processes. In addition, we used a spatial model that simulates fire and vegetation dynamics to generate chronosequences of historical landscape conditions. The LANDSUMv4 model, recreates historical landscapes using fire and succession parameters quantified from the LFRDB (Keane and others 2002b; Keane and others 2006; Pratt and others, Ch. 10).

The timespan for historical reference conditions would be 1600 AD to 1900 AD — Determining the benchmark years within which to frame the historical reference conditions posed a special challenge. The calculation of FRCC requires that current conditions be compared with historical reference conditions, yet these historical conditions differ according to the time span used to demarcate the historical temporal reference. The reference time span needed to be long enough to contain ample variation in fire and vegetation dynamics but short enough to ensure that the span is fully documented with field data and historical observations. We determined recent history to be a better reference for current conditions because climate, soil, and vegetation distributions are roughly similar and because recent history is the only era that contains field data of the resolution useful in LANDFIRE. We selected the year 1900 A.D. as the end of the historical period because it best represents the start of significant Euro-American influences on western U.S. landscape characteristics (Keane and others 2002c). The year 1900 marks the approximate start of the industrial revolution, the settlement of the West, the fire exclusion era, and active land management (Baron 2002). We used the findings of fire history studies to guide our determination of the start of the historical period, and we found most studies had recorded fires dating back to at least 1600 A.D., although some went back much further (Heyerdahl and others 1995; www.ngdc.noaa.gov/paleo/impd). This date of 1600 seemed the best compromise for all ecosystems and fire history findings. We concluded that this span of years best represented the historical reference conditions for use in managing today's landscapes. The historical reference years may need to be revisited when mapping the eastern portion of the U.S.

LANDFIRE Prototype Design

General Description

This chapter summarizes the scientific foundation underlying all phases of the LANDFIRE Prototype Project, and other chapters in this report detail each individual phase. A complete description of the procedures for creating the entire suite of LANDFIRE Prototype products is given in Rollins and others, Ch. 2. This chapter focuses on the *concepts* that were used to create the LANDFIRE products, rather than detail actual methods or processes.

The general flow of logic, product development, and analysis for the LANDFIRE Prototype can be followed in figure 1, and it illustrates the organization of the content in the following sections. In short, the computation of FRCC requires a comparison of current conditions to historical conditions. In the LANDFIRE Prototype Project, current conditions are described using maps of vegetation composition (cover types) and structure (structural stages) derived from a supervised classification of Landsat imagery and using continuous maps of biophysical gradients and Landsat imagery (fig. 1; Zhu and others, Ch. 8; Holsinger and others, Ch. 11). Vegetation composition and structure were described using cover type and structural stage classifications developed specifically for LANDFIRE. The biophysical gradient layers were created from two ecosystem simulation models that compute variables describing fundamental physical processes that govern vegetation dynamics (Holsinger and others, Ch. 5). These models used the DAYMET national weather database that, as mentioned above, has a 1-km^2 spatial resolution and daily temporal resolution spanning 18 years. Biophysical gradient layers created from these models were also used to construct a data layer describing potential vegetation types (PVTs) that was then used to aid in vegetation mapping and also used as an input layer for simulating historical reference conditions.

Historical reference conditions were simulated using LANDSUMv4, a spatially explicit landscape fire succession model that simulates vegetation development using deterministic succession pathways by potential vegetation type (PVT; described below) and simulates fire using a pixel-to-pixel cell percolation or spread approach (Keane and others 2001; Pratt and others, Ch. 10). This simulated, spatially explicit cover type/structural stage time series was compared with imagery-derived cover type/structural stage data layers describing current conditions using a GIS program that computes departure and ultimately FRCC (fig. 1) (Holsinger and others, Ch. 11). We also created a statistical program called the Historical Range and Variation Statistical Analysis Program (HRVStat; Steele and others, in preparation) that computes another index of departure with a corresponding measure of statistical significance. This departure index can be collapsed into the three classes to define FRCC.

Several secondary data layers – considered secondary because they were not used to compute the primary LANDFIRE product of FRCC – were developed using the intermediate layers created during this FRCC mapping process to aid fire management in planning and implementing ecosystem restoration and designing fuel treatments. We developed a new set of surface fire behavior fuel models specifically for LANDFIRE to distinguish subtle differences in fuelbeds resulting from fuel treatments (Scott and Burgan 2005). These represented a significant improvement over the original thirteen fire behavior fuel models of Anderson's (1982). Maps of these fuel models were created from the cover type, structural stage, and PVT maps (Keane and others, Ch. 12). The canopy fuel characteristics of bulk density and canopy base height were mapped using statistical landscape modeling (specifically, regression trees) using the biophysical layers, whereas canopy height and canopy closure maps were created using Landsat imagery (Quinlan 1993; Zhu and others, Ch. 8; Keane and others, Ch. 12). We also mapped fuel models representing actual estimations of loading (live and dead biomass per unit area) by fuel category for fire effects simulations using complex statistical modeling using the biophysical layers. Two classifications of fire effects fuel models were used: the Fuel Characterization Class System (FCCS; Cushon and others 2003; Sandberg and others 2001) and the Fuel Loading Models (FLMs) created by Lutes and others (in preparation). The FLMs were not yet developed at the conclusion of the prototype mapping effort but will be available for the national LANDFIRE implementation.

Creating the LANDFIRE Reference Database

As previously mentioned, we based all products in the LANDFIRE Prototype on an extensive, plot-level database called the LANDFIRE reference database (LFRDB) (fig. 1) (Caratti, Ch. 4). This ensured that each data layer could be recreated and revised, an especially important feature when additional data become available in the future. This data compilation process provided a source for accuracy assessment, and the reference plot data could be used to scale LANDFIRE products to finer scales by facilitating the development of additional, more detailed classifications of cover types, structural stages, and fuel models. Every product generated by LANDFIRE was developed from this legacy field data collected by diverse resource professionals and screened for quality and consistency.

The creation of the LFRDB was the most expensive task in LANDFIRE, but once created, the database became the foundation of nearly every task in the prototype effort. We used the database for many purposes, including:

- developing training sites for imagery classification;

- parameterizing, validating, and testing simulation models;
- developing vegetation classifications;
- creating empirical models;
- determining data layer attributes;
- describing mapped categories; and
- assessing accuracy of maps, models, and classifications.

The LANDFIRE reference database was actually composed of data from two separate sources: Forest Inventory and Analysis (FIA) and legacy ecological data. Through its Forest Service programs, the FIA has been collecting valuable tree data on fixed and variable radius plots for several decades and provided access to these valuable data for LANDFIRE tasks. The legacy data source was created by locating all possible georeferenced ecological data collected for any purpose and by any organization and then reformatting the data into LANDFIRE database structure (Caratti, Ch. 4).

Mapping Current Vegetation Composition and Structure

The creation of a national 30-m map of existing vegetation composition and structure presented substantial challenges. We quickly recognized that there were neither enough expertise nor computer resources to create these maps at MFSL. The EROS team had been collaborating with scientists at MFSL since 1980, researching fire-oriented remote sensing such as the development of national fuel and fire danger digital maps (Burgan 1984; Burgan and others 1998). Because the remote sensing scientists at EROS are internationally renowned, we asked them to collaborate, with the specific task of creating the current vegetation maps. We agreed that the MFSL team would develop all the fire, fuel, and biophysical layers, whereas the EROS team would develop the vegetation maps describing current or existing conditions. These vegetation layers were compared to historical reference conditions to determine FRCC. However, before any area was mapped, historical or current, a comprehensive and consistent vegetation classification was needed to define the map elements that describe vegetation composition and structure.

Developing vegetation classifications — The first and most important step in this collaborative effort was to develop classifications for vegetation composition and structure. In our previous attempts at large, regional classifications (Keane and others 1996a; Keane and others 1996b; Hann and others 1997; Schmidt and others 2002), we found that, for several reasons, it was difficult to use existing vegetation classifications to map vegetation across large areas. The most significant problem lay in the fact that existing classifications rarely match the resolution and detail of the entities that can be mapped using Landsat imagery. For example, some rangeland classifications stratify cover types by sagebrush species, but EROS scientists found it difficult to differentiate between these types using the Landsat imagery. Second, most existing classifications are limited to particular ecosystems or geographic areas. The Society of American Foresters' (SAF) classification of forest types (Eyre 1980) does not include types for rangeland species, for example. Further, most existing national vegetation classifications were developed for description rather than for mapping; the one exception is the National Vegetation Classification System (NVCS) (Anderson and others 1998; Grossman and others 1998); however, we found that this classification was difficult to scale to the detail required by LANDFIRE, and it was difficult to key plots from the LFRDB to the NVCS types.

We decided to create our own vegetation classification process using a top-down approach in which our categories were designed to be:

- *important to management*. The classification categories had to be useful to land management for mid-scale analyses.
- *conducive to modeling*. The categories needed to adequately represent stages of vegetation development to be compatible with our modeling approach.
- *distinguishable from satellite imagery*. The categories needed to represent cover types that can be easily detected with remotely sensed data.
- *identifiable using plot data*. The classification must have a key that will uniquely identify each category from data in the LFRDB (see LANDFIRE guidelines above).

