Chapter
2

An Overview of the LANDFIRE Prototype Project

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Introduction

This chapter describes the background and design of the Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, which was a sub-regional, proof-of-concept effort designed to develop methods and applications for providing the high-resolution data (30-m pixel) needed to support wildland fire management and to implement the National Fire Plan and Healthy Forests Restoration Act. In addition, this chapter provides synopses of the many interrelated procedures necessary for development of the 24 LANDFIRE Prototype products (see table 1 and appendix 2-A). Throughout this chapter, direction is provided for where, in this report and elsewhere, additional detailed information is available.

It is important to emphasize that the information presented in this report refers specifically to methods, procedures, and results from the LANDFIRE Prototype Project. National implementation of the methods developed during the LANDFIRE Prototype Project (LANDFIRE National) was chartered by the Wildland Fire Leadership Council in April of 2004 and continues on schedule. Approaches and methods for the national implementation of LANDFIRE differ slightly from those detailed in this report because the LANDFIRE National team used the wealth of knowledge gained from developing the LANDFIRE products for the two prototype study areas to improve the processes for national implementation. With the exception of the first three chapters, each chapter in this report describes in detail a major procedure required for successful creation of the LANDFIRE Prototype products. The final section of each chapter (again, with the exception of the first three chapters) contains the LANDFIRE Prototype technical team's recommendations for national implementation, which have been incorporated into the procedures and methods for LANDIFRE National.

Background

Status of Wildland Fire in the United States

A history of fire suppression and land use practices has altered fire regimes and associated wildland fuel loading, landscape composition, structure, and function across the United States over the last century (Brown 1995; Covington and others 1994; Frost 1998; Hann and others 2003; Leenhouts 1998; Pyne 1982; Rollins and

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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.

Table 1—LANDFIRE Prototype products created for mapping zones 16 and 19.

	Mapped products	Description	Relevant chapter in this report
1	Map Attribute Tables	Plot locations and associated themes used to develop training sites for mapping vegetation and wildland fuel.	4
2	Potential Vegetation Type	A map that identifies unique biophysical settings across landscapes. Used to link the process of succession to the landscape.	7
3	Existing Vegetation	Mapped existing vegetation.	8
4	Structural Stage Density/Cover	Percent canopy closure by life form of existing vegetation.	8
5	Structural Stage Height	Height by life form (in meters) of existing vegetation.	8
6	Fire Interval	The mean interval between wildland fires (simulated using LANDSUMv4).	10
7	Fire Severity 1	Probability of an area to experience non-lethal wildland fire (simulated using LANDSUMv4).	10
8	Fire Severity 2	Probability of an area to experience mixed-severity wildland fire (simulated using LANDSUMv4).	10
9	Fire Severity 3	Probability of an area to experience stand-replacing wildland fire (simulated using LANDSUMv4).	10
10	FRCC Vegetation-Fuel Class	Mapped combinations of vegetation and structure that represent seral stages of vegetation communities.	11
11	Fire Regime Condition Class (FRCC)	Discrete index (1-3) describing departure of existing vegetation conditions from those of the simulated historical reference period. Developed using Interagency FRCC Guidebook methods.	11
12	FRCC Departure Index	Index (1-100) describing the difference between existing vegetation and historical vegetation conditions. Developed using Interagency FRCC guidebook methods.	11
13	HRVStat Departure	Index (0-1) describing the difference between existing vegetation and simulated historical vegetation conditions. Developed using the HRVStat multivariate time series analysis program.	11
14	HRVStat Significance Index	Index (0-1) describing the confidence in the HRVStat departure index. Developed using the HRVStat multivariate time series analysis program.	11
15	Fire Behavior Fuel Models	Wildland fuel models for modeling the rate of spread, intensity, size, and shape of wildland fires. Serves as FARSITE/FLAMMAP input.	12
16	Canopy Base Height	Height from the ground to the bottom of the vegetation canopy. Required for predicting the conversion of surface fires to crown fires. Serves as FARSITE/FLAMMAP input.	12
17	Canopy Bulk Density	Metric that describes the density of crown fuels. Required to model the spread of crown fires. Serves as FARSITE/FLAMMAP input.	12
18	Canopy Height	Height of the dominant existing vegetation. Serves as FARSITE/FLAMMAP input.	8
19	Canopy Cover	Density of the dominant existing vegetation. Serves as FARSITE/FLAMMAP input.	8
20	Slope	Slope in percent. Serves as FARSITE/FLAMMAP input.	5
21	Aspect	Aspect in degrees. Serves as FARSITE/FLAMMAP input.	5
22	Elevation	Elevation in meters. Serves as FARSITE/FLAMMAP input.	5
23	Fuel Loading Models	Classification based on fuel loading that provides inputs to models that predict the effects of wildland fires (including smoke production).	12
24	FCCS Fuelbeds	Classification based on fuel loading across several fuel strata. Provides inputs to models that predict fire effects (including smoke production).	12

others 2001). As a result, the number, size, and severity of wildfires have departed significantly from that of historical conditions, sometimes with catastrophic consequences (Allen and others 1998; Leenhouts 1998; U.S. GAO 1999; U.S. GAO 2002b). Recent examples of increasing wildland fire size and uncharacteristic severity in the United States include the 2000 Cerro Grande fire near Los Alamos, New Mexico that burned 19,200 hectares and 239 homes; the 2000 fire season in the northwestern United States during which over 2 million hectares burned; and the 2002 Biscuit (Oregon), Rodeo-Chediski (Arizona), and Hayman (Colorado) fires that burned over one-half million hectares and cost nearly $250 million to suppress (U.S. GAO 2002b). More recently, the 2003 fire season was distinguished by catastrophic wildland fires that began in early summer with the Aspen Fire north of Tucson, Arizona in which 322 homes were burned. This was followed by large, severe fires in the northern Rocky Mountains of western Montana and northern Idaho and arson-caused wildland fires that burned over 304,000 hectares and 3,640 homes in southern California.

The National Fire Plan and Healthy Forests Restoration Act

In response to increasing severity of wildland fire effects across the United States over the last decade, the secretaries of Agriculture and Interior developed a National Fire Plan for responding to severe wildland fires, reducing hazardous fuel buildup, reducing wildland fire threats to rural communities, and maximizing wildland firefighting efficiency and safety for the future (USDA and USDOI 2001; U.S. GAO 2001; U.S. GAO 2002a; U.S. GAO 2002b; www.fireplan.org). To implement this plan, the United States Department of Agriculture Forest Service (USFS) and Department of Interior (USDOI) developed both independent as well as interagency management strategies, with the primary objectives focused on hazardous fuel reduction and restoration of ecosystem integrity in fire-adapted landscapes through prioritization, adaptive planning, land management, and maintenance (USDA and USDOI 2001). In 2003, President George W. Bush signed the Healthy Forests Restoration Act into law. The main goals of the act are to reduce the threat of destructive wildfires while upholding environmental standards and encouraging early public input during review and planning processes for forest management projects (www.healthyforests.gov).

Importance of Nationally Consistent Spatial Data for Wildland Fire Management

The factors that affect wildland fire behavior and effects are inherently complex, being dynamic in both space and time. The likelihood that a particular area of a landscape will burn is often unrelated to the probability that a wildland fire will ignite in that area because wildland fires most often spread into one area based on the complex spatial arrangement and condition of fuel across landscapes. Spatial contagion in the process of wildland fire highlights the critical need for data that provide a comprehensive spatial context for planning and monitoring wildland fire management and hazardous fuel reduction projects. Furthermore, nationwide, comprehensive, consistent, and accurate geospatial data are critical for implementation of the National Fire Plan and the Healthy Forests Restoration Act (U.S. GAO 2002a; U.S. GAO 2002b; U.S. GAO 2003; U.S. GAO 2005). Specifically, consistent and comprehensive geospatial data are necessary for the following:

- planning wildland fire management with a landscape perspective,
- allocating resources across administrative boundaries,
- strategic planning for hazardous fuel reduction,
- tactical planning for specific wildland fire incidents, and
- monitoring the geographic consequences of wildland fire management.

The LANDFIRE process provides standardized, comprehensive mapped wildland fuel and fire regime information to address the objectives listed above. LANDFIRE maps were created using consistent methods over all ecosystems and geographic areas, which allows for reliable representation of “wall-to-wall” wildland fire hazard across entire regions and administrative areas. The spatial components of LANDFIRE ensure that individual areas within landscapes may be considered with a spatial context and therefore analyses can incorporate the potential influence of adjacent areas where wildland fires may occur more frequently or with different ecological or socioeconomic effects.

History of LANDFIRE

In 2000, the United States Department of Agriculture Forest Service Missoula Fire Sciences Laboratory developed coarse-scale (1-km grid cells) nationwide maps of simulated historical fire regimes and current departure from these historical conditions (Hardy and others 2001; Schmidt and others 2002). These data were designed to assist landscape and wildland fire management at national levels (for example, 10,000,000s – 100,000,000s km^2) and to facilitate comparison of wildland fire hazard between regions and states (Schmidt and others 2002). These coarse-scale, nationwide data layers include mapped potential natural vegetation groups, existing vegetation, historical fire regimes, departure from historical fire regimes, fire regime condition class (FRCC), national fire occurrence histories, and wildland fire risk to structures (Schmidt and others 2002). These data layers rapidly became the foundation for national-level, strategic wildland fire planning and for responding to national- and state-level concerns regarding the risk of catastrophic fire. Specifically, FRCC became a key metric for assessing fire threats to both people and ecosystems across the United States (U.S. GAO 2004).

While well-accepted and valuable for comparative analyses at the national level, the coarse-scale FRCC data lacked the necessary spatial resolution and detail for regional planning and for prioritization and guidance of specific local projects. In addition, the coarse-scale FRCC maps relied heavily on expert opinion, which led to inconsistent classification of vegetation across regional boundaries. Further, the low resolution and scale incompatibilities in underlying data resulted in overestimates of the number of areas with highly departed conditions (Aplet and Wilmer 2003).

As a result of the coarse-scale FRCC data's shortcomings, U.S. Government Accountability Office (formerly General Accounting Office) reports stated that federal land management agencies lacked adequate information for making decisions about and measuring progress in hazardous fuel reduction (U.S. GAO 2002b). The U.S. GAO (2002b) stated, "The infusion of hundreds of millions of dollars of new money for hazardous fuel reduction activities for fiscal years 2001 and 2002 and the expectation of sustained similar funding for these activities in future fiscal years accentuate the need for accurate, complete, and comparable data." United States GAO reports (U.S. GAO 1999, U.S. GAO 2002a, U.S. GAO 2002b, U.S. GAO 2003) have pointed to three main information gaps in wildland fire management planning:

- Federal land agencies lack information for identifying and prioritizing wildland-urban interface communities within the vicinity of federal lands that are at high risk of wildland fires.
- Federal land agencies lack adequate field-based reference data for expediting the project planning process, which requires complying with numerous environmental statutes that address individual resources, such as endangered and threatened species, clean water, and clean air.
- Federal agencies require consistent monitoring approaches for measuring the effectiveness of efforts to dispose of the large amount of brush, small trees, and other vegetation that must be removed to reduce the risk of severe wildland fire.

The LANDFIRE Prototype Project

The LANDFIRE Prototype Project started in 2001 and 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 project's purpose was to develop methods and tools for creating the baseline data needed to implement the National Fire Plan and to address the concerns of the GAO. LANDFIRE was designed specifically to provide the spatial data required to implement the National Fire Plan at regional levels and to fill critical knowledge gaps in wildland fire management planning. To achieve these objectives, LANDFIRE integrates information from extensive field-referenced databases, remote sensing, ecosystem simulation, and biophysical modeling to create maps of wildland fuel and fire regime condition class across the United States (Rollins and others 2004).

The main strengths of the LANDFIRE Prototype Project approach included:

- a standardized, repeatable method for developing comprehensive fuel and fire regime maps (see appendix 2-A for an outline of the procedures followed in developing the data products of the LANDFIRE Prototype Project);
- a combination of remote sensing, ecosystem simulation, and biophysical gradient modeling to map fuel and fire regimes;
- a robust, straightforward, statistical framework and quantitative accuracy assessment; and
- a seamless, Internet-based data-dissemination system.

In addition to the strengths of the approach, the main strengths of the LANDFIRE Prototype data included:

- a resolution fine enough (30-m pixel) for wildland fire managers to evaluate and prioritize specific landscapes within their administrative units;

- national coverage, ensuring that the data may be used for regional and national applications;
- comprehensive and consistent methods, allowing for both an integrated approach to wildland fire management and the ability to compare potential treatment areas across the entire United States through equivalent databases; and
- the ability to monitor the efficacy of hazardous fuel treatments as LANDFIRE updates become available over time.

Study Areas

The LANDFIRE Prototype Project was implemented within two large areas in the western United States: the central Utah highlands and the northern Rocky Mountains (fig. 1). These prototype landscapes were chosen because each represents a wide variety of vegetation assemblages that are common in the western U.S. They were chosen also because pre-processing of the Landsat satellite imagery had already been completed as part of the USGS Multi-Resolution Land Characteristics (MRLC) 2001 project (Homer and others 2002; landcover.usgs.gov/index.asp).

As the LANDFIRE Prototype depended on imagery solely from the MRLC 2001 project, LANDFIRE adopted the use of MRLC mapping zones to divide the United States into workable spatial areas. Use of these delineation units ensured that the LANDFIRE timetable requirements would be met by the MRLC image processing schedule.