Rather than construct or use a system that classified all vegetation types within the conterminous U.S., we decided to first identify those vegetation types that we could successfully distinguish through satellite imagery and identify in the reference database. We developed classification categories for forests and rangelands based on a blend of many national efforts (Holdridge 1947; Kuchler 1975; Eyre 1980; Loveland and others 1991; Running and others 1994; Shiflet 1994; Bailey 1995; Grossman and others 1998) and synthesized lists of categories within the context of the two prototype mapping zones. We based the vegetation composition on dominant plant cover and called the classification categories *cover* *types*. We then used the cover type categories to name the potential vegetation types (discussed below); therefore, these categories needed to discriminate between successional stages based on relative shade tolerance and ecological amplitude (Long and others, Ch. 9).

We generated a list of cover types for the central Utah prototype area (Zone 16) by conducting a series of informal workshops with ecologists and members of the LANDFIRE team (Long and others, Ch 6). First, we reviewed the national classifications and devised a list of possible categories, keeping in mind our mid-scale objective. We determined that the selected cover types had to meet the minimum area guideline for mid-scale mapping (occupying at least five percent of a mapping zone) as well as meet the above mentioned guideline that "all themes must be identifiable, scalable, mappable, and model-able." We then created a set of keys to identify the cover type of each plot in the LFRDB based on the predominance of plant cover by species. Next, we inspected the plot distribution by cover type and merged or deleted cover types that were represented by less than 50 plots. We also modified the key to reduce the number of plots that were unclassified and misclassified (Caratti and others, Ch. 4). Categories were also eliminated or merged to distribute plots evenly across all classification categories.

We then submitted this preliminary list of cover types and the keyed reference database plots to the EROS team for evaluation. They assessed whether the imagery could successfully distinguish between cover type categories and sent suggestions and a modified list back to MFSL to evaluate whether the suggestions and modified list fit within the modeling framework. This process continued until we mutually agreed upon on a final cover type list for the prototype areas. We then cross-referenced the LANDFIRE vegetation classification with all other national classifications to provide linkages to other mapping efforts (Long and others, Ch. 6). In the end, we were satisfied that the final list represented those types that we could successfully identify, scale, map, and model using the reference database and Landsat imagery.

For the northern Rockies prototype area (Zone 19), we decided to use a bottom-up approach in which we aggregated classes in the NVCS using the classification's inherent hierarchy. We based the final level of aggregation on the above mentioned guideline that "all themes must be identifiable, scalable, mappable, and model-able." We sent this aggregated list to the EROS scientists for their review, and both teams mutually agreed upon a final set of cover types (Long and others, Ch. 6). Both approaches (top-down and bottom-up) have advantages and disadvantages, and the choice for the national effort will depend on the ability of NVCS to meet the needs of the LANDFIRE Project.

The structural stage classification proved easier to develop because it contained far less detail than the cover type classifications (Long and others, Ch. 6). After much discussion with the scientists at EROS, we were convinced that there was little chance of successfully using commonly accepted structural stage classifications because Landsat imagery has difficulty detecting subtle changes in forest strata (see Lavigne 1992, O'Hara and others 1996a, O'Hara and others 1996b, Oliver and Larson 1990, and Pfister 1981 for examples of structural stage classifications). We therefore decided to base our structural stage classification on two structural components that the EROS team had some success in mapping: canopy cover and canopy height. These two attributes are mapped using a statistical modeling approach in which cover and height are regressed against Landsat imagery spectral values and other ancillary data layers (Zhu and others, Ch 8). We constructed a four-category forest structure classification with two categories of height (short and tall) and two categories of cover (low and high), and the thresholds delineating categories were based on cover type (Long and others, Ch. 6). We used a similar approach for shrublands and grasslands. We then constructed mock succession pathways using these structure categories and found that they were consistent with our modeling approach for creating the historical reference time series.

Describing biophysical settings — Many studies have shown that augmenting a satellite imagery classification with a quantitative description of the biophysical environment (temperature, elevation, and precipitation, for example) improves the mapping of ecological characteristics such as vegetation and fuel (Keane and others 2002a; Rollins and others 2004). Moreover, our landscape modeling approach for quantifying historical reference conditions was predicated on the assumption that the landscape is stratified into settings that represent broad environmental categories and that these categories also represent similar succession and disturbance responses, such as plant associations and habitat types. We needed to invent a classification of biophysical settings that would be useful to both the mapping and modeling efforts, and this biophysical classification must also be useful for scaling LANDFIRE products to finer scales for local land management applications. In addition, a biophysical classification was needed for simulation of historical vegetation reference conditions. This classification had to correlate with the potential vegetation types that would eventually inhabit the area in the absence of disturbance because this is the premise for simulating succession in LANDSUMv4. Most importantly, each plot in our LFRDB needed to be keyed to a specific biophysical setting category. This last criterion ultimately guided the biophysical classification.

We wanted the biophysical settings classification to be based on fundamental, process-oriented environmental gradients. Austin and Smith (1989) define these as direct gradients and resource gradients. Direct gradients, such as temperature and humidity, have a direct physiological impact on vegetation, but these gradients are not consumed by vegetation. On the other hand, the energy and matter used or consumed by plants, such as light, water, and nutrients, define resource gradients. Direct and resource gradients are important for mapping vegetation and ecosystem characteristics because they can fundamentally define the potential species' niches. Indirect gradients, such as slope, aspect, and elevation, have no direct physiological influence on plant dynamics, yet we included them in the biophysical mapping effort because they can be proxies for other unknown or immeasurable gradients. Of course, these biophysical gradients needed to be spatially explicit, and this requirement involved identifying and creating a suite of environmental spatial data layers that describe major climate and ecosystem variables, such as temperature and evapotranspiration, that might be useful for mapping and modeling. The layers that represent major biophysical gradients are used for a variety of tasks in LANDFIRE including 1) the creation of the potential vegetation type layer used by the LANDSUMv4 model (Frescino and others, Ch. 7) and in fuel mapping (Keane and others, Ch. 12), 2) the mapping of existing vegetation composition and structure (Zhu and others, Ch. 8), and 3) the statistical mapping of canopy fuel and fuel models (Frescino and others, Ch. 7).

As mentioned above, we found very few existing, nationally consistent data layers that met the LANDFIRE design criteria. The few biophysical data layers that have a national extent often have pixel sizes of 1 km or greater (Hargrove and Luxmore 1998). Finer resolution data were available but highly localized and variable in quality and consistency. It was evident that there were not enough independently developed, 30-meter national gradient databases to create the set of biophysical layers required by LANDFIRE. We then turned to simulation modeling as the primary tool for creating a comprehensive and consistent set of useful biophysical gradient layers.

In the mid 1990s, we created a prototype system called Landscape Ecosystem Inventory System (LEIS) that used data from local weather stations with various input data layers to simulate and summarize a wide variety of climate and ecosystem processes (Keane and others 1997a; Keane and others 2002a; Rollins and others 2004). This system used a collection of software, including the mechanistic ecosystem process model Biome-BGC (Running and Coughlan 1988; Running and Gower 1991; Thornton and White 1996; White and others 2000), to create biophysical layers that were then used to map fuel and vegetation. The addition of biophysical layers to predict ecosystem attributes increased mapping accuracies by over 20 percent. Although the accuracy of the estimates of the actual values of the biophysical variables was sometimes low, the precision was high because relative differences between the variables across landscapes were spatially consistent. This spatial representation of the relative differences was highly important because the biophysical gradients were used as spatial predictors in the mapping process, rather than an accurate portrayal of the actual values of the biophysical variables. However, the LEIS system was built for regional – not national – applications, so we needed to modify several pieces of software to meet LANDFIRE needs.

We redesigned two of the major programs in LEIS to access the 1-km national DAYMET weather database built by Thornton and others (1997) so that the simulated environmental gradient data layers would be nationally consistent and comprehensive. For LANDFIRE purposes, we modified the WXGMRS program in LEIS to create the WXFIRE program and modified the Biome-BGC model to create the LFBGC model (fig. 1). The WXFIRE program scales the DAYMET weather data to 30 meters using physical principles and then summarizes weather into climate descriptors over the 18-year record (for complete documentation, see Keane and Holsinger 2006). It also simulates some ecosystem processes, such as soil water fraction and evapotranspiration, and computes annual summaries. The LFBGC program simulates ecosystem processes to compute carbon, water, and nitrogen fluxes over time, and then outputs summaries of these fluxes for the 18-year DAYMET daily record (Running and Coughlan 1988; Thornton 1998). These two programs (WXFIRE and LF-BGC) provided us with the ability to create consistent and comprehensive spatial data layers for LANDFIRE mapping and modeling tasks, especially regarding the biophysical settings.

We encountered several issues when designing a system for classifying biophysical settings. Our first approach was to stratify landscapes into biophysical units based on simulated weather, climate, and ecosystem process variables (outputs from WXFIRE and LFBGC) using an unsupervised approach (Hargrove and Luxmore 1998; Hessburg and others 1999; Hessburg and others 2000). This stratification involved creating a suite of environmental gradient spatial data layers, such as temperature and evapotranspiration, using the WXFIRE and LF-BGC software. We performed an unsupervised clustering classification on every pixel in the biophysical layers for the prototype mapping zones and mapped the resultant clusters as unique biophysical settings. This approach created a landscape stratified by categories of similar biophysical conditions. That is, this map had the advantage of dividing the landscape into areas that reflect unique climate, soil, and topographic conditions

We found the results from the unsupervised biophysical classification somewhat disappointing because we could not find significant correlations between the biophysical clusters and a vegetation-based classification, as required for the LANDSUMv4 succession modeling effort to produce simulated historical conditions. We found the connection between the unsupervised clusters of similar environmental conditions and the vegetation that these biophysical characteristics support was either missing or highly variable when we correlated with the field data from the reference database to potential vegetation classification categories (for example, contingency statistics between biophysical clusters and LANDFIRE potential vegetation type classifications were low and variable). These results were frustrating as we had planned to use the unsupervised biophysical settings layer to scale the LANDFIRE vegetation maps and models to local applications. For example, a new, more detailed potential vegetation type map could be created from the biophysical setting clusters by reassigning the plots in the LFRDB a new potential vegetation type category using a more complex and detailed key. These results caused us to switch from an unsupervised to a supervised approach for mapping biophysical settings.