Central Utah Highlands mapping zone — The 69,907 km^2 Central Utah Highlands mapping zone begins at the northern tip of the Wasatch Mountains in southern Idaho and extends through central Utah to the southern border of the state (fig. 1). Elevations range from 980 m to 3,750 m. Vegetation communities range from alpine forb communities in the Uinta and Wasatch Mountains in the northern portion of the mapping zone to desert shrub communities in the southern deserts. Extensive areas of pinyon-juniper/mountain big sagebrush and both evergreen and deciduous shrub communities are found at mid-elevations throughout the Central Utah Highlands mapping zone. The climate of the this mapping zone is highly variable. Thirty-year average temperatures range from –4°C in the high Uinta Mountains to 15°C in the southern deserts. Average annual precipitation varies from 10 cm in the southwestern deserts to nearly 2 meters in the northern mountains (Bradley 1992).

Northern Rocky Mountains mapping zone — The 117,976 km^2 Northern Rocky Mountains mapping zone begins at the Canadian border in northern Montana and extends south into eastern Idaho (fig. 1). Elevations range from 760 m to 3,400 m. Vegetation communities range from alpine forbs in the highest mountain ranges to prairie grasslands east of the Rocky Mountain front. Forest communities are prevalent, with spruce-fir communities found near the timberline and extensive forests of lodgepole pine, western larch, Douglas-fir, and ponderosa pine at middle elevations. Thirty-year average annual temperatures range from –5°C in the

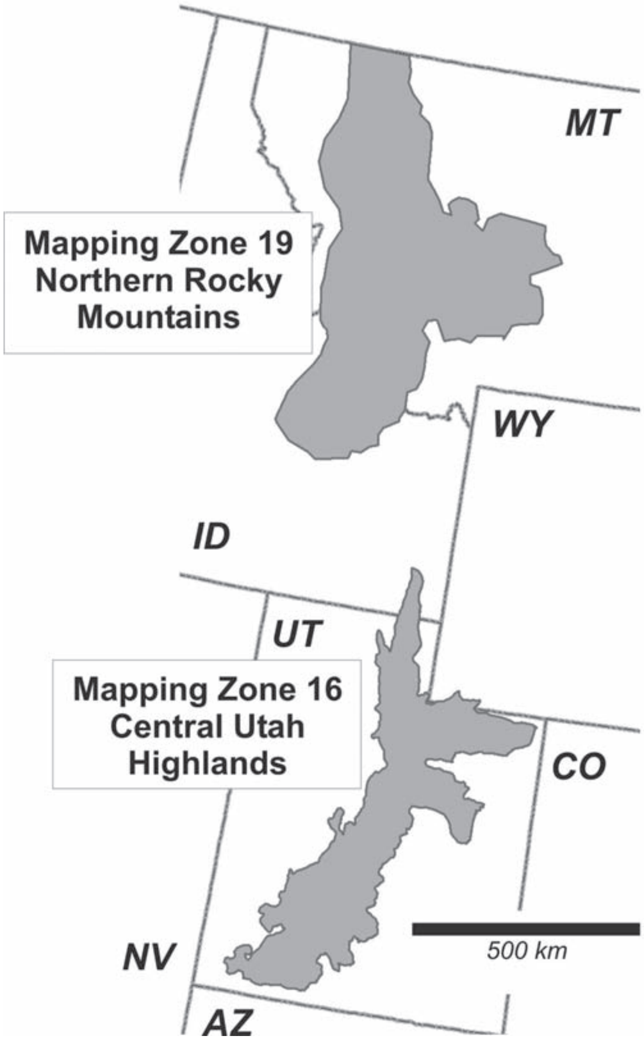

Figure 1—The study areas for the LANDFIRE Prototype Project were located in the central Utah highlands (Mapping Zone 16) and the Northern Rocky Mountains (Mapping Zone 19). LANDFIRE used mapping zones delineated for the Multiple Resolution Land Cover (MRLC) 2001 Project (http://landcover.usgs.gov/index.asp). All of the 24 core LANDFIRE Prototype products were produced for each zone. Lessons learned in the central Utah study area resulted in refinements that were applied in the northern Rocky Mountains.

high mountains of Glacier National Park to 15°C in the valley bottoms. Average precipitation varies from 14 cm in the valley bottoms to approximately 3.5 meters in the northern mountains (Arno 1980).

Methods

Many interrelated and mutually dependent tasks had to be completed to create the suite of databases, data layers, and models needed to develop scientifically credible, comprehensive, and accurate maps of fuel and fire regimes (see fig. 2, table 2, and appendix 2-A). After a brief introduction, each of these tasks is detailed below. First, the LANDFIRE reference database (LFRDB) was compiled from existing, georeferenced, ground-based databases from both government and non-government sources. Second, mapped biophysical gradients, potential vegetation types (PVTs), cover types (CT) (existing vegetation composition), and structural stages (SS) (existing vegetation structure) were mapped using the LFRDB, existing geospatial data, ecological simulation, Landsat imagery, and statistical landscape modeling at 30-meter pixel resolution to describe the existing vegetation and biophysical environment of each prototype study area. Third, succession pathway models and disturbance frequencies were entered into the LANDSUMv4 landscape fire succession model (described in the *LANDFIRE Fire Regime Modeling* section below) to simulate disturbance dynamics and vegetation development over time. These simulations served to quantify both the historical reference conditions and the range and variation of fire regime characteristics critical for determining current departure from historical conditions. Fourth, wildland fuel characteristics were mapped using field-referenced data, biophysical data, Landsat imagery, and LANDFIRE vegetation products.

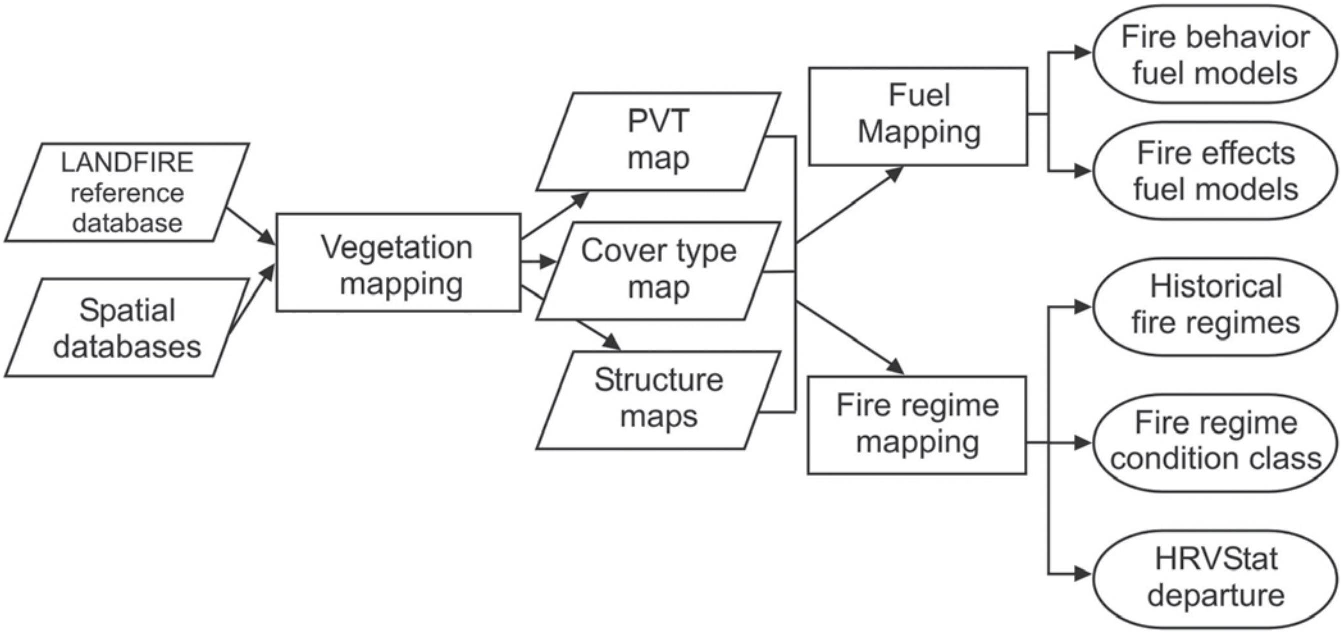

Figure 2—An overview of the LANDFIRE Prototype Project procedures. The LANDFIRE mapping processes began with the creation of the LANDFIRE reference database, which is comprised of a set of all available georeferenced plot information from within each mapping zone. The reference and spatial databases were used in a classification and regression tree-based machine learning framework for creating maps of biophysical settings (potential vegetation types), existing vegetation composition (cover type), and vegetation structure (canopy height and density). These core vegetation maps formed the foundation for the simulation of historical fire regimes and the subsequent calculation of current departure from historical vegetation conditions. In addition, the vegetation maps served as the basis for mapping wildland fuel for simulation of fire behavior and effects.

Table 2—Tasks essential for the creation of the LANDFIRE Prototype products. The first column directs the reader to the appropriate chapter sections containing general descriptions of the project's individual tasks. The second column directs the reader to the appropriate chapter in this GTR containing detailed background and procedural information about the project's individual tasks. Corresponding inputs/dependencies, methods for completion, and outputs/products are also listed for each task.

Task / chapter section heading	Chapter in this report	Inputs/dependencies	Methods for completion	Outputs/products
Compiling the LANDFIRE Reference Database	4	• Existing georeferenced field databases • Automated conversion utilities	• Compiled data from existing field databases. • Re-projected and reformatted data from native format into LFRDB format. • Produced attribute tables for all LANDFIRE mapping applications.	• Map attribute tables used as training data for mapping biophysical settings, vegetation, and fuel. • Data for accuracy assessment, quality control, and product evaluation.
Developing the Physiography and Biophysical Gradient Layers	5	• Topographic data from USGS • STATSGO soils data • DAYMET daily weather data • WXFIRE ecosystem simulator	• Derived simulation units. • Implemented WXFIRE. • Evaluated and processed output.	• Thirty-eight biophysical gradient layers used for mapping biophysical settings, vegetation, and fuel. • Data for comparing mapped themes using biophysical information consistently across mapzones.
Developing the LANDFIRE Vegetation Map Unit Classifications	6	• LFRDB • LANDFIRE design criteria • Existing national classification systems • Literature review	• Synthesized existing classifications describing potential vegetation, existing vegetation, and structure. • Compiled hierarchical classifications • Developed keys/queries to implement classifications in LFRDB to produce map attribute tables.	• Custom LANDFIRE classifications meeting design criteria that vegetation classes are identifiable, scaleable, mappable, and model-able. • Rules/keys for implementing classifications in LFRDB. • Lists of vegetation types to be used in vegetation mapping and modeling and fuel mapping.
Mapping Potential Vegetation	7	• Biophysical gradient layers • PVT classification • LFRDB	• Developed training sites based on map attribute tables from LFRDB. • Compiled biophysical gradient layers for use as spatial independent variables. • Developed classification trees predicting PVT. • Created final map in ERDAS/Imagine.	• Maps of PVT. • Maps of probabilities of CT by PVT. • Stratification for vegetation succession modeling. • Simulation units for LANDSUMv4. • Basis for stratification for mapping wildland fuel.
Mapping Existing Vegetation	8	• MRLC 2001 Landsat Image Catalog • Biophysical gradient layers • Existing vegetation classifications • LFRDB	• Developed training sites based on map attribute tables from LFRDB. • Compiled 3 dates of Landsat imagery and biophysical gradient layers for use as mapped predictor variables. • Developed classification and regression trees predicting CT and SS. • Created final map in ERDAS imagine.	• Maps of existing vegetation composition and structure. • Current baseline for comparison with reference conditions to determine ecological departure. • Description of the current successional status of landscapes across mapping zones. • Foundation for wildland fuel mapping.
Developing Succession Pathway Models	9	• VDDT model • LFRDB • Vegetation classifications • PVT and existing vegetation maps • Vegetation development workshops	• Conducted workshops for developing modeling frameworks. • Evaluated disturbance probabilities and transition times from literature. • Assigned local ecologists to derive and refine models using VDDT. • Compiled models in the vegetation and disturbance development database.	• Evaluation and refinement of classification systems. • Set of vegetation development models for each mapped PVT. • Parameters used to simulate fire effects and post vegetation recovery in LANDSUMv4. • Historical reference conditions for evaluation of ecological departure.

(continued)

Table 2—(Continued)

Task / chapter section heading	Chapter in this report	Inputs/dependencies	Methods for completion	Outputs/products
Simulating Historical Landscape Composition	10	• LFRDB • Succession pathway models (VADDD) • Parameter database (VADDD) • PVT and existing vegetation maps • LANDSUMv4 model	• Divided landscape into simulation units and landscape reporting units. • Parameterized LANDSUMv4 with information from VADDD. • Ran LANDSUMv4. • Compiled and summarized results.	• Time series of historical vegetation conditions for simulation period. • Maps of simulated historical fire intervals. • Probability maps of fire severity. • Reference conditions for comparison with current conditions to evaluate ecological departure.
Estimating Departure using Interagency RCC Guidebook Methods	11	• Cover type map • PVT Map • SS map • Reference conditions from LANDSUMv4	• Implemented Interagency FRCC Guidebook methods adapted to LANDFIRE map classification systems. • Quantified reference conditions based on LANDSUMv4 output. • Calculated departure and created discrete FRCC classes.	• Consistently mapped FRCC across each map zone. • Consistent baseline information for determining relative levels of ecological departure across broad regions.
Estimating Departure Using HRVStat	11	• HRVStat statistical software • Cover type map • PVT Map • SS map • Reference conditions	• Compiled input analysis database for HRVStat including reference conditions and current CT and SS. • Determined departure from reference conditions. • Determined frequency distribution of departure estimates using time series of historical vegetation conditions. • Compiled final HRVStat departure and confidence maps.	• Multivariate, statistically robust measure of ecological departure. • Measure of the significance of the measurement of ecological departure (p-value). • Ecological departure mapped as a continuous variable. • Consistently mapped ecological departure across each map zone.
Mapping Surface Fuel	12	• LFRDB • Vegetation classifications • PVT map • CT and SS maps • Look-up tables and rule sets for assigning fuel models	• Compiled fuel mapping database as a subset of the LFRDB. • Created look-up tables and rule sets to link fuel models to biophysical settings and vegetation composition and structure. • Compiled final maps in ArcGIS.	• Maps of fire behavior fuel models for simulating potential fire spread and intensity. • Maps of fire effects models for simulating the effects of fires on vegetation.
Mapping Canopy Fuel	12	• LFRDB • FUELCALC model • biophysical gradient layers • MRLC 2001 Landsat Image Catalog • PVT maps • Existing vegetation maps	• Populated fuel mapping database with FUELCALC output. • Developed training sites from fuel database. • Compiled Landsat imagery, biophysical gradients, and LANDFIRE vegetation maps for use as mapped predictor variables. • Developed regression trees predicting CBH and CBD. • Created final maps in ERDAS imagine.	• Maps of canopy fuels for simulating the initiation and behavior of crown fires.

Compiling the LANDFIRE Reference Database

The LFRDB comprised a compilation of all existing georeferenced field data available for the prototype mapping zones (fig. 3). This database of georeferenced plot information formed the foundation for most phases of the LANDFIRE Prototype Project. The database was designed in Microsoft ACCESS and had a three-tiered hierarchical structure (Caratti, Ch. 4). Existing data were entered into the database and incorporated into the FIREMON database structure (Lutes and others 2002). The data were then further summarized and reformatted to ensure consistency across the entire database. This involved steps such as converting geographic coordinates to the LANDFIRE map projection, converting measurement units to metric, ensuring that all vegetation cover estimates represent absolute cover as opposed to relative cover, and populating fields that can be used for quality assurance and quality control (Caratti, Ch. 4). The final step in developing the LFRDB was classifying each plot to the appropriate CT, PVT, and SS using the LANDFIRE map unit classification systems (Long and others, Ch. 6) and assigning appropriate fuel characteristics using the LANDFIRE fuel map unit classification systems (Keane and others, Ch. 12). LANDFIRE map attribute tables describing georeferenced vegetation and fuel types were then used as training databases for developing most LANDFIRE products.

For inclusion in the LFRDB, all field data needed to be georeferenced and quantify at least one LANDFIRE mapping attribute (for example, CT or SS). All field data were evaluated for suitability and assigned quality control indices based on summary image overlay, logic checking, and associated metadata (Caratti, Ch. 4). Sources of data for the LFRDB include but are not limited to the following:

- Forest Inventory and Analysis (Gillespie 1999)
- Forest Health Monitoring (USDA Forest Service 2003)
- Landscape Ecosystem Inventory Systems (Keane and others 2002a)
- ECODATA (Jensen and others 1993)
- FIREMON fire monitoring data (Lutes and others 2002)
- Interior Columbia River Ecosystem Management Project (Quigley and others 1996)
- Natural Resources Conservation Service (USDA 2002)
- National Park Service fire monitoring database (USDI 2001)

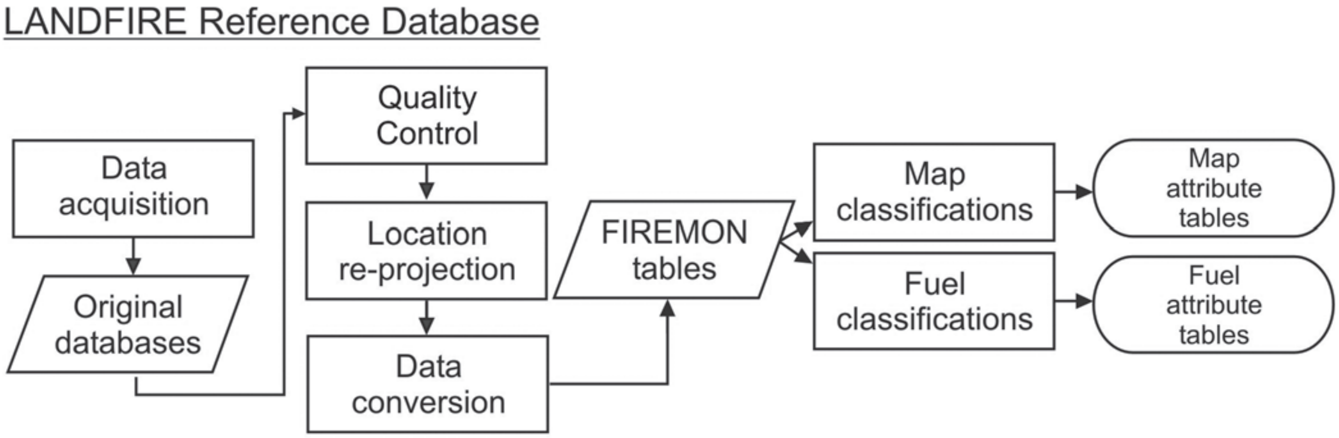

Figure 3—The procedure for developing the LANDFIRE reference database. Existing georeferenced plot data were acquired from numerous sources, including USDA Forest Service Forest Inventory and Analysis data, State GAP programs, and additional government and non-government sources. These data were processed through automated quality control and re-projection procedures and compiled in the FIREMON database architecture. The custom LANDFIRE vegetation classes (cover type, PVT, structural stage, and surface fuel models) were determined for each plot using sets of dichotomous sequence tables. The final stage of compiling the reference database was the development of map attribute tables that are implemented as training databases in the LANDFIRE mapping processes.

The LFRDB was used to classify, map, and evaluate each of the LANDFIRE products. For example, the LFRDB was used to classify existing vegetation communities and biophysical settings (Long and others, Ch. 6), to map PVTs (Frescino and others, Ch. 7), to map cover types (Zhu and others, Ch. 8), to evaluate and quantify succession model parameters (Long and others, Ch. 9 and Pratt and others, Ch. 10), to develop maps of wildland fuel (Keane and others, Ch. 12), and to evaluate the quality of LANDFIRE products (Vogelmann and others, Ch. 13).

Developing the Physiography and Biophysical Gradient Layers

Several spatial data layers provided baseline information for the LANDFIRE Prototype Project and served mainly as independent spatial predictor variables in the LANDFIRE mapping processes (fig. 4). We used topographic data from the National Elevation Database (NED) to represent or derive gradients of elevation, slope, aspect, topographic curvature, and other topographic characteristics (Holsinger and others, Ch. 5). The National Elevation Database, developed by the USGS Center for Earth Resources Observation and Science (EROS), was compiled by merging the highest-resolution, best-quality elevation data available across the United States into a seamless raster format. More information about the NED may be found at http://ned.usgs.gov/.

Topographic variables represent indirect biophysical gradients, which have no direct physiological influence on vegetation dynamics (Müller 1998); however, the addition of even indirect gradients has been shown to improve the accuracy of maps of vegetation (Franklin 1995). We used an ecosystem simulation approach to create geospatial data layers that describe important environmental gradients that directly influence the distribution of vegetation, fire, and wildland fuel across landscapes (Rollins and others 2004). The simulation model WXFIRE was developed for the purpose of employing standardized and repeatable modeling methods to derive landscape-level weather and ecological gradients for predictions of landscape characteristics such as vegetation and fuel (Keane and others 2002a; Keane and Holsinger 2006). WXFIRE was designed to simulate biophysical gradients using spatially interpolated daily weather information in addition to mapped soils and terrain data. The spatial resolution is defined by a user-specified set of spatial simulation units. The WXFIRE model computes biophysical gradients - up to 50 - for each simulation unit, where the size and shape of simulation units are determined by the user.

The implementation of WXFIRE requires the three following steps: 1) develop simulation units (the smallest unit of resolution in WXFIRE), 2) compile mapped daily weather, and 3) execute the model (Holsinger and others, Ch. 5). Using the DAYMET daily weather database, WXFIRE was executed over 10 million simulation units

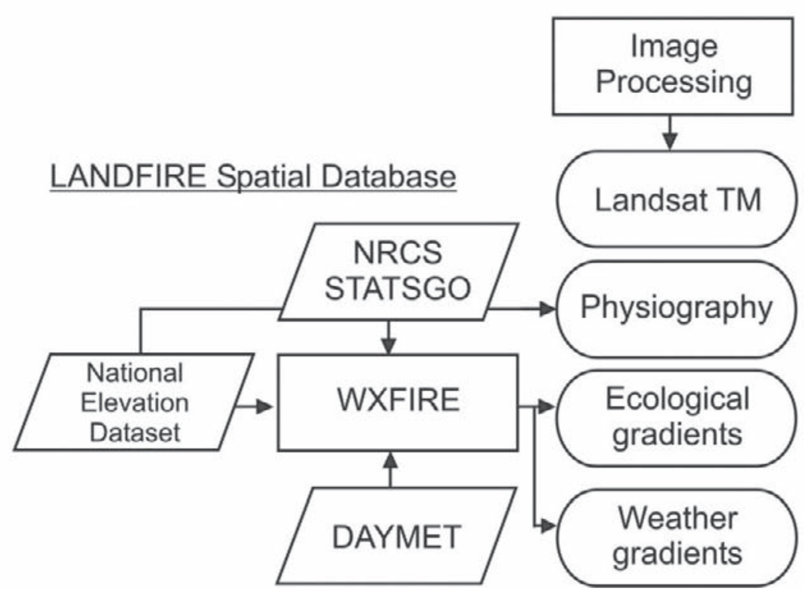

Figure 4—The procedure for developing the LANDFIRE base geospatial data layers. Topographic information from the National Elevation Database, soils information from the NRCS STATSGO database, and data from the DAYMET daily weather database were input into the WXFIRE weather and ecosystem model. WXFIRE was used to develop 38 gradients describing the factors that define the distribution of vegetation across landscapes. These gradients were incorporated into the LANDFIRE mapping processes to increase the overall accuracy of mapped products. Three dates of Landsat imagery from the MRLC 2001 project were used as the basis for mapping existing vegetation composition and structure. All information included in the LANDFIRE spatial database was developed using strict design criteria to ensure that these data could be developed consistently across the entire United States.

for Zone 16 and over 26 million for Zone 19 (Thornton and others 1997). Thirty-eight output variables from WXFIRE describing average annual weather and average annual rates of ecosystem processes (such as potential evapotranspiration) were then compiled as raster grids and used in developing the final LANDFIRE products (Holsinger and others, Ch. 5). Specifically, these layers were used as a basis for mapping PVT, CT, and SS (Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) and for mapping both surface and canopy wildland fuel (Keane and others, Ch. 12). Additionally, biophysical gradient layers facilitated comparison of map units across mapping zones during the map unit development. For example, an equivalent CT in two different mapping zones should have similar biophysical characteristics. Vast differences in biophysical characteristics may indicate that a new CT should be developed.

Developing the LANDFIRE Vegetation Map Unit Classifications

The LANDFIRE Prototype Project developed vegetation map unit classifications that, combined with rule sets (keys), allowed the linkage of LFRDB plot data to geospatial data layers in a systematic, hierarchal, and scaleable framework. These hierarchal classification systems were directly related to the predictive landscape modeling of PVT, CT, and SS (Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) for defining the developmental stages within succession models for landscape fire regime modeling (Long and others, Ch. 9 and Pratt and others, Ch. 10) and for mapping surface and canopy fuel (Keane and others, Ch. 12). In order for LANDFIRE to be successful, the LANDFIRE vegetation map units need to be:

- **identifiable** – Map units must be easily identifiable in the field, and the process for assigning map units based on existing plot data (such as FIA) needs to be efficient and straightforward.
- **scalable** – Map unit classifications must have a hierarchy that is flexible for addressing the spatial scales used in landscape- to national-level assessments (for example, 100,000s to 1,000,000s km^2). This flexibility in spatial scale also facilitates links with existing classifications.
- **mappable** – Only map units that can be delineated using remote sensing and biophysical modeling will be mapped.
- **model-able** – Map units must fit into the logical frameworks of the vegetation and landscape simulation models that are essential for the creation of many LANDFIRE products.

The LANDFIRE Prototype Project vegetation map unit classifications were based on combinations of extensive literature review, existing national vegetation classifications and mapping guidelines, development of vegetation succession models, summaries from the LFRDB, and classifications from other existing fuel and fire regime mapping projects (Long and others, Ch. 6). Each of the classifications is composed of two types of units (map and taxonomic) with several different nested levels possible (Long and others, Ch. 6). Map units are collections of areas defined in terms of component taxonomic and/or technical group characteristics. Map units may exist at any level of a hierarchical map unit classification based on physiognomic or taxonomic units or technical groups (Brohman and Bryant 2005). Taxonomic units were used to define and develop map units from the LFRDB and may also be used by land managers to scale the LANDFIRE CT map unit classification to floristically finer scales. Hierarchically nested, taxonomically defined map units allowed the vegetation map units to be aggregated or disaggregated to suit multiple purposes (such as vegetation modeling or fuel mapping). Taxonomic information was also used to link the LANDFIRE classifications to other existing vegetation classification systems (Long and others, Ch. 6). The individual classifications are described below.