The supervised approach required that we develop complex statistical models directly from the field data and then implement these models in space using the simulated environmental gradient layers (Fresino and Rollins, Ch. 7). The plot data in the LFRDB had to be keyed to a biophysical classification that is useful for both the LANDFIRE mapping and modeling efforts. We reviewed a number of biophysical classifications, such as terrain models, habitat types, plant associations, and fire groups, but found few existing classifications that had complete coverage across the conterminous U.S. (Pfister 1980; Pfister 1989). Moreover, very few of the plots in the LFRDB could be keyed to existing biophysical categories, which would facilitate national implementation. The biophysical settings classification needed to be keyed from consistently collected plot data attributes to satisfy the design criteria that LANDFIRE be based on the best available science, be repeatable, and be objective.

Creating the potential vegetation type classification — We decided to develop our own biophysical classification based on the potential vegetation approach used in habitat type classifications (Pfister 1989; Pfister and Arno 1980; Pfister and others 1977) and other site classifications based on climax vegetation (Daubenmire 1962, 1966; Ferguson and others 1989). In concept, the PVT approach assumes that the climax vegetation that would eventually develop on a stand in the absence of disturbance and this climax community can be used to uniquely identify environmental conditions and can therefore provide the foundation for a biophysical classification. This approach has a long history in vegetation mapping, and potential vegetation type classifications have been developed for most of the forests of the western U.S. (Ferguson and others 1989; Pfister 1981; Pfister and Arno 1980). The approach has had limited success in non-forested environments because extensive disturbance histories in rangelands has eliminated many climax indicator species; yet overall, this approach was fitting for LANDFIRE because it provided a vegetation-based classification of potential plant communities needed for simulation modeling.

We modified this approach extensively to match the scale and limitations of the LFRDB and mapping efforts. First, we assumed that the potential vegetation for forested ecosystems could be keyed from plot data based on the shade tolerance of tree species according to the hypothesis that the tree species with the highest shade tolerance will, without disturbance, eventually become dominant on a given plot. Following Daubenmire's theory (1966), the tree species with the highest shade tolerance will have a high fidelity to unique biophysical settings. The *potential natural vegetation* (PNV) approach to classifying vegetation integrates disturbance into succession dynamics as classification criteria and, as such, was not useful for the LANDFIRE effort because it was incompatible with the LANDSUMv4 modeling structure. We made no inference that the shade-tolerant species will become the climax species since the term climax has many limitations and is often misconstrued. Climax is often associated with plant communities rather than species, and many ecologists have noted that climax vegetation is an unrealistic endpoint since climate, genetics, and exotic migrations, among other factors, are in constant flux and thus making a stable climax community impossible (Hironaka 1987; Huschle and Hironaka 1980). For this reason, we do not assume that the shade-tolerant species will become climax; rather, we believe that the most shade-tolerant species is an indicator of distinctive environmental conditions.

For lack of a better term, we named our biophysical classification after PVTs, assuming that these shade-tolerant species best indicate potential vegetation under the current climate regime, not an ultimate climax community (fig. 1). This PVT approach facilitates the mapping of unique biophysical settings and also allows these settings to be directly linked to the succession pathways that we use in our simulation modeling to determine historical reference conditions. A common misconception is that the PVT classification is a vegetation classification; however, the PVT classification is a biophysical classification that uses plant species' names as category names because the most shade-tolerant species are indicators of site conditions. This classification was useful because, in the LANDSUMv4 succession pathway protocols, the PVT classification categories had to match the existing cover type classification categories. For example, the Douglas-fir cover type category is keyed based on the dominance of Douglas-fir (Caratti, Ch. 4), but the Douglas-fir PVT is keyed from the presence of Douglas-fir on the plot. This is somewhat confusing for the user but is absolutely critical for LANDFIRE integration.

Each forested plot in the reference database was assigned a PVT based on the coverage or tree density data collected for that plot. We sorted all tree species present on a plot by shade tolerance using information in the literature (Burns and Honkala 1990; Fowells 1965; Minore 1979). We then identified the most shade-tolerant species on the plot that exceeded a designated abundance threshold (Caratti, Ch. 4) and matched this species with the associated cover type category used in the mapping of existing vegetation (Long and others, Ch. 6). For example, a plot having 50 percent canopy cover of ponderosa pine and 5 percent cover of Douglas-fir would have an existing cover type category of ponderosa pine but a PVT category of Douglas-fir. The matching of PVT and existing vegetation legends ensured logical combinations between maps and a consistent linkage for the development of the LANDSUMv4 modeling pathways used in simulating historical reference conditions.

As mentioned above, the rangeland ecosystems presented a special problem in the PVT determination since late successional species are rarely observed because of high frequency of disturbance such as grazing and fire (Bunting 1994; Sieg 1997; Westoby 1980). We therefore arranged the rangeland cover type categories along a moisture gradient from xeric to mesic communities, and this arrangement was used as the key criterion for classifying plots in the reference database (Long and others, Ch. 6). Presence, rather than dominance, however, was used to determine the rangeland PVTs in the key. There were some inconsistencies in this approach, so we used dominant species autecological characteristics to further refine the rangeland types (Long and others, Ch. 6). Although this approach had a number of additional flaws, most importantly the inability to consistently model successional development, it proved to be the best considering the limited resources and data available.

The mapping of PVT was performed by mapping zone, so it was important to ensure that PVTs were mapped consistently across zones (fig. 1). We did this by conducting a study that generated the set of WX-FIRE and LF-BGC simulated biophysical variables for 14 million 1-km pixels across the conterminous U.S. These pixel values were then used in complex clustering algorithms to create a national set of biophysical settings using a supervised approach (Hargrove and Luxmore 1998; Hessburg and others 1998). The resulting cluster map was used to guide the mapping of PVTs using the assumption that similar clusters across mapping zones should identify similar PVTs. This coarse-scale biophysical settings map was not finished by the end of the LANDFIRE Prototype but will be available for national LANDFIRE implementation.

Mapping existing cover type and structural stage with satellite imagery — Using all the classifications, digital map layers, and tools detailed above, we were able to map current vegetation conditions using the cover type and structural stage vegetation classifications. This complex task was performed by the EROS team using Landsat imagery (Zhu and others, Ch. 8; fig. 1). The team used the set of simulated biophysical data layers as covariates in the mapping process and also used landscape metrics and the PVT layer to guide cover type and structural stage mapping. Another aid that the EROS team found very useful was a summary from the LFRDB containing the distribution of plots across all cover type and structural stage categories, which was used to guide the selection of vegetation classes that were difficult to distinguish.

For the two prototype mapping zones, Landsat images were acquired on three different dates over the time period between 1999 and 2001 to capture several annual growth phases, such as growing season and dormant season, to maximize the ability to distinguish cover types. All images were corrected for terrain using NED, and the raw satellite digital numbers were converted to at-satellite reflectance for the six Landsat bands (Markham and Barker 1986). We used at-satellite reflectance-based coefficients to calculate values for tasseled-cap brightness, greenness, and wetness, which have been found useful for vegetation characterization

In the LANDFIRE Prototype Project, we created maps of cover types using a training database developed from the LFRDB, satellite imagery from Landsat, the biophysical gradient layers, the PVT map (for limiting the types of vegetation that may exist in any area) and classification and regression tree (CART; Breiman and others 1984; Quinlan 1993) algorithms similar to those used to map PVT. We selected CART-based classification methods for the following reasons. First, as a non-parametric alternative for regression, CART is more appropriate for broad-scale mapping than parametric methods (such as maximum likelihood estimation or discriminant analysis). Second, CART-based models may be trained hundreds of times faster than some other non-parametric classifiers like neural networks or support vector machines. Yet, CART is comparable to and performs similarly with regard to accuracy to these methods (Franklin 2003; Rollins and others 2004). Third, the CART framework explicitly represents logics and rules that may be interpreted in and incorporated into expert systems for further analysis. Neural networks and support vector machines work like "black boxes," with classification logics difficult to interpret or simply "invisible". Lastly, CART has been successfully used recently for modeling and mapping vegetation at broad scales, including the MRLC 2001 project (Zhu and others, Ch. 8).

The EROS team mapped cover types using a hierarchical set of classification models, with the first model separating broader land cover types (such as life form) and subsequent models separating more detailed levels of the vegetation classification. The LFRDB, biophysical settings layers, and other ancillary data layers were incorporated to guide the classification.

Regression trees in a CART framework and applied through a custom See5/ERDAS IMAGINE interface (ERDAS 2004; Quinlan 1993; Rulequest 1997) were used to map canopy closure and canopy height using spectral information from Landsat imagery and the 38 biophysical gradient layers. Again, a training database was developed using the LFRDB. The resultant maps represented canopy closure and canopy height continuously across each prototype mapping zone. When compared to standard, parametric linear regression, regression trees developed using CART have the advantage of being able to approximate complex nonlinear relationships (Quinlan 1993). The final structural stage layer was developed by assigning structural stage classes to combinations of PVT, cover type, and the continuous canopy closure and height class layers. Structural stage assignments were based on the classification described above (Long and others, Ch. 6).