Cover type map unit classification — The LANDFIRE cover type (CT) map unit classifications described existing vegetation composition in each mapping zone (Long and others, Ch. 6). Generally, CT map units were distinguished by dominant species or species assemblages. Records in the LFRDB were classified to CT based on indicator types with the highest relative canopy cover. The LANDFIRE Prototype CT map unit classification was based on the National Vegetation Classification System (NVCS) and the USDA Forest Service Existing Vegetation Classification and Mapping Guide (Brohman and Bryant 2005; Grossman and others 1998; Long and others, Ch. 6) but was modified to meet the LANDFIRE classification criteria listed above. By using NVCS and the Forest Service Existing Vegetation Classification and Mapping Technical Guide (Brohman and Bryant 2005), the LANDFIRE CT map unit classification quantitatively combined both physiognomic and floristic systems and adhered to important Federal Geographic Data Committee classification standards (FGDC 1997). The LANDFIRE vegetation map units were used for mapping existing vegetation and vegetation structure (Zhu and others, Ch. 8), modeling succession (Long and others, Ch. 9), parameterizing the LANDSUMv4 model (Pratt and others, Ch. 10), quantifying departure from historical conditions (Holsinger and others, Ch. 11), and for mapping wildland fuel (Keane and others, Ch. 12).

Structural Stage Map Unit Classification — The LANDFIRE structural stage (SS) map unit classification was based on summary analyses of vegetation characteristics contained within the LFRDB. The two main criteria for developing custom SS map units were that these map units had to be useful for describing vegetation developmental stages in succession models and they needed to be relevant for describing vegetation structure for mapping wildland fuel. In addition, LANDFIRE SS map units had to be distinguishable using Landsat imagery. The structural stages of forest CTs were broken into four SS map units based on a matrix of independently mapped canopy cover (CC) and height class (HC) map units (Long and others, Ch. 6). Structure classification of non-forest CTs was composed of only two map units describing canopy density. Height status was not included in these SS map units because most growth in non-forest areas occurs relatively swiftly in the first couple of years after regeneration and then levels out over time; therefore, height status is less relevant to vegetation succession in non-forest types than in forest types (Long and others, Ch. 6). LANDFIRE structural stages were used to develop models of vegetation development (Long and others, Ch. 9) and for mapping wildland fuel (Keane and others, Ch. 12).

Potential Vegetation Type Map Unit Classification — Potential vegetation type (PVT) is a site classification based on environmental gradients such as temperature, moisture, and soils (Pfister and others 1977). Potential vegetation types are analogous to aggregated habitat types or vegetation associations and are usually named for the late successional species presumed to dominate a specific site in the absence of disturbance (Cooper and others 1991; Daubenmire 1968; Frescino and Rollins, Ch. 7; Keane and Rollins, Ch. 3; Pfister and Arno 1980).

The LANDFIRE PVT map unit classification was created based on summaries from the LFRDB, extensive literature reviews, and existing PVT classifications (Long and others, Ch. 6). We began with PVT classifications that already existed for each of the prototype mapping zones (such as the USDA Forest Service regional classifications) and then refined these PVT classifications through expert opinion and data from the LFRDB. The resultant map unit classification was based on the presence of indicator types across gradients of shade tolerance, plant water relationships, and ecological amplitude. The LANDFIRE Prototype Project PVT map units were used to link the ecological process of succession to landscapes (Long and others, Ch. 9), to guide the parameterization and calibration of the landscape fire succession model LANDSUMv4 (Pratt and others, Ch. 10), and to stratify vegetation communities for wildland fuel mapping (Keane and others, Ch. 12).

Mapping Potential Vegetation

We mapped PVT using a predictive landscape modeling approach (fig. 5). This approach employs spatially explicit independent or predictor variables and georeferenced training data to create thematic maps (Franklin 1995; Keane and others 2002a; Rollins and others 2004). For the LANDFIRE Prototype, the training data were created by implementing the PVT map unit classification as a set of automated queries that access the LFRDB and classify each plot to a LANDFIRE PVT based on vegetation composition and condition (Long and others, Ch. 6). Each georeferenced plot and its assigned PVT were overlaid with the 38 biophysical gradients using GIS software. This resulted in a PVT modeling database where PVT was the dependent variable and the biophysical gradient layers were the predictor variables (Frescino and Rollins, Ch, 7).

In the LANDFIRE Prototype, we used classification trees (also known as decision trees) along with the PVT modeling database to create a spatially explicit model for mapping PVT within GIS applications. Classification trees, used as an analog for regression, develop rules for each category of a dependent variable (in this case, PVT). Classification trees for mapping PVTs were developed using the See5 machine-learning algorithm (Quinlan 1993; www.rulequest.com) and were applied within an ERDAS Imagine™ interface (ERDAS 2004; Frescino and Rollins, Ch. 7). See5 uses a classification and regression tree (CART) approach for generating a tree with high complexity and pruning it back to a simpler tree by merging classes (Breiman and others 1984; Friedl and Bradley 1997; Quinlan 1993).

Maps of PVT are a principal LANDFIRE Prototype product (table 1). In addition, the LANDFIRE PVT maps were used with the LFRDB to create layers that represent the probability of a particular CT to exist in a specific area (Frescino and Rollins, Ch, 7), used in the mapping of CT (Zhu and others, Ch. 8). The PVT map also facilitated linkage of the ecological process of vegetation succession to the simulation landscapes used in modeling historical reference conditions. In the LANDFIRE Prototype, vegetation ecologists created succession pathway models for individual PVTs that

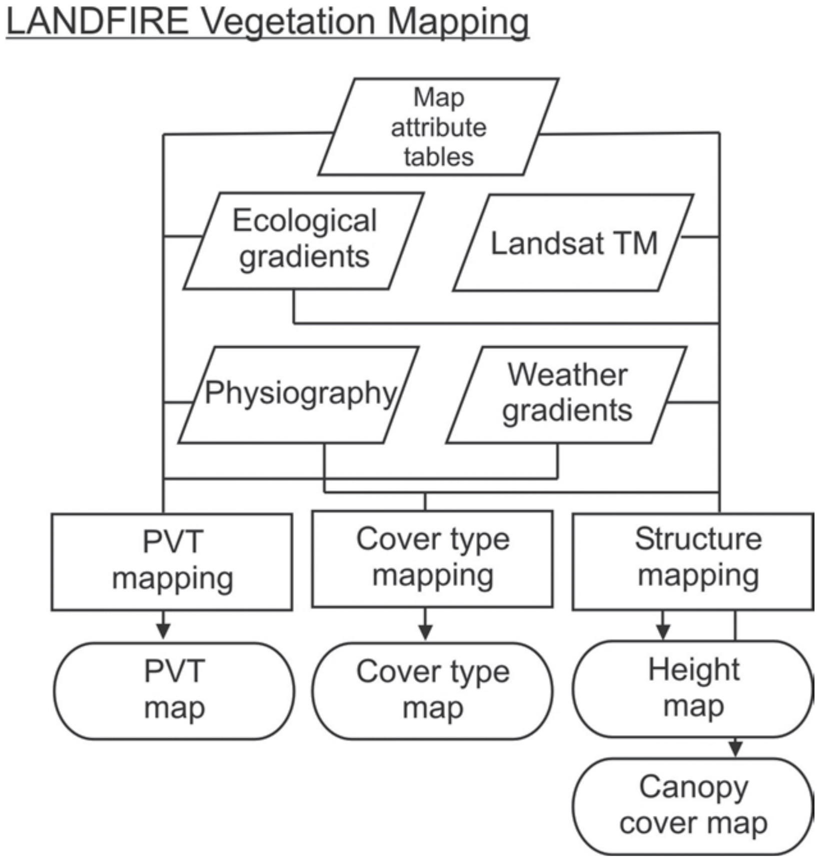

Figure 5—The LANDFIRE vegetation mapping process. Information from the LANDFIRE reference and spatial databases was used in a classification and regression tree framework and then implemented within ERDAS IMAGINE™ mapping software to create all mapped vegetation products. The mapping of potential vegetation was based purely on biophysical gradients including weather, topography, and soil information. Landsat imagery was used to create all maps of existing vegetation composition and structure.

served as input to the LANDSUMv4 landscape fire succession model used to simulate historical fire regimes and reference conditions (Long and others, Ch. 9; Pratt and others, Ch. 10). Maps of PVT were also used for stratification purposes in wildland fuel mapping (Keane and others, Ch. 12).

Mapping Existing Vegetation

Maps of existing vegetation composition and structure at spatial resolutions appropriate for wildland fire management are principal LANDFIRE products (table 1). Maps of existing vegetation serve as a benchmark for determining departure from historical vegetation and for creating maps of wildland fuel composition and condition. Satellite imagery was integrated with biophysical gradient layers and the LFRDB to create maps of CT, canopy closure (CC), and height class (HC) map units (HC) (fig. 5). Structural stage (SS) is an integration of CC and HC as described above in the *Structural Stage Map Unit Classification* section.

Mapping Cover Type

Many mapping algorithms have been developed for deriving vegetation maps from satellite imagery (Cihlar 2000; Foody and Hill 1996; Homer and others 1997; Knick and others 1997). For the LANDFIRE Prototype Project, we created maps of CT using a training database developed from the LFRDB, Landsat imagery, biophysical gradient layers (described above in Developing the Physiography and Biophysical Gradient Layers), the PVT map (for limiting the types of vegetation that may exist in any area) and classification tree algorithms similar to those described above for mapping PVT (Zhu and others, Ch. 8).

The LANDFIRE team developed maps of CT using a hierarchical and iterative set of classification models, with the first model separating more general land cover types (for example, life form) and subsequent models separating more detailed levels of the vegetation map unit classification until a final map of CT map units resulted. Specifically, life form information from the

MRLC 2001 program (Homer and others 2002) was used as a stratification to create separate models for mapping CT. An iterative approach was implemented where mapping models were developed using a "top-down" approach for successively finer floristic levels in the LANDIRE vegetation map unit classification (Long and others Ch. 6). The LFRDB, biophysical settings layers, and ancillary data layers were incorporated to guide the mapping process.

Mapping Structural Stage

We used empirical models for estimating canopy closure (CC) using satellite imagery and biophysical gradients. Though often considered unsophisticated and criticized for lack of focus on mechanistic processes, empirical models have proved more successful than other types of models in applications involving large areas (Iverson and others 1994; Zhu and Evans 1994). We used regression trees, applied through a Cubist/ERDAS Imagine interface, to map CC and HC separately. Model inputs included elevation data and derivatives, spectral information from Landsat imagery, and the 38 biophysical gradient layers. Similar to PVT and CT mapping, a training database was developed using the LFRDB that contained georeferenced values for CC and HC for each plot. The resultant maps represented these two structure variables continuously across each prototype mapping zone. Prior to the LANDFIRE Prototype Project, CC and HC had been modeled successfully using CART for Zone 16 as well as several additional areas (Huang and others 2001).

The final SS layer was developed by combining CC and HC map units into SS map units and assigning SS map units to combinations of PVT and CT. Structural stage assignments were based on the SS map unit classification (Long and others, Ch. 6). This integrated height and density information was used as an important determinant of wildland fuel characteristics and successional status of existing landscapes. The SS map units also formed the structural framework for the vegetation modeling described in the next section and in detail in Long and others, Ch. 9.

Modeling Fire Regimes

In the LANDFIRE Prototype Project, historical and current vegetation composition and structure were compared to estimate departure from historical conditions. To characterize historical conditions, we used the PVT map and succession pathway modeling as key input to the LANDSUMv4 landscape fire succession model (fig. 6). We then used two separate methods for estimating departure from historical conditions: the Interagency FRCC Guidebook method (Hann and others 2004) and the HRVStat spatial/temporal statistics software (Holsinger and others Ch. 11; Steele and others, in preparation).

The Interagency FRCC Guidebook provides detailed methods for estimating departure from historical conditions based on estimation of historical vegetation condition and disturbance regimes. The FRCC classification, established by Hann and Bunnell (2001), is defined as: a descriptor of the amount of "departure from the historical natural regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings." Fire regime condition class is a metric for reporting the number of acres in need of hazardous fuel reduction and is identified in the National Fire Plan and Healthy Forests Restoration Act as a measure for evaluating the level of efficacy of wildland fuel treatment projects. In the FRCC Guidebook approach, low departure (FRCC 1) describes fire regimes and successional status considered to be within the historical range of variability, while moderate and high departures (FRCC 2 and 3, respectively) characterize conditions outside of this historical range (Hann and Bunnell 2001; Schmidt and others. 2002). Detailed description of how the Interagency FRCC Guidebook methods were implemented in the LANDFIRE Prototype Project follow in the below section titled *Estimating Departure using Interagency FRCC Guidebook Methods*.

Developing Succession Pathway Models

Succession pathway models were created using the multiple pathway approach of Kessell and Fischer (1981) in which succession classes are linked along pathways defined by stand development and disturbance probabilities within a PVT. Succession pathways describe the seral status of vegetation communities in the context of disturbances such as wildland fire, forest pathogens, and land use (Arno and others 1985). These pathways link seral vegetation communities or succession classes (described by combinations of PVT-CT-SS) over time. Each succession class is parameterized with disturbance probabilities and transition times. Transition times required to move from one seral succession class to another define the development of vegetation across landscapes over time. Disturbance probabilities determine the type and severity of disturbance. Pathways associated with disturbances determine where the post disturbance vegetation community trends over time.

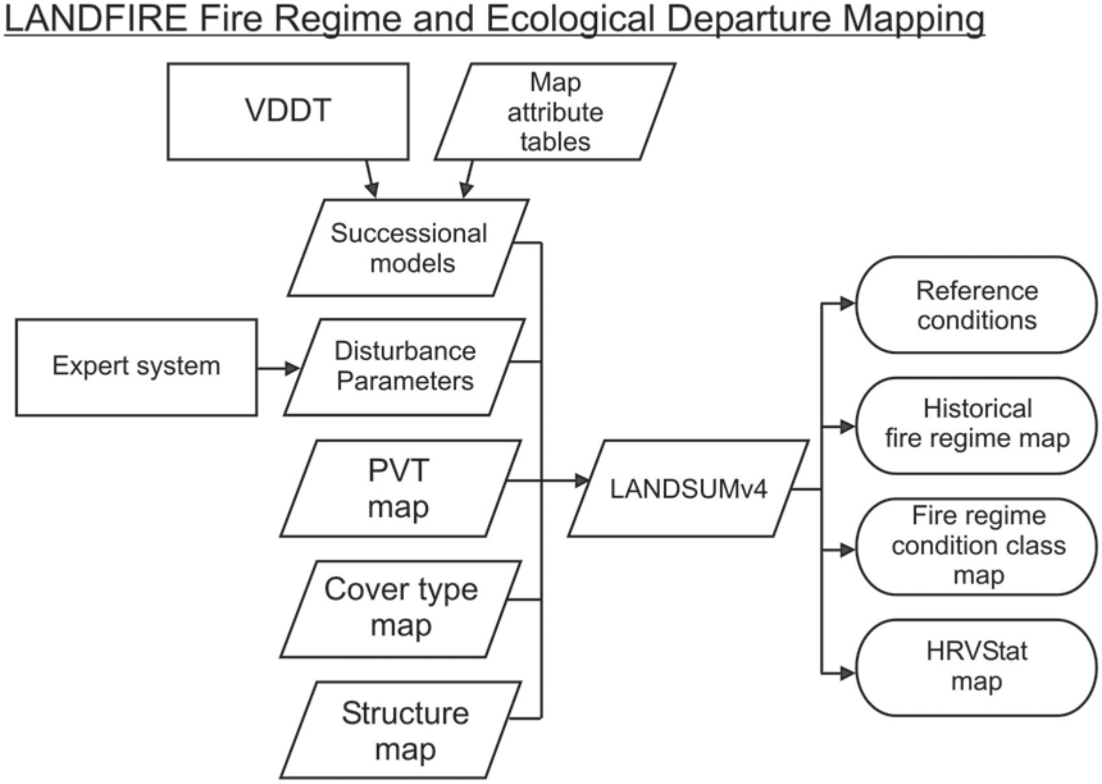

Figure 6—The LANDFIRE fire regime and ecological departure mapping procedure. Succession models were developed for each mapped PVT. These models, along with the PVT map and a suite of disturbance and weather parameters developed from empirical modeling or acquired from expert opinion, were implemented within the LANDSUMv4 landscape fire succession model to simulate spatial time series of vegetation characteristics and wildland fire. This information was summarized using the Interagency Fire Regime Condition Class Guidebook methods and the HRVStat software application to create maps of simulated historical fire regimes and departure from historical vegetation conditions.

We used a computer model called the Vegetation Dynamics Development Tool (VDDT; Beukema and others 2003) to build succession pathway models for each PVT defined in the LANDFIRE Prototype PVT map unit classifications. Specialists in forest and rangeland ecology facilitated this succession pathway modeling process (Long and others, Ch. 9). Based on the list of PVTs mapped for each zone, the specialists used VDDT to construct succession models. The existing vegetation map legends that describe both dominant species and structural stage were used to define the stages of vegetation development over time, called succession classes. Summaries from the LFRDB provided a list indicating which succession classes were most likely to occur in each PVT. An extensive literature search formed the basis for the input parameters (primarily transition times and disturbance occurrence probabilities) for each model. Each specialist used the VDDT software to both construct succession models and evaluate the behavior of each model. Final models were then reformatted and loaded into a relational database called the Vegetation and Disturbance Dynamics Database (VADDD) (Long and others, Ch. 9; Pratt and others, Ch. 10). This database was constructed specifically to facilitate the compilation and conversion of the succession pathway models into the proper format for LANDSUMv4.

Simulating Historical Landscape Composition

The fourth version of the Landscape Succession Model (LANDSUMv4) is a spatially explicit application where vegetation succession is modeled deterministically and disturbances are modeled stochastically over long simulation periods. LANDSUMv4 output is summarized for user-defined landscape reporting units to spatially describe simulated historical vegetation composition and structure and fire regimes (Keane and others 2002b).

LANDSUMv4 simulates succession using the LANDFIRE succession models described above. In LANDSUMv4, ignition of wildland fires is simulated based on separate probabilities by succession class and defined as a part of initial model parameterization. Simulated fires then spread across the landscape based on simple topographic and wind factors.

LANDSUMv4, stochastically simulates fire effects based on the distribution of fire severity types as specified during model parameterization. These effects are determined based on the information contained in VADDD. Finally, LANDSUMv4 outputs the amount of area in each succession class in each landscape reporting unit every 50 years over the simulation period. Landscape reporting units for the LANDFIRE Prototype Project were fixed at 900-m by 900-m to register with the 30-m grid cell size of the other LANDFIRE layers and to be comparable with the coarse-scale maps produced by Schmidt and others (2002). For detailed information on the background and implementation of LANDSUMv4 in the LANDFIRE Prototype Project, see Keane and Rollins, Ch. 3 and Pratt and others, Ch. 10.

Estimating Departure using Interagency FRCC Guidebook Methods

Comparison of current vegetation condition with that of the historical or reference period forms the foundation of FRCC calculation. Calculating FRCC using the Guidebook approach involves four distinct steps: 1) evaluate current vegetation conditions, 2) compute reference vegetation conditions, 3) calculate departure, and 4) estimate FRCC. For the LANDFIRE Prototype, current vegetation conditions were assessed by landscape reporting unit using the PVT, CT, and SS maps. Reference conditions for this analysis were estimated by executing the LANDSUMv4 model for a simulation period of several thousand years and reporting the area of each succession class every 50 years during the simulation period.

Calculation of FRCC begins with determining similarity, a concept addressed in depth by Hann and others (2004) and at www.frcc.gov. For the prototype, this simple metric was calculated by comparing current conditions with those of the reference period in the same reporting unit for each individual PVT. Percent composition of each PVT-CT-SS combination in the FRCC vegetation-fuel class map was compared with that of the reference conditions for a given landscape reporting unit. The lesser of the two percentages is defined as the similarity. That is, if a reporting unit currently has a smaller percent composition of a PVT-CT-SS combination than the reference conditions (modeled by LANDSUMv4) then the similarity equals the percent composition of the current PVT-CT-SS combination. Conversely, if the percent composition of a PVT-CT-SS combination in the reference conditions is less than that of the current conditions, the similarity value equals the percent composition of the reference conditions. For each PVT in a reporting unit, the similarity values were totaled and departure was calculated by subtracting the aggregate similarity from 100. For details regarding the scientific background of and specific methods for FRCC calculation, see Holsinger and others, Ch. 11 and visit www.frcc.gov

Estimating Departure using HRVStat

HRVStat is a multivariate statistical approach to rigorously evaluate patterns of succession classes (PVT-CT-SS) over the LANDSUMv4 simulation period – the estimated historical conditions – for comparison with those of current conditions. One important aspect of HRVStat that distinguishes it from the FRCC Guidebook approach is that it evaluates the variance structure of all PVT-CT-SS combinations as they fluctuate across landscapes through time to compute departure (Holsinger and others, Ch. 11; Keane and others 2006*;* Steele and others, in preparation).

The LANDSUMv4 output and current conditions based on the CT and SS maps were compiled into a custom HRVStat analysis database. This database consisted of the area in each succession class in each landscape reporting unit over the LANDSUMv4 simulation period. The HRVStat method involved a two-step process (Holsinger and others, Ch. 11). First, HRVStat determined the extent to which current vegetation in a reporting unit differed from simulated reference conditions. In addition, the amount of area in each succession class for each reporting unit was compared with the same for every other reporting unit. This process provided information on the variance structure from the entire simulation period to estimate a pixel based confidence measure for departure across the entire mapping zone. Secondly, for each reporting unit, a frequency distribution of departure measurements was derived, and the proportion of values in the departure distribution greater than or equal to the current departure estimate formed the basis for determining the significance level, or p-value. This significance level served as a measure of confidence in the departure estimate for each reporting unit. From this information we then created maps of departure (as a continuous variable) and significance (Holsinger and others, Ch. 11; Steele and others, in preparation).

Mapping Wildland Fuel

The various wildland fuel layers developed through the LANDFIRE Prototype Project were selected for development because they provide critical input to existing fire modeling software used for strategic and tactical planning, such as FOFEM (Reinhardt and Keane 1998), BEHAVE (Andrews and Bevins 1999), NEXUS (Scott 1999), and FARSITE (Finney 1998) (fig. 7). When implemented within these existing models, these fuel layers may be used to simulate fire intensity, spread rate, and severity for current conditions or (with slight modifications based on treatment level) used to predict fire behavior of fuel characteristics that result as a consequence of fuel treatment activities.

Mapping Surface Fuel

Surface fuel classifications represent biomass components that occur on the ground (less than 2 meters above) and integrate all factors that contribute to the behavior and effects of fires burning near the ground's surface. For the LANDFIRE Prototype Project, we mapped four surface fuel model classifications to provide the inputs essential for implementing the fire behavior and fire effects applications used in wildland fire management planning (Keane and others, Ch. 12). The 13 fire behavior fuel models described by Anderson (1982) and the additional new 40 Scott and Burgan fire behavior fuel models (Scott and Burgan 2005) were mapped to facilitate the modeling of fire behavior variables such

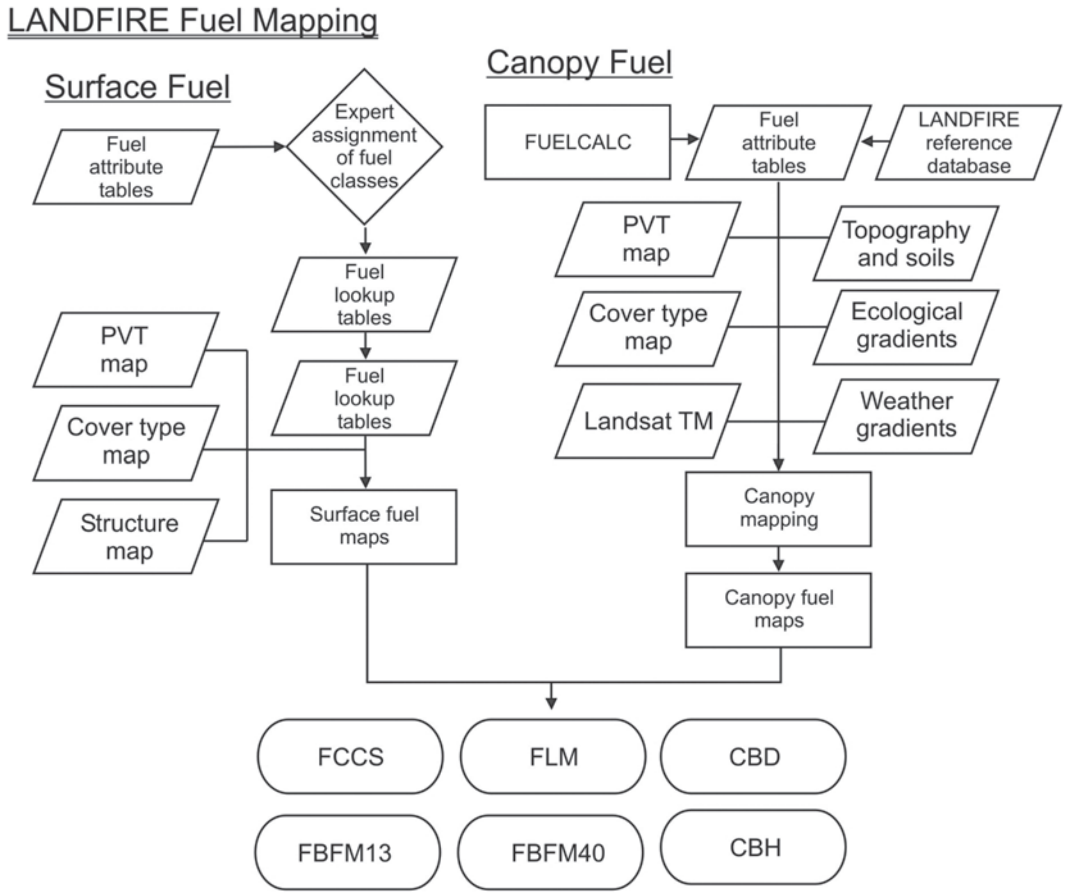

Figure 7—The LANDFIRE fuel mapping procedure. Surface fuel was mapped using a rule-based approach in which combinations of LANDFIRE map classes were matched with both fire behavior fuel models and fire effects models. These look-up tables and the LANDFIRE vegetation maps were used to create the final LANDFIRE surface fuel maps. Canopy fuel (crown base height and crown bulk density) was mapped with a predictive landscape modeling approach using Landsat imagery and a suite of biophysical gradient layers.

as fire intensity, spread rate, and size using models such as FARSITE and NEXUS (Finney 1998; Scott 1999). The Fuel Characterization Classification System fuel beds (Sandberg and others 2001) and the fuel loading models (Lutes and others, in preparation) were mapped to facilitate the spatially explicit modeling of fire effects such as vegetation mortality, fuel consumption, and smoke production (Keane and others, Ch. 12).