A major problem arose when the MFSL scientists received the vegetation maps from EROS. The cover type and structural stage maps did not match the PVT maps for approximately 20 percent of the pixels. For example, there were mesic cover types such as Grand Fir being mapped in xeric PVTs such as Douglas-fir, which is ecologically impossible under our PVT approach and inconsistent with the succession pathways used in the LANDSUMv4 modeling effort. These inconsistencies occurred because the EROS scientists felt confident that their mapping of cover type, based on a set of computed statistics, was correct, whereas they had low confidence in the PVT maps. Finally, both EROS and MFSL members agreed that we should create a map of confidence using indices from zero to one for the mapping of cover type, structural stage, and PVT. These indices were derived from our statistical modeling and analysis results. Any pixel mapped to PVT or cover type with a confidence lower than 0.5 would be changed to the most appropriate category according to a set of rules built from a statistical analysis of LFRDB. This iterative process eventually created a set of consistent vegetation maps useful in LANDSUMv4 modeling and in the ultimate mapping of FRCC.

Many additional layers were developed by the EROS team for specific uses in the LANDFIRE Prototype Project. As mentioned, the cover type, structural stage, and corresponding confidence layers were used to revise the PVT map and used in the computation of FRCC. The scientists at EROS also created maps of canopy height from regression analyses of Lidar data and Landsat imagery, as well as maps of canopy cover from the imagery and reference database information (Zhu and others, 8). These layers were used to map canopy fuel and are described in Keane and others, Ch. 12).

Describing Historical Conditions

The calculation of FRCC requires that current vegetation conditions be compared with the range and variation of conditions that existed during the historical era identified in the LANDFIRE guidelines (1600-1900 A.D.) to calculate a departure statistic (Hann 2004). This historical range and variation (HRV) has several forms. Historical range and variation can refer to ecosystem characteristics such as landscape composition described by the cover type, the structural stage, or the fuel model. It can also refer to landscape structure characteristics such as pattern, patch distribution, and contagion. In the LANDFIRE Prototype, we used only landscape composition as described by the combination of PVT, cover type, and structural stage to describe HRV. Maps of PVT, cover type, and structural stage were used because the combination provided the finest resolution for describing landscape dynamics in LANDFIRE. We did not address any historical variation in landscape pattern or patch dynamics because of time and computer resource limitations.

The only way to quantify HRV over space and time is by developing a sequential set of data layers that spatially describe the vegetation conditions over many points in time. These sequential data layers are referred to as *spatially explicit historical chronosequences*. The challenge in the LANDFIRE Prototype was to find a set of existing maps of historical vegetation conditions that were directly comparable to the maps of current conditions created from Landsat imagery and biophysical gradients as part of the LANDFIRE Prototype. These historical reference layers needed to be consistent and comprehensive across the conterminous U.S. at a 30-meter pixel resolution and created using the same map categories, resolution, and accuracy.

We faced a major dilemna when it came to deciding which source to use for the representation of historical landscape composition. Temporally deep chronosequences that are spatially explicit across the entire nation are rare, and we found no historical spatial data that fit our design specifications. There were many fire history studies and some historical vegetation maps, but many ecosystems and geographic areas of the country were inconsistently sampled or not sampled at all (Heyerdahl and others 1995; Heyerdahl and others 2001). We found no national map sequences of historical vegetation. Most historical maps were highly localized to small geographic areas and limited to one point in time, usually circa 1900. It became clear that previously derived historical time series for the conterminous U.S. were not available for the computation of FRCC.

Using landscape simulation modeling – This deficit left simulation modeling as the only tool for creating a spatial historical record that would be consistent with the other elements of the LANDFIRE Prototype. For the last decade, MSFL scientists have been developing spatially explicit landscape models that simulate fire and vegetation dynamics (Keane 2000; Keane and Finney 2003; Keane and Hann 1998; Keane and Long 1997; Keane and others 1996b; Keane and others 2002b) and therefore have had a great deal of experience with these complex computer programs.

Simulation provides several advantages for quantifying HRV (Keane and Finney 2003; Keane and others 2004a). Simulation models can generate temporally deep chronosequences that are limited only by the amount of computing resources available to run the model. These sequential data layers can be designed to be consistent with the data layers developed for describing current conditions (PVT, cover type, and structural stage), and they can be reported over long intervals so temporal autocorrelation is minimized. Modeling also allows the integration of spatially and temporally limited field data, which are mostly point data, into the simulation framework as parameterization or validation sources for the creation of spatially explicit predictions. For example, data from local fire history studies can be used to quantify fire frequency and severity parameters in the LANDSUMv4 simulation model. Moreover, spatial models can be designed so that disturbance and succession dynamics are consistently modeled across the entire simulation area. These same models can also be used to generate chronosequences for other applications such as climate change research or a national fire management policy.

Simulation models also have their limitations. Most importantly, models are simplifications of reality, and it is easy to oversimplify model design such that the simulation results are meaningless. In addition, simulation models are difficult to test and validate, especially spatially explicit landscape models, because of the scarcity of field data that are appropriate in scale, accuracy, and detail for comparisons with model predictions. Complex simulation models also have difficulty computing accurate predictions because the varied algorithms implemented in models come from disparate sources and resolutions. The real strength of modeling is precision rather than accuracy because prediction errors tend to be the same across large spatial and temporal extents. Because mapping efforts such as LANDFIRE are more concerned with relative differences across large areas, we identified simulation modeling as an appropriate vehicle for generating the HRV spatial data layers.

The LANDSUMv4 model used in the LANDFIRE effort is in a class of models called *landscape fire succession models* (LFSMs) because they spatially simulate the complex processes of fire and vegetation succession across landscapes. We evaluated many LFSMs that were deemed appropriate for LANDFIRE implementation (Keane and others 2004a) and found most of them to be inadequate for various reasons, mainly because of the extensive input data required by most models. In addition, many complex LFSMs are difficult to parameterize and initialize because the suite of data layers required for these tasks are unavailable across the nation. Complex biogeochemical models for fire and vegetation dynamics, such as the Fire-BGC model (Keane and others 1996c), not only require extensive parameterization and initialization but also require vast amounts of computing resources to execute the program. When we identified the data sources available for parameterization and initialization (in essence, the LFRDB and map products) and evaluated the LFSMs in this context, we found that the LANDSUMv4 model best met the needs of the LANDFIRE Prototype (see Keane and others 1996b, Keane and others 1997c, and Keane and others 2002b for details).

LANDSUMv4 is the fourth version of the LANDSUMv4 model and was developed specifically for the LANDFIRE Prototype (Keane and others 2006) (fig. 1). It contains a deterministic simulation of vegetation dynamics in which successional communities are linked along multiple pathways of development that converge in an end-point community. Disturbances, except fire, are stochastically modeled at the stand level from probabilities specified by the user. Fire ignition is computed from fire frequency probabilities specified by PVT, cover type, and structural stage categories in model input files (Keane and others 2001). Fire is then spread across the landscape based on simplistic slope and wind factors. LANDSUMv4 does not mechanistically simulate fire growth because of the lack of fuel inputs, daily weather records, and computing resources. The effects of fires are stochastically simulated based on the fire severity types as specified in the input files. Finally, LANDSUMv4 outputs the historical composition by PVT, cover type, and structural stage for areas called landscape reporting units. We selected the size of the reporting unit to be 900 meters by 900 meters so that it was compatible with the 30-meter pixel size of the base maps and approximated the resolution of the coarse-scale maps produced by Schmidt and others (2002).

A significant LANDFIRE Prototype Project task involved estimating the succession and disturbance parameters needed to execute LANDSUMv4. Previous attempts at parameter quantification used the "Delphi" method in which local and regional experts (ecologists and land managers) collaborated through a series of workshops to build succession pathways and estimate pathway disturbance and development parameters using local knowledge rather than field data (Hann and others 1997). This approach proved productive because most of the experts were familiar with the literature and able to make realistic approximations. However, these workshops were difficult and expensive to stage, and the final results were often inconsistent between succession pathways and were incompatible with LANDFIRE modeling and mapping goals. For these reasons, we employed several vegetation, fire, and landscape ecologists to construct and parameterize the LANDSUMv4 succession pathways so that the entire modeling effort was consistent and comprehensive. Each ecologist constructed and parameterized succession pathways and disturbance parameters for an assigned a set of PVTs (see Keane and others 2006 for details on succession and disturbance parameters). These professionals used information from the literature, the LFRDB, and local area knowledge to perform this task and thoroughly documented their work (Long and others, Ch. 9).

An important end product of the LANDSUMv4 simulations was the creation of a set of four fire regime maps (fig. 1; Keane and others 2003; Keane and others 2004b). The fire frequency map details the number of fires over the entire landscape, whereas the three fire severity maps represent the probabilities of stand-replacing fires, mixed severity fires, and non-lethal surface fires, respectively. These maps provide a useful reference for locating those areas that tend to experience frequent fire so that fuel treatments can be located and scheduled. They also represent an important scaling tool for fire management in that they can be used to plan the frequency and severity of proposed burn treatments.