The following is a general description of procedures that were used for mapping surface fuel during the LANDFIRE Prototype Project; see Keane and others, Ch. 12 for detailed descriptions of these procedures. First, the LANDFIRE fuel database was compiled from the LFRDB by summarizing all georeferenced fuel data to the PVT-CT-SS combinations. Each PVT-CT-SS combination was assigned to each of the four surface fuel model classification systems based on data contained within the LFRDB. Information gaps resulting from lack of fuel data in the LFRDB were filled using either information from the literature or estimates from local fire behavior experts. Next, the LANDFIRE fuel database was converted to a rule set and implemented within a GIS to create the four surface fuel maps.

All surface fuel maps were created using similar classification protocols in which a fuel model category was directly assigned to a PVT-CT-SS combination. The rule set approach allowed the inclusion of additional detail by augmenting the PVT-CT-SS stratification with other biophysical and vegetation spatial data. For example, a rule set might assign the Anderson Fuel Model 8 to a specific PVT-CT-SS combination on slopes less than 50 percent and the Anderson Fuel Model 10 to the same combination on slopes greater than 50 percent (Keane and others, Ch. 12).

Mapping Canopy Fuel

Canopy fuel represents the amount and arrangement of live and dead biomass in the canopy of the vegetation. Characteristics of canopy fuel are important for estimating the probability and characteristics of crown fires, and the spatial representation of canopy fuel is important for assessing fire hazard on forested landscapes (Chuvieco and Congalton 1989; Keane and others 1998; Keane and others 2001). Spatially explicit maps of canopy fuel provide the critical input to simulation models of wildland fire required to simulate the initiation, spread, and intensity of crown fires across landscapes (Finney 1998).

Maps of canopy height (CH), canopy cover (CC), canopy bulk density (CBD), and canopy base height (CBH) were produced through the LANDFIRE Prototype Project. These layers are required input (along with maps of elevation, aspect, slope, and surface fuel models) for the FARSITE fire behavior model to simulate wildland fire behavior (Finney 1998). FARSITE is currently used by many fire managers to plan prescribed burns as well as to manage wildland fires. It is designed to model fire behavior over a continuous surface. These same canopy characteristics may also be used in NEXUS to calculate the critical wind threshold for propagating a crown fire (Scott 1999).

Canopy height and canopy cover map layers were developed from the stand height and canopy closure layers created by the EROS team using satellite imagery and statistical modeling (Zhu and others, Ch. 8). We calculated CBD and CBH for each georeferenced plot in the LFRDB using FUELCALC, a prototype program developed by Reinhardt and others at the Missoula Fire Sciences Laboratory in Missoula, Montana (Reinhardt and Crookston 2003). FUELCALC computes a number of canopy fuel characteristics for each field referenced plot based on allometric equations relating individual tree characteristics to crown biomass. Georeferenced values of CBD and CBH were implemented along with Landsat imagery and biophysical gradient layers within CART to create mapped CBD and CBH using an approach identical to that used in the mapping of existing vegetation composition and structure (Keane and others, Ch. 12).

Conclusion

Throughout the course of the LANDFIRE Prototype Project – from fall of 2001 to spring of 2005 – many lessons were learned that have proved valuable for the successful implementation of LANDFIRE mapping methods and procedures across the entire United States. The LANDFIRE team has refined the prototype processes and applications to ensure that LANDFIRE National will meet its objective of creating nationally comprehensive and consistent data for wildland fire management. In addition, LANDFIRE Prototype products have been successfully used in fire management applications, including hazard analyses for communities in the Color Country area of southern Utah and fire behavior analyses at the regional to local levels during the 2003 fire season in the northern Rocky Mountains. LANDFIRE National products will be available for the western U.S. in 2006, for the eastern U.S. in 2008, and for Alaska and Hawaii in 2009.

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

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Appendix 2-A – LANDFIRE Prototype Project procedure table

1. LANDFIRE reference database (LFRDB)

1.1. Determine the geographic extent of existing plot data.

 1.1.1. Acquire existing plot data from mapping zone for mapping LANDFIRE attributes.

 1.1.2. Extract plot locations and convert coordinates to LANDFIRE map projection.

 1.1.3. Conduct cursory quality assurance / quality control (QA/QC) on data to eliminate data with irreconcilable geospatial or information content errors.

 1.1.4. Plot locations of useful data on LANDFIRE mapping zones to determine spatial gaps in coverage of the reference data.

 1.1.5. Acquire additional field data in areas of mapping zones lacking sufficient field-referenced data.

1.2. Convert existing plot data into the relevant FIREMON and LANDFIRE attribute tables.

 1.2.1. Create a separate directory for each data set.

 1.2.2. Build an Access database for each data set.

 1.2.3. Import empty LANDFIRE attribute tables into the Access database.

 1.2.4. Develop data conversion queries to populate each LANDFIRE attribute table.

 1.2.5. Develop data append queries to insert data into each FIREMON and LANDFIRE attribute table.

 1.2.6. Document the data conversion process and populate the FIREMON Metadata (MD) table.

 1.2.7. Create a subdirectory for all digital plot photos.

1.3. Conduct QA/QC procedures for all plot data.

 1.3.1. Check again for geospatial errors in the data. Examples include plots located well outside the known study area for a particular database and plots located in bodies of water.

 1.3.2. Check for information content errors. Examples include null values in required fields such as plot locations, duplicate records and/or plot locations, and erroneous plant species heights.

 1.3.3. Visually inspect LANDFIRE cover types (CTs) with the Multi-Resolution Land Characteristics (MRLC) 2001 Landsat data and the 1992 National Land Cover Dataset (NLCD) Landsat imagery.

 1.3.4. Visually inspect plots for gross differences in LANDFIRE CTs and NLCD land cover types.

 1.3.5. Difference the Normalized Difference Vegetation Index (NDVI) values from the MRLC 2001 and the MRLC 1992 Landsat data.

 1.3.6. Determine appropriate thresholds that suggest major land cover change.

 1.3.7. Examine reference data plots that have values above these thresholds by overlaying them on the MRLC 2001 imagery.

Appendix 2-A — (Continued)

1.4. Populate the combined LFRDB

  1.4.1. Create an Access database with empty FIREMON and LANDFIRE attribute tables as the LFRDB for each mapping zone.

  1.4.2. Link FIREMON and LANDFIRE attribute tables from each data set to the LFRDB for each mapping zone.

  1.4.3. Write append queries to add data from each linked table to its associated table in the LFRDB for each mapping zone.

  1.4.4. Assign a LANDFIRE CT to each plot using the LANDFIRE CT map unit classification for each mapping zone.

  1.4.5. Assign a LANDFIRE potential vegetation type (PVT) to each plot using the LANDFIRE PVT tables and queries for each mapping zone.

  1.4.6. Assign a LANDFIRE structural stage (SS) to each plot using the LANDFIRE SS classification for each mapping zone.

  1.4.7. Create the LANDFIRE map attribute table (MAT) with the PVT, CT, and SS assignments for each plot.

  1.4.8. Develop data summary queries used in subsequent LANDFIRE tasks. Examples include plot counts by PVT/CT/SS, constancy cover tables by PVT/CT/SS, and fuel loading by PVT/CT/SS.

  1.4.9. Place all digital plot photos and metadata documents for the LFRDB into one photo directory and one documents directory.

  1.4.10. Connect the FIREMON database application to the LFRDB to hyperlink plot photos and metadata documents.

2. Mapping biophysical gradients

2.1. Acquire data to develop input layers for WXFIRE.

  2.1.1. Acquire Digital Elevation Model (DEM) layer to create elevation, aspect, slope, and topographic shading layers.

  2.1.2. Acquire STATSGO soils coverage and associated tabular data.

  2.1.3. Acquire NLCD layer to create Ecophysiological Site layer.

  2.1.4. Acquire DAYMET weather database.

  2.1.5. Acquire Landsat imagery for leaf-on reflectance date to create Leaf Area Index (LAI) layer.

2.2. Create terrain-related layers.

  2.2.1. Create Slope layer using Arc/Info SLOPE command with PERCENTRISE as units of slope.

  2.2.2. Create Aspect layer using Arc/Info ASPECT command.

Appendix 2-A — (Continued)

2.2.3. Create Topographic Shading layer using Arc/Info HILLSHADE command. (Azimuth and altitude data were developed using NOAA Solar Position calculator, assuming summer solstice as the date and using center coordinates for each zone.)

2.3. Create Soil Texture layers (percent sand, percent silt, percent clay).

2.3.1. Using STATSGO database, compute four soil textures (percent sand, percent silt, percent clay, and coarse fragment).

2.3.2. Weight each soil texture by the layers' depths and spatial extent for each of soil sequences within STATSGO polygons.

2.3.3. Remove coarse fragment proportion from the composition of soil textures and rescale sand, silt, and clay components to comprise 100 percent of soil texture estimates.

2.3.4. Calculate average slope in STATSGO database from high and low values for each STATSGO polygon and associated sequences and classify average slope into 4 classes:
(1) ≤ 4 percent; (2) >4 percent and ≤8 percent; (3) > 8 percent and ≤ 15 percent; and
(4) >15 percent.

2.3.5. Calculate average soil texture using data from step 2.3.3 for each slope class within each STATSGO polygon.

2.3.6. Classify Slope layer (from 2.2.1) into same 4 slope classes.

2.3.7. Partition STATSGO polygon coverage by Classified Slope layer and link this spatial layer with the STATSGO variables of soil texture by polygon and slope class (from 2.3.5).

2.4. Create Soil Depth layer.

2.4.1. Extract data on maximum depth per soil sequence from the STATSGO database.

2.4.2. Weight maximum depth per soil sequence by areal extent of sequences to calculate maximum soil depth per polygon.

2.4.3. Calculate Topographic Soil Index (TSI) for each pixel using the following relationship:

$$TSI = \ln\left(\frac{a}{\tan B}\right)$$

where a is upslope area (m^2) draining past a certain point per unit width of slope calculated using Arc/Info FLOWACCUMULATION and FLOWDIRECTION commands and B is local surface slope angle (degrees) calculated using Arc/Info SLOPE command with DEGREE as units of slope.

2.4.4. Integrate STATSGO Maximum Depth layer and TSI to calculate soil depth value for each pixel using scalars to adjust for skewed TSI distributions in the equation:

$$\text{Soil Depth} = \{M_1, M_2\} * TSI.$$

where M_1 is scalar used if pixel's TSI is ≤ mean across a mapping zone, and M_2 is used if TSI value is > mapping zone's mean.

Appendix 2-A — (Continued)

Calculate M_1 and M_2 by the formulas:

$$M_1 = \frac{\text{Ave. Max. Depth}}{0.5 * (LN_{mo} + LN_{me})} \text{ and } M_2 = \frac{\text{Max. Depth}}{LN_{\max}}$$

where ave. max. depth is mean value of the STATSGO Maximum Depth layer across each zone, and LN_{mo} and LN_{me} are the mode and mean of the natural log of TSI for each STATSGO polygon calculated using Arc/Info's ZONALMAJORITY and ZONALMEAN commands, respectively.

2.4.5. For Zone 19: increase data resolution using slope data from STATSGO database and Classified Slope layer.

2.4.5.1. Use slope classes calculated from STATSGO database in step 2.3.1.

2.4.5.2. Calculate average maximum depth for each slope class within each STATSGO polygon using data from step 2.3.2.

2.4.5.3. Link STATSGO polygon coverage partitioned by Classified Slope layer from step 2.3.7 with STATSGO average maximum depth by polygon and slope class data calculated in 2.4.5.2.

2.5. Create LAI layer.

2.5.1. Calculate corrected Normalized Difference Vegetation Index (NDVI) using LANDSAT leaf-on reflectance imagery and the equation:

$$NDVI_c = \left(\frac{NIR - RED}{NIR + RED}\right) * \left(1 - \frac{MIR - MIR_{\min}}{MIN_{\max} - MIR_{\min}}\right)$$

where NIR is near infrared (band 4), RED is infrared (band 3), and MIR is mid-infrared (band 5); MIR_{min} is minimum value in mid-infrared band in an open canopy; and MIR_{max} is maximum value in the mid-infrared band in a closed canopy.

2.5.2. Convert $NDVI_c$ layer to LAI using the equation:

$$LAI = \frac{1\mathrm{n}(0.7 - NDVIc}{-0.7}$$

2.6. Create Weather layer.

2.6.1. Using any one of the DAYMET layers (for example, daily temperature), clip DAYMET layer to zonal boundary using Arc/Info GRIDCLIP command.