Calculating FRCC — The computation of FRCC from the comparison current conditions to historical reference conditions presented a unique set of challenges. In the LANDFIRE Prototype Project, we coded the field methods of Hann (2004) into a GIS program that uses the LANDSUMv4 simulated historical chronosequences to determine the range of landscape conditions and then compares this range to current conditions to compute an index of departure from historical conditions (fig. 1). This departure index ranges from zero to 100 in which an index of 100 represents the current landscape as being totally departed from simulated historical conditions. FRCC is then computed by grouping the index into classes (see Holsinger and others, Ch. 11). FRCC was computed for divisions of the LANDFIRE mapping zones called *landscape reporting units*. These

900-meter by 900-meter landscape delineations served as the smallest units for evaluating departure (Holsinger and others, Ch. 11). Hann's (2004) methodology is the only approach officially accepted by FAM for computing FRCC and so, to be consistent with FAM's protocol, the final FRCC map created by the LANDFIRE Prototype Project used these methods. However, because of the many limitations to Hann's approach, we determined that a complete exploration of the computation of departure from historical conditions was warranted to ensure a scientifically credible protocol.

The idea that historical ecological data can be used as a reference to inform land management's decisions regarding today's landscapes is somewhat new and has only recently been put into practice (Hessburg and others 1999; Keane and others 2002b; Landres and others 1999; Reed and others 1998; Swetnam and others 1999). Although the theory is sound and well-founded, its implementation in land management is still in its infancy. There are few standardized methods and protocols for quantitatively comparing historical reference conditions with current conditions and evaluating their differences. Standard parametric statistics are not always appropriate for historical time series since the chronosequences are autocorrelated in time and in space. Also, HRV has to be evaluated across all elements or mapping entities that comprise the landscape; in LANDFIRE, the elements evaluated over time are cover type and structural stage combinations by PVT. These combinations are correlated to each other because a decrease in the area of one combination will result in increases in the areas of other combinations on the simulation landscape. In addition, these combinations are correlated in space because simulated fire spread will tend to burn contagious pixels. It is also difficult to ascertain the thresholds of departure that determine whether human intervention via fuel treatments is warranted. We therefore explored an entirely new, alternative, statistically based method for comparing the simulated historical chronosequences with the imagery derived from existing conditions using indices of departure and a measure of statistical significance. In addition, these new methods could be compared with Hann's (2004) FRCC field method for computing departure so that either or both methods could be improved at a later date.

A set of complex statistical methods for computing departure from historical conditions were developed by Steele and others (in preparation) specifically for the LANDFIRE Project (fig. 1). They created a statistical technique that is sensitive to the autocorrelation of simulated data over time, space, and vegetation categories. This technique computes an index of departure that varies from zero (no departure) to one (most departed). In addition, a measure of statistical significance is computed as a probability value (p-value), also varying from zero to one. Steele and others (in preparation) implemented this statistical technique in the HRVStat program that compares summaries of simulated historical chronosequences with current conditions by reporting unit within the mapping zone and outputs a departure value and a p-value for each landscape unit or strata. By design, Steele and others (in preparation) created this program to work with any historical chronosequence, not only simulated time series, so that local land management offices can replace the simulated data with actual historical observations, if they exist. Moreover, this program can be used for reference sequences other than historical that are more germane to land management, such as climate change chronosequences' effects on exotics.

Another potentially fruitful area of HRV research exists in the determination of the size and shape of the reporting unit used as the context analysis landscape for calculating departure. The most perplexing problem we encountered while developing these protocols was deciding the size of the landscape for evaluation. Simulation results from landscapes that were too small did not adequately capture the full range of conditions within the area, whereas results from landscapes too large were not sensitive to subtle changes in cover type and structural stages, such as those caused by fuel treatments. We decided to use a 900-meter by 900-meter analysis landscape reporting unit because it closely matched the coarse-scale project by Schmidt and others (2002) and could thereby facilitate (limited) comparisons, and it fit well with the 30-meter grid cell resolution of the input layers. We are currently conducting a study to determine the characteristic landscape size appropriate for computing FRCC and departure statistics.

Ancillary LANDFIRE Prototype Products

The previously discussed LANDFIRE biophysical, vegetation, and historical data layers constitute a remarkable set of spatial data sources for describing vegetation characteristics and dynamics across the entire nation. However, the utility of these data layers is seriously limited because there are few applications that use these layers directly as inputs. For example, extensive expertise and funding would be required to create a map of fire hazard across a region from merely the mapped vegetation characteristics. Similarly, whereas the FRCC map may be used as a reference for the distribution of funding and resources to land management agencies and regions, it has little application in terms of designing, implementing, and monitoring fuel treatments. Additional layers and software tools were needed to provide local land management with applications that were consistent with all other LANDFIRE products. We therefore generated a set of fuel data layers and companion analysis models to aid fire managers in the design, implementation and monitoring of fuel treatments for their respective areas. These fuel layers were developed as ancillary products in the LANDFIRE process because they were not central to the computation of FRCC, but these products were critically important as they provided a means by which to use LANDFIRE products to more efficiently plan and design ecological restoration projects and fuel treatments for local applications.

Creating the LANDFIRE Fuel Layers

It was essential that the entire array of fuel characteristics be mapped in the LANDFIRE Prototype Project to ensure that fire hazard analyses be germane to fire management. Both surface and canopy fuel had to be mapped so that they could be used in fire behavior and fire effects predictive models. Since fuel is highly variable and complex, many fire applications use classifications of fuel as inputs instead of using actual fuel loading sampled in the field. Fuel classifications contain fuel classes with representative fuel loading for a set of fuel components, and these fuel classes are often referred to as “fuel models”. To complicate matters, most fire behavior simulation models require fuel models that are actually abstract representations of expected fire behavior and therefore cannot be used to simulate fire effects (Anderson 1982). Moreover, existing fire behavior fuel models are quite broad and do not match the resolution needed to detect changes in fuel characteristics after fuel treatments (Anderson 1982). Because our design criteria specified that, with the implementation of the National Fire Plan, the LANDFIRE layers must be able to identify changes in FRCC and fire hazard, we needed to overcome these limitations. We therefore developed a new set of fire behavior fuel models and a new classification of fire effects fuel models to ensure that the fuel layers could be used for local to regional assessments and analyses.

A new set of fire behavior fuel models was created by Scott and Burgan (2005) using funding from – but developed independently of – the LANDFIRE effort. This suite of 40 models represents a significant improvement in detail and resolution over Anderson’s original 13 (1982). The new fire behavior fuel models were developed independently of LANDFIRE because we wanted to ensure their use in accepted fire behavior applications such as BEHAVE (Andrews 1986; Andrews and Bevins 1999) and FARSITE (Finney 1998). Each model has a complete description and includes graphs showing fire behavior under different fuel moisture and weather conditions (www.fire.org).

Fire effects fuel models differ from fire behavior fuel models in that they represent real fuel loading by fuel category, not abstract representations of expected fire behavior. This loading information by fuel component is used to calculate important fire effects such as fuel consumption, soil heating, smoke, and tree mortality. Because there were no national classifications of fuel loading at the time of LANDFIRE’s inception, we created our own. Our classification of Fuel Loading Models (FLMs) attempts to identify unique fuel loading models from an analysis of the variance of fuel loading by fuel category (Lutes and others, in preparation). Fuel loading categories include four downed woody size classes, live and dead shrub and herbaceous biomass, duff and litter depth, and crown fuel characteristics. Many studies have noted that high variation of fuel loading across temporal and spatial scales often precludes correlations with vegetation characteristics (see Brown and Bevins 1986 and Brown and See 1981). We examined this variance across and between fuel categories to identify clusters of fuel loading that might facilitate fire effects fuel model mapping. We gathered fuel loading data sets from past field efforts across the nation and reformatted them in the LFRDB and then performed complex clustering analyses to identify unique fuel loading clusters or models (Lutes and others, in preparation). Resultant fuel classes matched the mid-scale development framework specified in the project guidelines. The FLM maps were not available for the prototype effort because the FLM classification was not completed; however, the national LANDFIRE effort will map FLMs for use in fire effects models such as FOFEM (Reinhardt and others 1997; Reinhardt and Keane 1998) and CONSUME (Ottmar and others 1993).

Another classification of fuel loading was needed for finer-scale applications because the FLM classification is quite broad and meant for mid-scale analyses. We used the national Fuel Characterization Class (FCC) classification developed by Sandberg and others (2001) and Cushon and others (2003). This classification was developed through sampling fuel extensively in various vegetation, structure, and stand history combinations in forest and rangeland settings across the nation and then assigning the computed fuel loading to the categories within the classifications of vegetation and stand condition called default fuelbeds. We mapped these default fuelbeds from information collected in the intensive sampling effort using the PVT, cover type, and structural stage maps (Long and others, Ch. 6). Using software developed by the FCC effort, land managers can modify fuel loading for their default FCC fuel model to create a more site-specific, locally realistic fuel model for use in fire effects computer models.

Most fire behavior and effects predictive models require a quantification of several canopy characteristics to simulate crown fire initiation and propagation (Albini 1999; Rothermel 1991; van Wagner 1993). These characteristics include canopy bulk density, top height, base height, and closure. Fortunately, the EROS team mapped canopy top height and canopy closure using satellite imagery (Zhu and others, Ch. 8), but canopy bulk density and canopy base height had to be mapped at MFSL by calculating the two canopy attributes from tree inventory information in the reference database using the Fuel Calculation system (FUELCALC) program (Reinhardt and Crookston 2003). This program uses tree measurements of species, height, and diameter to compute the vertical distribution of crown biomass from a set of biomass equations. The program also contains an algorithm that computes the canopy base height from the vertical distribution of crown biomass (Reinhardt and Crookston 2003). These two canopy characteristics are then statistically modeled using complex statistical analyses from variables spatially represented in all LANDFIRE biophysical layers (Keane and others, Ch. 12). The statistical models are then implemented across the mapping zones using the biophysical layers. FUELCALC is still under development but will be released before the LANDFIRE Prototype Project is finished.

Creating analysis tools — Maps of fuel characteristics have limited use until they are linked with an appropriate application. An existing application that can be used directly with LANDFIRE products is the FARSITE fire growth model that simulates the spread of fire as it moves across landscapes (Finney 1998). The sister program to FARSITE, called FLAMMAP, is used for fire hazard analysis and computes fire behavior for every pixel based on user-defined weather scenarios. A drawback to these programs, however, is that FLAMMAP and FARSITE compute fire behavior from weather data with no temporal distribution. For example, crown fires are more important to fire management if they occur frequently due to a dry weather record, as in dense ponderosa pine stands, than if infrequently, as in crown fires of lodgepole pine forests found at high elevations. A tool was needed to analyze fire behavior and fire effects across a landscape over a temporal domain so that fire hazard could be assessed in time and space.

We initiated the development of the FIREHARM program to compute fire hazard across large landscapes over long time periods. This program accepts the fuel map inputs from LANDFIRE and then uses the DAYMET weather database to calculate the probability that a fire event could happen on any given day in the 18-year weather record. A fire event can be defined from fire danger (such as burning index, spread index, and energy release component), fire behavior (such as flame length, spread rate, and fire intensity), and fire effects (such as fuel consumption, soil heating, and tree mortality) variables. For example, a user might define a fire event as those days when fuel consumption is greater than 50 percent. The resultant maps of fire event probability can be used to target treatment locations, or they can be used with other layers to perform other estimations of fire hazard. The FIREHARM model is still in development and will be released sometime after LANDFIRE Prototype Project completion.

A last application that is still in development is the LANDFIRE decision support tool that uses LANDFIRE data layers as inputs to an expert system that uses fuzzy logic and decision uncertainty to prioritize the selection of areas for fuel treatment and restoration activities, depending on management objectives (Reynolds and Hessburg 2005).

Discussion

Despite our best efforts, some elements of subjectivity crept into LANDFIRE methods, and perhaps the task infused with the highest bias was the development of the vegetation map classification. It was difficult to avoid subjectivity in creating a comprehensive list of cover types that matched the sensitivity of the Landsat imagery and simulation models because of the wide variety of cover type classifications and vegetation communities possible for each individual mapping zone and the inherent variability of vegetation across the mapping landscape. One possible solution would be to use an existing cover type classification for the entire U.S. so that bias is minimized and the list of cover types remains constant across mapping zones. Yet this option poses problems. Often, the composition of a cover type can change across large regions, making it difficult to develop one classification key that fits all areas. Perhaps the best method would be to use an existing classification, determine the list of cover types to map according to each mapping zone, and then vary the keys to these cover types to reflect the subtle differences across zones.

The LANDFIRE task of assigning the new fire behavior fuel models to combinations of cover type, structural stage, and PVT also contained some subjectivity (Keane and others, Ch. 12). This was primarily the result of the lack of a comprehensive and consistent key, which precluded our ability to assign a fuel model to each plot in the LFRDB. In addition, since the fire behavior fuel model classification had been recently created, none of the plots in the reference database contained information about the new fuel models. Furthermore, the new fuel models could not be assigned to any plots in the reference database because of a lack of consistent key criteria. Without a link to field data, we had to assign a fuel model to each PVT-cover type-structural stage combination based on the best estimate by the authors of the fuel model classification (Scott and Burgan 2005) and by specialists on the LANDFIRE team (Keane and others, Ch. 12). Future efforts should attempt to derive a key that objectively assigns fuel models based on the data collected in the field or present in the reference database.

LANDFIRE products can be scaled to local applications using a variety of approaches. The biophysical layers can be used in concert with the field-referenced data to refine local vegetation maps and with the PVT maps to reflect environmental conditions. For example, precipitation can be used to create two Ponderosa Pine cover types, one including larch and one without larch, or elevation could be used to separate a LANDFIRE Sagebrush cover type into Mountain Sage and Black Sage LANDFIRE cover types. LANDFIRE fuel assignments to combinations of PVT, cover type, and structural stage can be linked to local digital maps of vegetation and biophysical settings to create a fine-scale fuel layer. In addition, local maps of vegetation conditions, such as basal area and tree density, can be augmented with the suite of LANDFIRE maps to improve fuel model assignments.

In addition to a host of other land management applications, LANDFIRE products can also be used to help prioritize, plan, and implement fuel treatments. Maps of vegetation and fuel can be used as inputs to a number of existing fine-scale computer models, such as SIMMPPLE (Chew 1997) or FVS-FFE (Reinhardt and Crookston 2003), to evaluate alternative fuel treatments and their effects on project landscapes. In addition, scenarios can be developed for the LANDSUMv4 model to simulate the effects of alternative management strategies. The FIREHARM program can use the LANDFIRE maps and DAYMET database to create data layers that show the probability of fire events, such as a crown fire or lethal soil heating, across small analysis landscapes. The set of LANDFIRE fuel layers can be used in FARSITE and FLAMMAP to simulate fire growth or predict fire hazard for local landscapes. Furthermore, fire regime maps can be used to prioritize, plan, locate, and schedule ecological landscape restoration and fuel treatments across small landscapes by identifying those areas that burn frequently and therefore needing treatment more urgently.

Conclusion

The LANDFIRE Prototype Project has created a process for mapping fire, fuel, and vegetation conditions across the entire United States by integrating satellite imagery, statistical analyses, and simulation modeling using scientifically credible methods. This process is currently being implemented through the national LANDFIRE effort with the complete set of LANDFIRE products scheduled to be delivered by 2008. The methods, procedures, and protocols implemented within this process ensure consistency across all regions, ecosystems, and land types and allow for future replications of the process to monitor the efficacy of the National Fire Plan and Healthy Forest Restoration Act. The LANDFIRE products can be scaled from local applications to national assessments and will facilitate detailed fuel and fire hazard analyses.

For further project information, please visit the LANDFIRE website at www.landfire.gov

The Authors

Robert E. Keane is a Research Ecologist with the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 U.S. Highway 10 W., Missoula, MT 59808; phone: (406) 329-4846; fax: (406) 329-4877; email: rkeane@fs.fed.us. Since 1985, Keane has developed various ecological computer models for the Fire Effects Project for research and management applications. His most recent research includes the development of a first-order fire effects model, construction of mechanistic ecosystem process models that integrate fire behavior and fire effects into succession simulation, restoration of whitebark pine in the Northern Rocky Mountains, spatial simulation of successional communities on landscapes using GIS and satellite imagery, and the mapping of fuel for fire behavior prediction. He received his B.S. degree in Forest Engineering in 1978 from the University of Maine, Orono, his M.S. degree in Forest Ecology in 1985 from the University of Montana, and his Ph.D. degree in Forest Ecology in 1994 from the University of Idaho.

Matthew Rollins is a Landscape Fire Ecologist at the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (MFSL), 5775 U.S. Highway 10 W., Missoula, MT 59808; phone: (406) 329-4960; fax: (406) 329-4877; email: mrollins@fs.fed.us. His research emphases have included assessing changes in fire and landscape patterns under different wildland fire management scenarios in large western wilderness areas, relating fire regimes to landscape-scale biophysical gradients and climate variability, and developing predictive landscape models of fire frequency, fire effects, and fuel characteristics. Rollins is currently the lead scientist of the LANDFIRE Project, a national interagency fire ecology and fuel assessment being conducted at MFSL and the USGS Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota. He earned a B.S. in Wildlife Biology in 1993 and an M.S. in Forestry in 1995 from the University of Montana in Missoula, Montana. His Ph.D. was awarded by the University of Arizona in 2000, where he worked at the Laboratory of Tree-Ring Research.

Acknowledgments

We thank Denny Simmerman of the USDA Forest Service Rocky Mountain Research Station Missoula Fire Sciences Laboratory (MFSL) for graphics support, Kevin Ryan of MFSL for administrative support, Wendel Hann of the USDA Forest Service Fire and Aviation Management for technical support, and Christine Frame of Systems for Environmental Management for editorial and technical review. We thank the entire LANDFIRE Prototype Project team members for their excellent work.

References

Albini, F. A. 1999. Crown fire spread rate modeling. USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, Montana. Progress Report RJVA RMRS-99525.

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Anderson, M.; Bourgeron, P.; Bryer, M.T.; Crawford, R.; Engelking, L.; Faber-Langendoen, D.; Gallyoun, M.; Goodin, K.; Grossman, D.H.; Landaal, S.; Metzler, K.; Patterson, K.D.; Pyne, M.; Reid, M.; Sneddon, L.; Weakley, A.S. 1998. International classification of ecological communities: Terrestrial vegetation of the United States. Arlington, Virginia: The Nature Conservancy.

Andrews, P. L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system — BURN subsystem. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Andrews, P. L.; Bevins. C.D. 1999. BEHAVE Fire Modeling System: redesign and expansion. Fire Management Notes. 59:16-19.

Austin, M. P.; Smith, T.M. 1989. A new model for the continuum concept. Vegetatio. 83:35-47.

Bailey, R. G. 1995. Description of the ecoregions of the United States. Miscellaneous Publication Number 1391 Washington D.C. USDA Forest Service, Headquarters. 77p.

Baron, J. S., ed. 2002. Rocky Mountain Futures: an ecological perspective. Washington, DC: Island Press.

Breiman, L.; Friedman, J.H.; Olshen, R.A.; Stone, C.J. 1984. Classification and Regression Trees. Pacific Grove, CA: Wadsworth & Brooks/Cole Advanced Books & Software. 358 p.