2.6.2. Use clipped DAYMET layer to obtain center coordinates for each 1-km pixel.

2.7. Create Ecophysiological Site layer.

2.7.1. For Zone 16, partition landscape by 4 elevational breaks using DEM: Site 1 – 0 to 4,000 ft mean sea level (MSL); Site 2 – 4,000 to 6,000 ft MSL; Site 3 – 6,000 to 9,000 ft MSL; and Site 4 – 9,000+ ft MSL.

Appendix 2-A — (Continued)

2.7.2. For Zone 19, reassign 21 broad CTs from NLCD to 4 general plant functional types and one non-vegetated class: water/barren. Reassign developed land CTs to plant functional types based on surrounding pixels using FOCALMAJORITY command.

2.8. Classify WXFIRE input layers.

2.8.1. Classify Elevation layer into 100-m ranges.

2.8.2. Classify Slope layer (from 2.2.1) into low (0-10%), moderate (10-30%), and high (>30%) slope classes.

2.8.3. Classify Aspect layer into SW (165° to 255°), NW (255° to 345°), NE (345° to 75°), and SE (75° to 165°) classes.

2.8.4. Classify Topographic Shading Index layer into 0.25 intervals.

2.8.5. Classify Soil Depth layer into 0.5-m intervals.

2.8.6. Classify LAI layer into 1.0 intervals.

2.9. Create simulation units for running WXFIRE model.

2.9.1. Combine classified input layers (terrain, soil depth, and LAI), and ecophysiological site and weather layers such that each unique combination forms one simulation unit using Arc/Info's COMBINE command.

2.9.2. Associate values from each input layer to each simulation unit.

2.9.3. Create ASCII file for input to WXFIRE model that lists all the simulation units in a mapping zone with their associated site, terrain, weather-coordinates, soils, and LAI values.

2.10. Run WXFIRE simulations and develop biophysical gradient layers.

2.10.1. Input ASCII file to WXFIRE model.

2.10.2. Link each record in ASCII output file from WXFIRE model to its geo-referenced simulation unit (from step 2.9).

2.10.3. Create individual biophysical gradient layers for each simulation unit.

3. Mapping potential vegetation type (PVT)

3.1. Prepare data for model building.

3.1.1. Prepare spatially explicit predictor layers (biophysical and topographic gradients).

3.1.1.1. Acquire biophysical and topographic gradients for 3-km buffered zone.

3.1.1.2. Scale all layers to unsigned 8-bit or 16-bit integers and output summary statistics for each layer.

3.1.1.3. Convert layer to unsigned 8-bit or 16-bit integer images.

Appendix 2-A — (Continued)

        - 3.1.1.4. Quality-check all predictor layers.
            - 3.1.1.4.1. Check projections and row / column numbers for consistency.
            - 3.1.1.4.2. Check all images for erroneous numbers or patterns.
    - 3.1.2. Prepare response data (PVT classes).
        - 3.1.2.1. Acquire LFRDB MAT with uniqueID, spatial reference, and PVT assignments for plots within zone boundary.
        - 3.1.2.2. Examine data spatially and non-spatially, looking for outliers or unusual spatial distributions.
        - 3.1.2.3. Evaluate number of available plots by PVT class to see if classes need to be collapsed or dropped.
        - 3.1.2.4. Label each PVT plot as forest or non-forest type using values 1 and 2, respectively.
    - 3.1.3. Perform data extraction.
        - 3.1.3.1. Extract values from each predictor gradient for each X and Y plot coordinate and link to the LFRDB MAT.
    - 3.1.4. Perform data exploratory exercises.
        - 3.1.4.1. View data spatially, looking for unusual spatial patterns or outliers.
        - 3.1.4.2. Import data into a statistical package (in other words, R) and examine data for outliers or unusual features.
            - 3.1.4.2.1. Examine summary statistics of response (box plots, etc.).
            - 3.1.4.2.2. Examine summary statistics of predictors (distributions, scatter plots, correlation matrices, and principal components).
- 3.2. Generate PVT life form (forest / non-forest) model and map.
    - 3.2.1. Set up input files for the See5 application.
        - 3.2.1.1. Generate an ERDAS Imagine image (dependent variable) of training plots using forest / non-forest values.
        - 3.2.1.2. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names input file.
        - 3.2.1.3. Delete .data and .test files that are output from the NLCD Sampling Tool.
        - 3.2.1.4. Export refined training data set to a comma-delimited file (.data) including the uniqueID, the predictor gradient values (in the same order as listed in the .names file) and dependent (forest / non-forest) value.

Appendix 2-A — (Continued)

3.2.2. Use See5 to build forest / non-forest model.

3.2.2.1. From See5, open input files (.data and .names).

3.2.2.2. Specify options (such as winnow, boosting, and misclassification cost).

3.2.2.3. Run model with 10-fold cross-validation (for accuracy assessment).

3.2.2.4. Run model without cross-validation (for generating .tree file for prediction).

3.2.3. Apply model across buffered zone.

3.2.3.1. Use NLCD Mapping Tool to generate a Forest / Non-forest map with an associated map of confidence.

3.3. Extract value from predicted map of forest / non-forest and link to LFRDB MAT.

3.4. Generate 2 mask images of PVT life form (forest / non-forest).

3.4.1. Create a new image by recoding forest / non-forest image to forest – 1; non-forest – 0.

3.4.2. Create a new image by recoding forest / non-forest image to forest – 0; non-forest – 1.

3.5. Generate forest PVT model.

3.5.1. Set up input files for the See5 application.

3.5.1.1. Query data for forest PVTs, where predicted PVT life form is forest (life form = 1).

3.5.1.2. Generate an ERDAS Imagine image (dependent variable) of training plots using forest PVT values from query.

3.5.1.3. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names file.

3.5.1.4. Delete .data and .test files that are output from the NLCD Sampling Tool.

3.5.1.5. Export a randomly selected 10% of the data set to a comma-delimited *.test file.

3.5.1.6. Export remaining 90% of the data set to a comma-delimited *.data file.

3.5.2. Use See5 to build forest PVT classification tree.

3.5.2.1. From See5, open input files (.data and .names).

3.5.2.2. Specify options (such as winnow, boosting, and misclassification cost).

3.5.2.3. Run model (no cross-validation) to generate .tree file for prediction.

3.5.3. Apply model across buffered zone.

3.5.3.1. Use NLCD Mapping Tool and Classifier Tool to generate a map of forest PVTs with an associated map of confidence using the forest mask to limit prediction extent.

Appendix 2-A — (Continued)

3.6. Generate non-forest (shrub and herbaceous) PVT model.

  3.6.1. Set up input files for the See5 application.

    3.6.1.1. Query database for non-forest PVTs, where predicted PVT life form is forest (life form = 2).

    3.6.1.2. Generate an ERDAS Imagine image (dependent variable) of training plots using non-forest PVT values from query.

    3.6.1.3. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names file.

    3.6.1.4. Delete .data and .test files that are output from the NLCD Sampling Tool.

    3.6.1.5. Export a randomly selected 10% of the data set to a comma-delimited *.test file.

    3.6.1.6. Export remaining 90% of the data set to a comma-delimited *.data file.

  3.6.2. Use See5 to build non-forest PVT classification tree.

    3.6.2.1. From See5, open input files (.data and .names).

    3.6.2.2. Specify options (such as winnow, boosting, and misclassification cost).

    3.6.2.3. Run model (no cross-validation) to generate .tree file for prediction.

  3.6.3. Apply model across buffered zone.

    3.6.3.1. Use NLCD Mapping Tool to generate a map of non-forest PVTs with an associated map of confidence using the non-forest mask to limit prediction extent.

3.7. Make final maps and assess accuracy.

  3.7.1. Combine forest and non-forest maps.

  3.7.2. Combine forest and non-forest error matrices.

  3.7.3. Calculate accuracy measures (for example, percent correctly classified, user and producer accuracy, and Kappa statistic).

4. Mapping existing vegetation

4.1. Conduct spatial QA/QC of field plot data

  4.1.1. Conduct QA/QC for non-Forest Inventory Analysis (FIA) data point identification.

    4.1.1.1. Convert map attribute coordinate data to point attribute (vector) data.

    4.1.1.2. Intersect vector coverage with NDVI Change layer

    4.1.1.3. Populate table with NDVI difference values. Large differences in NDVI values are likely to represent plots without recent major vegetation change. (such as ± 2 std dev. from mean NDVI value for table).

Appendix 2-A — (Continued)

4.1.1.4. Identify plots with a “distance to road” of > 30m.

4.1.1.5. If NLCD data for 2001 is available, compare CTs to NLCD classes to check for matches. If NLCD 2001 data is not available, try NLCD 1992 data (provided in LFRDB).

4.1.1.6. Flag values in MAT that require attention based on analyses performed in 4.1.

4.1.2. Identify questionable plots.

4.1.2.1. Overlay points onto imagery stratified by CTs.

4.1.2.1.1. Identify and flag points on roads or other similar types of locations (such as urban or agriculture) that should not be used for training.

4.1.2.1.2. Identify and flag those points that indicate change has occurred since the field data were obtained.

4.1.2.1.3. Identify plots with forest CTs located in relatively intact non-forest locations (and vice versa).

4.1.2.1.4. Identify plots typed as conifer located in relatively intact deciduous forest (and vice versa).

4.1.2.2. Flag questionable plots in MAT and omit from future analyses.

4.1.3. Develop a modified MAT storing only field plots that pass the QA/QC process in 4.1.2.

4.1.4. Conduct QA/QC for FIA data (same general process as in 4.1.1 but requires FIA analyst).

4.1.5. Isolate 2% of the sample points to be used for accuracy assessment using the 3x3 km, 2% block design.

4.2. Preprocess imagery.

4.2.1. Ensure that Landsat imagery used for LANDFIRE mapping is processed to the following specifications:

4.2.1.1. For each path/row, acquire and process 3 seasonally separate dates (spring, summer, and autumn) of Landsat scenes

4.2.1.2. Conduct geometric rectification to terrain precision correction level, resulting in less than ± 15m root mean square error (RMSE) spatial accuracy.

4.2.1.3. Conduct radiometric normalization to calibrate radiance values to at-satellite reflectance values.

4.2.1.4. Calculate NDVI and tasseled cap transformation values for each of the three dates of the data.

4.2.1.5. Develop preliminary maps of forest, shrub, and herbaceous CTs using methods listed in 3 (potential vegetation mapping) Provide the preliminary maps to the PVT mappers and vegetation modelers for internal use.

Appendix 2-A — (Continued)

4.2.2. Ensure that the PVT map and PVT probability layers are stored in data library

4.2.3. Conduct visual quality check on the PVT layers to ensure no obvious seam lines, dropped pixels, or other quality problems exist.

4.2.4. Assemble imagery, topographic data, biophysical gradient layers, PVT probability layers, and riparian-wetland mask (if available).

4.3. Map life form-specific CT

4.3.1. Extract digital values from the spatial layers (4.2.4) using field plots that have passed the visual QA/QC inspection process (4.1.3 and 4.1.4).

4.3.2. Determine if a "hierarchical approach" (mapping by high-level stratifications) is needed: if there are strong environmental differences between life form-specific CT classes, consider taking the hierarchical approach. For example, stratify desert shrub CTs from upland and riparian shrub CTs. If the hierarchical approach is needed, go to 4.3.2.1; otherwise, go to 4.3.3.

4.3.2.1. Recode field plot data to high-level CT groups and run decision tree model for high-level CT groups.

4.3.2.2. Model CTs with decision tree model under each of the high-level CT groups.

4.3.2.3. Calculate overall cross-validation accuracy by weighting and summarizing all CT groups

4.3.2.4. If weighted cross-validation is satisfactory, merge all CT groups into one CT map by major life form.

4.3.2.5. If weighted cross-validation is not satisfactory, consider rearranging high level groups or abandoning the approach.

4.3.3. Run decision tree model separately for forest, shrub, and herbaceous life forms.

4.3.4. Generate life form-specific cross-validation error matrices.

4.3.5. Generate life form-specific CT layers by applying decision tree models (create separate tree, shrub, and herbaceous layers).

4.3.6. Check for any visual and information content problems by examining CT maps and interpreting error matrices

4.3.7. Determine if there are any rare classes (< 30 field plots) and decide how to treat such rare classes.

4.3.7.1. Option 1: drop rare classes and re-run decision tree models.

4.3.7.2. Option 2: re-run decision tree models without the rare classes and then "burn" rare class field plots onto the map.

4.3.7.3. Option 3: merge rare classes with floristically similar classes (solicit feedback from Vegetation Working Group).

4.3.7.4. Option 4: retain the rare classes in the map.

Appendix 2-A — (Continued)

4.3.8. Determine if other major mapping errors exist and correct by altering input parameters (if possible) as well as field-referenced data.

4.3.9. Apply water, urban, and agriculture masks to life form-specific CT maps.

4.3.10. Merge the 3 life form-specific CT layers to form one CT layer.

4.4. Map life form-specific canopy height (CH)

4.4.1. Assign life form-specific CH classes to plots in modified MAT (4.1.3 and 4.1.4).

4.4.2. Extract digital values from the spatial layers, including life form-specific CTs (4.3.10), and use field plots classified to CH class values from 4.4.1 above.

4.4.3. Run decision tree models separately for the three life forms (tree, shrub, and herbaceous).

4.4.4. Generate life form-specific cross-validation error matrices for CH classes.

4.4.5. Generate life form-specific CH class maps using decision trees.

4.4.6. Check for errors in the three life form-specific CH maps, ensuring ranges of CH values are logical for their corresponding CTs.