Brown, J. K.; Bevins, C.D. 1986. Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains. Research Note INT-358. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Brown, J. K.; See, T.E. 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. Gen. Tech. Rep. INT-117. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Bunting, S. C. 1994. Effects of fire on juniper woodland ecosystems in the Great Basin. In: Monson, S.B.; Kitchen, S.G., eds. Proceedings — Ecology and management of annual rangelands. USDA Forest Service General Technical Report INT-GTR-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. Pp. 53-55.

Burgan, R. E.; Klaver, R.W.; Klaver, J.M. 1998. Fuel models and fire potential from satellite and surface observations. International Journal of Wildland Fire. 8:159-170.

Burgan, R. E.; Shasby, M.B. 1984. Mapping broad-area fire potential from digital fuel, terrain, and weather data. Journal of Forestry. 228-231.

Burns, R. M.; Honkala, B.H. 1990. Silvics of North America: Volume one, conifers. Agriculture Handbook 654, Washington DC. USDA Forest Service, Headquarters.

Chew, J. D. 1997. Simulating vegetation patterns and processes at landscape scales. In: Integrating spatial information technologies for tomorrow: GIS '97 conference proceedings; 1997 February 17-20; Fort Collins, CO: GIS World: 287-290.

Cushon, G.;Ottmar, R.; Sandberg, D.; Greenough, J.; Key, J. 2003. Fuelbed characteristic classification: Characterizing wildland fuelbeds in the United States. In: Galley, K. E. M.; Klinger, R. C.; Sugihara, N.G., eds. Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention and Management. Misc. Publication Number 13 Tall Timbers Research Station, Orlando, Florida. Pp. 221-226

Daubenmire, R. 1962. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. Ecological Monographs. 22:301-329.

Daubenmire, R. 1966. Vegetation: identification of typal communities. Science. 151:291-298.

EOSAT. 1992. Landsat technical notes. EOSAT Inc. Lanham, MD-USA.

ERDAS 2004. ERDAS IMAGINE 8.7. SP1. Leica Geosystems GIS & Mapping, Atlanta, GA, USA.

Eyre, F. H. E. 1980. Forest cover types of the United States and Canada. Washington D.C.: Society of American Foresters.

Ferguson, D.E.; Morgan, P.; Johnson, F.D., eds. 1989. Proceedings – land classifications based on vegetation: Applications for resource management. Gen. Tech. Rep. INT-257. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Finney, M. A. 1998. FARSITE: Fire Area Simulator — model development and evaluation. Res. Pap. RMRS-RP-4. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Fowells, H. A. 1965. Silvics of the forest trees of the United States. Agricultural Handbook Number 271, Washington D.C. USDA Forest Service, Headquarters.

Grossman, D. H.; Faber-Langendoen, D.; Weakley, A.S.; Anderson, M.; Bourgeron, P.; Crawford, R.; Goodin, K.; Landaal, S.; Metzler, K.; Patterson, K.; Pyne, M.; Reid, M.; Sneddon, L. 1998. International classification of ecological communities: Terrestrial vegetation of the United States Volume I. The National Vegetation Classification System: development, status, and applications Arlington, VA: The Nature Conservancy.

Hann, W. J.; Jones, J.L.; Karl, M.G.; Hessburg, P.F.; Keane, R.E.; Long, D.G.; Menakis, J.P.; McNicoll, C.H.; Leonard, S.G.; Gravenmier, R.A.; Smith, B.G. 1997. An assessment of ecosystem components in the Interior Columbia Basin and portions of the Klamath and Great Basins Volume II — Landscape dynamics of the Basin. Gen. Tech. Rep. PNW-GTR-405. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Hann, W. J. 2004. Mapping fire regime condition class: a method for watershed and project scale analysis In: Engstrom, R.T.; Galley, K.E.M.; De Groot, W.J., eds. Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temprate, Boreal,and Montane Ecosystems. Tallahassee, FL: Tall Timbers Research Station.

Hardy, C. C.; Schmidt, K.M.; Menakis, J.P.; Sampson, N.R. 2001. Spatial data for national fire planning and fuel management. International Journal of Wildland Fire. 10:353-372.

Hargrove, W. W.; Luxmore, R.J. 1998. A New High-Resolution National Map of Vegetation Ecoregions Produced Empirically Using Multivariate Spatial Clustering. In: Proceedings of the Environmental Systems Research Institute Annual Users conference, Redlands CA: Environmental Systems Research Institute.

Hessburg, P. F., B.G. Smith, S.G. Kreiter, and a. others. 1998. Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins. Part I: Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. General Technical Report PNW-GTR-558, USDA Forest Service.

Hessburg, P. F.; Smith, B.G; Kreiter, S. D.; Miller, C.A.; Salter, R.B.; McNicoll C.H.; Hann, W.J. 1999. Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins. Part II: Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. Gen. Tech. Rep. PNW-GTR-458. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Hessburg, P. F.; Smith, B.G.; Salter, R.B.; Ottmar, R.D.; Alvarado, E. 2000. Recent changes (1930's-1990's) in spatial patterns of interior northwest forests. USA. Forest Ecology and Management. 136:53-83.

Heyerdahl, E. K.;Berry, D.; Agee, J.K. 1995. Fire History Database of the Western United States. Final Report EPA/600/R-96/081 NHEERL-COR-851, US Environmental Protection Agency, USDA Forest Service, and University of Washington, Seattle.

Heyerdahl, E. K.; Brubaker, L.B.; Agee, J.K. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology. 82:660-678.

Hironaka, M. 1987. Primary successional theories In Symposium on Land Classifications Based on Vegetation: Applications for Resource Mangement., Moscow, ID: University of Idaho Press. Pp. 29-31.

Holdridge, L. R. 1947. Determination of world plant formations from simple climatic data. Science. 105:367-368.

Huschle, G.; Hironaka, M. 1980. Classification and ordination of seral plant communities. Journal of Range Management. 33:179-182.

Keane, R. E.; Long, D.G. 1997. A comparison of coarse scale fire effects simulation strategies. Northwest Science. 72:76-90.

Keane, R. E. 2000. Landscape fire succession modeling: Linking ecosystem simulations for comprehensive applications. In: Hawkes, B. C.;Flannigan, M.D., eds.. Landscape fire modeling-challenges and opportunitites. Victoria, BC: Northern Forestry Centre. Pp. 5-8.

Keane, R. E.; Menakis, J.P; Hann, W.J. 1996a. Coarse scale restoration planning and design in Interior Columbia River Basin Ecosystems — An example using Whitebark Pine (Pinus albicaulis) forests. In: Arno, S.F.; Hardy, C.C., eds. The use of fire in forest restoration — a general session at the annual meeting of the Society of Ecosystem Restoration "Taking a broader view." Pacific Northwest Forest and Range Experiment Station. Seattle, Washington. Pp. 14-20.

Keane, R. E.; Long, D.G.; Menakis, J.P.; Hann, W.J.; Bevins, C.D. 1996b. Simulating coarse-scale vegetation dynamics using the Columbia River Basin succession model: CRBSUM. Gen. Tech. Rep. INT-GTR-340. Ogden, UT: U.S. Deptartment of Agriculture, Forest Service, Intermountain Research Station.

Keane, R. E.; Morgan, P.; Running, S.W. 1996c. FIRE-BGC - a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. Res. Pap. INT-RP-484. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Keane, R. E.; McNicoll, C.H.; Schmidt, K.M.; Garner, J.L. 1997a. Spatially explicit ecological inventories for ecosystem management planning using gradient modeling and remote sensing. In: Proceedings of the sixth Forest Service remote sensing applications conference — Remote sensing; people in partnership with technology. Bethesda, MD: American Society of Photogrammetry and Remote Sensing. Pp. 135-146

Keane, R. E.; Hardy, C.C.; Ryan, K.C.; Finney, M.A. 1997b. Simulating effects of fire on gaseous emissions from future landscape of Glacier National Park, Montana, USA. World Resources Review. 9:177-205.

Keane, R. E.; Long, D.; Basford, D.; Levesque, B.A. 1997c. Simulating vegetation dynamics across multiple scales to assess alternative management strategies. IIn Conference Proceedings - GIS 97, 11th Annual symposium on Geographic Information Systems — Integrating spatial information technologies for tomorrow. GIS World, INC., Vancouver, British Columbia, Canada. Pp. 310-315.

Keane, R. E.; Hann, W.J. 1998. Simulation of vegetation dynamics after fire at multiple temporal and spatial scales : a summary of current efforts. In: Fire management under fire (adapting to change): proceedings of the 1994 Interior West Fire Council meeting and program; 1994 November 1-3; Coeur d'Alene, ID. Fairfield, WA: International Association of Wildland Fire: 115-124.

Keane, R. E.; McNicoll, C.; Rollins, M.G. 2002a. Integrating ecosystem sampling, gradient modeling, remote sensing, and ecosystem simulation to create spatially explicit landscape inventories. Gen. Tech. Rep. RMRS-GTR-92. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Keane, R. E.; Parsons, R.; Hessburg, P. 2002b. Estimating historical range and variation of landscape patch dynamics: Limitations of the simulation approach. Ecological Modeling. 151:29-49.

Keane, R. E.; Veblen, T.; Ryan, K.C.; Logan, J.; Allen, C.; Hawkes, B. 2002c. The cascading effects of fire exclusion in the Rocky Mountains. In: Baron, J.S., ed. Rocky Mountain Futures: An Ecological Perspective. Washington, D.C.: Island Press: 133-153.

Keane, R. E.; Cary, G.J.; Parsons, R. 2003. Using simulation to map fire regimes: an evaluation of approaches, strategies, and limitations. International Journal of Wildland Fire. 12:309-322.

Keane, R. E.; Cary, G.; Davies, I.D.; Flannigan, M.D.; Gardner, R.H.; Lavorel, S.; Lennihan, J.M.; Li, C.; Rupp, T.S. 2004a. A classification of landscape fire succession models: spatially explicit models of fire and vegetation dynamic. Ecological Modeling. 256:3-27.

Keane, R. E.; Parsons, R.; Rollins, M.G. 2004b. Predicting fire regimes across multiple scales. In: Perera, A.; Buse, L., eds. Emulating Natural Disturbances: Concepts and Techniques. Cambridge, UK: Cambridge University Press.

Keane, R. E.; Holsinger, L. 2006. Simulating biophysical environment for gradient modeling and ecosystem mapping using the WXFIRE program: Model documentation and application. Gen. Tech. Rep. RMRS-GTR-168DVD. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 61 p. [Online]. Available: http://www.fs.fed.us/rm/pubs/rmrs_gtr168.html [May 18, 2006].

Keane, R.E.; Holsinger, L.M.; Pratt, S.D. 2006. Simulating historical landscape dynamics using the landscape fire succession model LANDSUM version 4.0. Gen. Tech. Rep. RMRS-GTR-171CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 73 p. [Online]. Available: http://www.fs.fed.us/rm/pubs/rmrs_gtr171.html [May 18, 2006].

Kuchler, A. W. 1975. Potential natural vegetation of the conterminous United States: Manual and Map, 2 edition. New York, NY: American Geological Society.

Landres, P. B.; Morgan, P.; Swanson, F.J. 1999. Overview and use of natural variability concepts in managing ecological systems. Ecological Applications. 9:1179-1188.

Laverty, L.; Williams, J. 2000. Protecting people and sustaining resources in fire-adapted ecosystems — A cohesive strategy: Forest Service response to GAO Report GAO/RCED 99-65. USDA Forest Service, Headquarters. Washington DC. [Online]. Available: www.fs.fed.us/pub/fam [5-12-2006].

Lavigne, M. B. 1992. Exploring the possibilities of developing a physiological model of mixed stands. In: Kelty, M.J.; Larson, B.C.; Oliver, C.D., eds. The ecology and silviculture of mixed-species forests. The Netherlands: Kluwer Academic Publishers: 143-161.

Loveland, T. R.; Merchant, J.M.; Ohlen, D.O.; Brown, J.F. 1991. Development of a land-cover characteristics database for the conterminous U.S. Photogrammetric Engineering and Remote Sensing. 57:1453-1463.

Lutes, D.; Keane, R.E.; Caratti, J. [In preparation]. Fuel loading models: a national classification of wildland fuels for fire effects modeling. USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, Montana.

Markham, B.L.; Barker, J.L. 1986. Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures: EOSAT Landsat Technical Notes. v. 1, p. 3-8.

Minore, D. 1979. Comparative autecological characteristics of northwestern tree species: a literature review. Gen. Tech. Rep. PNW-87. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

O'Hara, K.; Latham, P.; Hessburg, P.; Smith, B. 1996a. Development of a forest stand structural stage classification for the Interior Columbia River Basin. Western Journal of Applied Forestry. 11:97-102.

O'Hara, K. L.; Latham, P. A.; Hessburg, P.; Smith, B.G. 1996b. A structural classification for inland northwest forest vegetation. Western Journal of Applied Forestry. 11:97-102.

Oliver, C. D.; Larson, B.C. 1990. Forest Stand Dynamics. New York, NY: McGraw Hill.

Ottmar, R. D.; Burns, M.F.; Hall, J.N.; Hanson, A.D. 1993. CONSUME users guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Pfister, R. D. 1980. Habitat type classification for managing western watersheds. In: Baumgartner, D.M., Ed. Proceedings from the Interior West Watershed Management Symposium, Spokane, WA: Washington State University, Cooperative Extension Pp. 59-67

Pfister, R. D. 1981. Status of forest successional studies in the northern Rocky Mountains. Proceedings of the Second US-USSR Symposium on Biosphere Reserves. US National Committee for Men and the Biosphere. Everglades National Park, FL. Pp. 80-90.

Pfister, R. D. 1989. Ecological site classification in northern Rocky Mountain Forests: putting theory to practice. In: Proceedings from the Forest Ecology Session of the SAF Convention. Spokane, WA: Society of American Foresters. Pp. 74-78

Pfister, R. D.; Arno, S.F. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science. 26:52-70.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R.C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Quinlan, J.R. 1993. C4.5: programs for machine learning. San Mateo, CA: Morgan Kaufman Publishers.

Reed, W. J.; Larsen, C. P. S.; Johnson, E. A.; MacDonald, G. M. 1998. Estimation of temporal variations in historical fire frequency from time-since-fire map data. Forest Science. 44:465-475.

Reinhardt, E.D.; Crookston, N.L., tech. eds. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. RMRS-GTR-116. 218 p.

Reinhardt, E.; Keane, R. E. 1998. FOFEM - a First Order Fire Effects Model. Fire Management Notes. 58:25-28.

Reinhardt, E.; Keane, R.E.; Brown, J.K. 1997. First Order Fire Effects Model: FOFEM 4.0 User's Guide. Gen. Tech. Rep. INT-GTR-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Reynolds, K.M.; Hessburg, P.F. 2005. Decision support for integrated landscape evaluation and restoration planning. Forest Ecology and Management. 207:263-278.

Rollins, M. G.; Keane, R. E. Parsons, R. 2004. Mapping ecological attributes using gradient analysis and remote sensing. Ecological Applications. 14:75-95.

Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT-438, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Rulequest Research. 1997. Data mining tools See5 and C5.0. [Online]. Available: http://rulequest.com/see5-info.html.

Running, S. W.; Coughlan, J. C. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modeling. 42:125-154.

Running, S.W.; Gower. S.T. 1991. FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree Physiology. 9:147-160.

Running, S. W.; Loveland, T. R.; Pierce, L. L. 1994. A vegetation classification logic based on remote sensing for use in global biogeochemical models. Ambio. 23:77-81.

Running, S. W.; Thornton, P. 1996. Generating daily surfaces of temperature and precipitation over complex topography. In: Goodchild, M.F.; Steyaert, L.T.; Parks, B.O.; Johnston, C.; Maidment, D.; Crane, M.; Glendinning, S., eds. GIS and Environmental Modeling: Progress and Research Issues. Ft. Collins, CO: GIS World Books. Pp. 93-98.

Sandberg, D. V.; Ottmar, R. D.; Cushon, G. H. 2001. Characterizing fuels in the 21st century. International Journal of Wildland Fire. 10:381-387.

Schmidt, K. M.; Menakis, J. P.; Hardy, C. C.; Hann, W. J.; Bunnell, D. L. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. Gen. Tech. Rep. RMRS-GTR-87. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Scott, J.H.; Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. For Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Shiflet, T. N. E. 1994. Rangeland cover types of the United States. Denver, CO: Society of Range Management.

Sieg, C. H. 1997. The role of fire in managing for biological diversity on native rangelands of the northern Great Plains. In: Proceedings of the symposium on Conserving Biodiversity on Native Rangelands. Gen. Tech. Rep. RM-GTR-298. Fort Collins, Co: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Pp. 31-38.

Steele, B. M.; Reddy, S. K.; Keane, R. E. [In preparation]. A methodology for assessing departure of existing plant communities from historical conditions over large landscapes. Ecological Applications. University of Montana, Missoula, MT.

Swetnam, T. W.; Allen, C. D.; Betancourt, J. L. 1999. Applied historical ecology: Using the past to manage for the future. Ecological Applications. 9:1189–1206.

Thornton, P., E.; White, J. D. 1996. Biogeochemical characterization of the Columbia River Basin using the BGC model: Model description, ecophysiological inputs and landscape description. Final report on file at USDA Forest Service, Rocky Mountain research station, Missoula Fire Sciences Laboratory, Missoula, MT.

Thornton, P., E.; Running, S.W.; White, M. A. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology. 190:214-251.

Thornton, P., E.; Hasenauer, H.; White, M. 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. Agricultural and Forest Meteorology. 104:225-271.

Thornton, P. E.; Law, B. E.; Gholz, H. L.; Clark, K. L.; Falge, E.; Ellsworth, D. S.; Goldstein, A. H.; Monson, R. K.; Hollinger, D. Y.; Falk, M.; Chen, J.; Sparks, J. P. 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agricultural and Forest Meteorology. 113:185-222.

United States Government Accountability Office 2002b. Severe Wildland Fires — Leadership and Accountability Needed to Reduce Risks to Communities and Resources. GAO Report. GAO-02-259, United States Government Accountability Office. Washington, D.C., USA.

United States Government Accountability Office. 2004. Wildland Fires: Forest Service and BLM Need Better Information and a Systematic Approach for Assessing the Risks of Environmental Effects. GAO Report. GAO-04-705. United States Government Accountability Office. Washington, D.C., USA.

van Wagner, C. E. V. 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research. 23:442-449.

Westoby, M. 1980. Elements of a theory of vegetation dynamics in arid rangelands. Isreal Journal of Botany. 28:169-194.

White, M., A.; Thornton, P.E.; Running, S. W.; Nemani, R. 2000. Parameterization and sensitivity analysis of the Biome-BGC terrestrial ecosystem model: Net primary production controls. Earth Interactions. 4:1-85.