4.4.7. Mask each CH map with water, urban, and agriculture masks.

4.5. Map life form-specific canopy cover (CC)

4.5.1. Map tree CC

4.5.1.1. Create training set of forest CC using 1-m digital ortho-photography quadrangles or 1-m satellite imagery.

4.5.1.2. Establish the relationship between Landsat data and plot data using regression trees.

4.5.1.3. Apply the regression-tree relationship to generate a spatial per-pixel estimate of tree canopy for all pixels.

4.5.1.4. Generate cross-validation error matrices, evaluate error and R^2 values, and determine effectiveness of the regression tree models.

4.5.1.5. Recode continuous tree CC data to CC classes defined by the Vegetation Working Group.

4.5.1.6. Apply land cover masks: water, urban, and agriculture.

4.5.2. Map shrub and herbaceous CC, option 1:

4.5.2.1. Extract digital values from the spatial layers using field plots that have shrub or herbaceous CC associated with them. Use the modified MAT (4.1.3 and 4.1.4).

4.5.2.2. Stratify digital values based upon dominant life form and run regression models.

4.5.2.3. Generate life form-specific error assessments based on cross-validation analysis.

Appendix 2-A — (Continued)

    - 4.5.2.4. Determine effectiveness of the regression tree models based on error analysis and determine whether changes need to be made to both field data and independent spatial layers.
    - 4.5.2.5. Generate life form-specific CC maps by applying the regression tree models.
    - 4.5.2.6. Recode continuous variables to CC classes defined by the Vegetation Working Group.
    - 4.5.2.7. Apply land cover masks: water, urban, and agriculture.
- 4.5.3. Map shrub and herbaceous CC, option 2:
    - 4.5.3.1. Recode plot CC values in modified MAT (4.1.3 and 4.1.4) into CC classes defined by Vegetation Working Group.
    - 4.5.3.2. Extract digital values from the spatial layers (4.2.4) using binned shrub or herbaceous field plots from step 4.5.3.1.
    - 4.5.3.3. Stratify digital values based upon dominant life form (shrub and herbaceous vegetation) and run decision tree models.
    - 4.5.3.4. Generate life form-specific error assessments based on cross-validation analysis.
    - 4.5.3.5. Determine effectiveness of the decision tree models based on error analysis and determine whether changes need to be made to both field data and independent spatial layers.
    - 4.5.3.6. Generate life form-specific CC layers by applying the decision tree models.
    - 4.5.3.7. Apply land cover masks: water, urban, and agriculture.
- 4.5.4. Map shrub and herbaceous CC, option 3:
    - 4.5.4.1. Measure field spectral bands (corresponding to Landsat red and NIR bands) from multiple shrub and grass sites and derive field NDVI values.
    - 4.5.4.2. Estimate percent shrub and herbaceous CC for sites where field spectral data has been acquired (1-m^2).
    - 4.5.4.3. Determine relationship between field percent CC estimates and field-measured NDVI values.
    - 4.5.4.4. Estimate continuous shrub and grass CC through application of relationship described in step 4.5.4.3 to Landsat NDVI to standardize Landsat CC estimates (stratified by life form using NLCD 2000 data and/or LANDFIRE CT data).
    - 4.5.4.5. Recode continuous shrub or herbaceous variables to CT classes defined by the Vegetation Working Group.
    - 4.5.4.6. Apply land cover masks: water, urban, and agriculture.
- 4.5.5. Refine and normalize CC estimates.

Appendix 2-A — (Continued)

4.5.5.1. Normalize individual tree, shrub, and herbaceous CC values such that tree, shrub, and herbaceous CC values combined do not exceed 100% per pixel.

4.5.5.2. Locate zones of low confidence using confidence layers and other sources of information.

4.5.5.3. Mask out zones of low confidence for shrub and grass CTs where forest is the dominant CT.

4.6. Generate merged CT and SS maps

4.6.1. Revisit, and revise if necessary, the merged CT map (4.3.10) by using forest, shrub, and herbaceous percent CC as reference. Ensure that CTs match life form CC maps.

4.6.2. Produce a Federal Geographic Data Committee (FGDC) -compatible metadata file for the final merged CT map (4.6.1) using a mapping zone metadata template for CT.

4.6.3. Generate a single CH layer using the CT data layer (4.6.1) for life form masking stratification.

4.6.4. Produce an FGDC-compatible metadata file for the final merged Canopy Height layer (4.6.3) using a mapping zone metadata template for CH.

4.6.5. Generate a single CC layer using the CT layer (4.6.1) for life form masking stratification.

4.6.6. Produce an FGDC-compatible metadata file for the final merged Canopy Cover layer (4.6.5) using a mapping zone metadata template for CC.

4.7. Conduct cross-validation and accuracy assessments

4.7.1. Summarize all cross-validation errors and accuracy tables for the mapping zone; provide information to the Accuracy Working Team.

4.7.2. Extract the final CT, CC, and CH class values and labels (from 4.6.1, 4.6.3, and 4.6.5) using withheld plot locations (4.1.5). Provide extracted data to the Accuracy Working Team.

4.7.3. Evaluate error matrices, overall accuracy, and user and producer accuracy.

5. Mapping ecological departure

5.1. Acquire and develop input layers.

5.1.1. Acquire vegetation layers: PVT, CT, and SS.

5.1.2. Create Landscape Reporting Unit (LRU) layer by building grid of 900-m x 900-m squares.

5.1.3. Acquire polygon coverage that partitions zone into smaller units – termed simulation landscapes – used in LANDSUMv4 simulations.

5.2. Calculate ecological departure and index of significance using HRVStat approach.

5.2.1. Acquire data for historical reference conditions of vegetation patterns, developed using LANDSUMv4 model, including year, LRU, PVT, succession class, and area (m^2).

Appendix 2-A — (Continued)

5.2.1.1. Partition data into series of files, which function as LANDSUMv4 output for each simulation landscape within a zone.

5.2.1.2. Remove agriculture and urban CTs from reference conditions database.

5.2.2. Combine CT and SS layers to represent current succession classes using ArcInfo's COMBINE command.

5.2.3. Combine Succession Class layer with LRU and simulation landscape layers.

5.2.4. Join historical reference conditions with current succession class data for each unique LRU within each simulation landscape of zone data. Create series of ASCII files with these data for each simulation landscape.

5.2.5. Convert ASCII files from text to binary format.

5.2.6. Run the HRVStat program. The HRVStat program outputs ASCII text files containing calculations of departure, observed significance level, and classified HRVStat departure for each LRU within each simulation landscape file.

5.2.7. Link HRVStat ASCII output files to LRU layer to develop individual layers of ecological departure, observed significance level, and classified HRVStat departure.

5.3. Calculate ecological departure using FRCC Guidebook approach.

5.3.1. Isolate analysis to individual simulation landscapes.

5.3.2. Combine values for LRU, PVT, CT, and SS. Combined CT and SS information form succession classes.

5.3.3. Concatenate the LRU, PVT, CT, and SS fields to create unique IDs for LRU/PVT/succession class and LRU/PVT combinations.

5.3.4. Calculate current fire regime (CFR) by dividing the area of each succession class within an LRU/PVT combination into the total area (m^2) of the LRU/PVT combination.

5.3.5. Access the LANDSUMv4 files for each simulation landscape.

5.3.5.1. Create unique IDs for the LANDSUMv4 data corresponding to those of the CFR data.

5.3.5.2. Calculate the 90th percentile for each LRU/PVT/succession class combination and then export to historical fire regime (HFR) database.

5.3.6. Join HFR database records for the current simulation landscape with CFR database records using the LRU/PVT/succession class field.

5.3.7. Compute similarity, which is the smaller of CFR or HFR.

5.3.8. Total the similarity values across each LRU/PVT combination.

5.3.9. Compute departure as 100 – similarity. This represents the estimated ecological departure for a PVT in an LRU.

Appendix 2-A — (Continued)

5.3.10. Compute departure for entire LRU on an area-weighted basis. Weighting factors are derived by dividing the area (m^2) of each individual PVT into the area of each LRU (constant at 81 ha or 900 x 900 meters).

5.3.11. Merge all individual simulation landscapes together to create map for entire zone.

6. Mapping surface fuel models

6.1. Acquire rectified CT, PVT, and SS layers.

6.2. Combine these layers in a GIS format.

6.3. Export combined vegetation data and import into Access.

6.3.1. Assign CT, PVT, and SS names to the coded information from GIS layers.

6.4. Build rule sets for Anderson's (1982)13 fire behavior fuel models and Scott & Burgan's (2005) 40 fire behavior fuel models.

6.4.1. Use Forest Vegetation Simulator-Fire and Fuels Extension (FVS-FFE) documentation on variant fuel rules from Reinhardt and Crookston (2003).

6.4.2. Use additional information, such as local fire and fuel plans, fire behavior studies, other fuel research.

6.4.3. When necessary, consult local experts.

6.4.4. Compare rate of spread and flame length for each fuel model to ensure that fuel models are not illogically assigned to a specific vegetation combination. For example, we would not assign a FBFM 3 in grass systems that are only 1 foot tall.

6.4.5. Construct logical crosswalks between combined vegetation layers and fuel models.

6.4.5.1. Timber-dominated systems are usually assigned timber FBFMs.

6.4.5.2. Herbaceous systems are usually assigned grass FBFMs. Shrub systems can be assigned timber, shrub, or grass models, depending on composition and structure.

6.5. Apply rule set to vegetation combinations and assign surface fuel models in Access table.

6.5.1. Use key to assign fuel models to each combination of vegetation attributes.

6.5.2. Map fire behavior fuel models by linking the combination database to a GIS layer.

7. Mapping canopy fuel

7.1. Prepare data for model building.

7.1.1. Prepare spatially explicit predictor layers (biophysical and topographic gradients and Landsat satellite imagery).

7.1.1.1. Acquire biophysical and topographic gradients for 3-km buffered zone (as unsigned 16-bit images).

Appendix 2-A — (Continued)

- 7.1.1.2. Acquire Landsat imagery.
- 7.1.1.3. Quality-check all predictor layers.
    - 7.1.1.3.1. Ensure all layers are unsigned 8-bit or 16-bit integers.
    - 7.1.1.3.2. Check projections and row/column numbers for consistency.
    - 7.1.1.3.3. Check all images for erroneous numbers or patterns.

7.1.2. Prepare response data (canopy bulk density [CBD] and canopy base height [CBH]).

- 7.1.2.1. Set up input table for FUELCALC program, including field-referenced tree attributes from LFRDB.
- 7.1.2.2. Run the FUELCALC program.
- 7.1.2.3. Link FUELCALC output with LFRDB table (or FIA table).

7.1.3. Perform data extraction.

- 7.1.3.1. Extract values from each predictor gradient for each X and Y plot coordinate and link to the LFRDB MAT.

7.1.4. Perform data exploratory exercises.

- 7.1.4.1. Import coordinates into ArcMap and view data spatially, looking for unusual spatial patterns or outliers.
- 7.1.4.2. Import all data into a statistical package (in other words, R) and examine data for outliers or unusual features.
    - 7.1.4.2.1. Examine summary statistics of response (histograms, box plots, etc.).
    - 7.1.4.2.2. Examine summary statistics of predictors (distributions, scatter plots, correlation matrices, and principal components).
- 7.1.4.3. Create another variable, CBDx, in database with value: CBD * 100.
- 7.1.4.4. Create another variable, CBHx, in database with value: CBH * (0.3048 * 10).

7.2. Use NLCD Mapping Tool to set up input files for Cubist application.

7.2.1. Generate an ERDAS Imagine image (dependent variable) of training plots using CBDx/CBHx values.

- 7.2.1.1. Import Access table with X/Y coordinates (Albers) and CBDx/CBHx data into Arcmap.
- 7.2.1.2. Define extent identical to that of predictor layers.

Appendix 2-A — (Continued)

- 7.2.2. Use NLCD Mapping Tool and Sampling Tool to generate Cubist .names input file.
    - 7.2.2.1. Set dependent (response) variable as the CBDx image.
    - 7.2.2.2. Set independent (predictor) variable as the list of imagery, gradient, and topographic layers used for modeling (in the refined data set).
    - 7.2.2.3. Specify sampling process: set sample to random and set number of samples to 99% training and 1% validation.
    - 7.2.2.4. Set name and location of output files.
    - 7.2.2.5. Select model as Cubist.
    - 7.2.2.6. Review .names file to make sure all variables are specified and all discrete variables have codes.
- 7.2.3. Export .data input file from Access to Cubist.
    - 7.2.3.1. Delete .data and .test files that are output from the NLCD Sampling tool.
    - 7.2.3.2. Export refined training data set from Access to a comma-delimited file (.data), including the predictor gradient values and dependent (CBD) value.

7.3. Use Cubist to build model.

- 7.3.1. From Cubist, open input files (.data, .names).
- 7.3.2. Specify options
- 7.3.3. Run cubist model with test data set (generating a .rules file for prediction).
- 7.3.4. Run multiple models with different options and select the model with the highest accuracy.

7.4. Apply model across buffered zone.

- 7.4.1. Use NLCD Mapping Tool to generate a map of CBDx/CBHx with associated map of confidence.
- 7.4.2. Analyze output maps.
- 7.4.3. Check accuracy and run diagnostics.