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LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment

Matthew G. Rollins

US Geological Survey, Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198, USA. Email: mrollins@usgs.gov

Abstract. LANDFIRE is a 5-year, multipartner project producing consistent and comprehensive maps and data describing vegetation, wildland fuel, fire regimes and ecological departure from historical conditions across the United States. It is a shared project between the wildland fire management and research and development programs of the US Department of Agriculture Forest Service and US Department of the Interior. LANDFIRE meets agency and partner needs for comprehensive, integrated data to support landscape-level fire management planning and prioritization, community and firefighter protection, effective resource allocation, and collaboration between agencies and the public. The LANDFIRE data production framework is interdisciplinary, science-based and fully repeatable, and integrates many geospatial technologies including biophysical gradient analyses, remote sensing, vegetation modelling, ecological simulation, and landscape disturbance and successional modelling. LANDFIRE data products are created as 30-m raster grids and are available over the internet at www.landfire.gov, accessed 22 April 2009. The data products are produced at scales that may be useful for prioritizing and planning individual hazardous fuel reduction and ecosystem restoration projects; however, the applicability of data products varies by location and specific use, and products may need to be adjusted by local users.

Introduction

Legacies of fire exclusion and land-use practices have altered fire regimes, wildland fuel characteristics, and landscape composition, structure, and function across the United States (Pyne 1982; Covington *et al*. 1994; Brown 1995; Rollins *et al*. 2001; Keane *et al.* 2002*a*; Hann *et al*. 2003). As a result, the number, size, and severity of wildfires have departed significantly from historical conditions, sometimes with catastrophic consequences (Allen *et al*. 1998; Leenhouts 1998; US General Accounting Office 1999; National Interagency Fire Center 2007*a*). Recent examples include:

- The 2000 Cerro Grande fire near Los Alamos, New Mexico that burned 19 200 ha and destroyed 239 homes;
- The 2000 fire season in the north-western United States with over 2 million hectares burned;
- The 2002 Biscuit, Rodeo-Chediski, and Hayman fires burned over one-half million hectares and cost nearly US$250 million for suppression efforts;
- The 2003 fire season that began with catastrophic wildland fires in late spring with the Aspen fire north of Tucson, Arizona, that destroyed 250 homes followed by large, severe fires in the northern Rocky Mountains of western Montana and northern Idaho, and the arson-caused Cedar fire that burned over 113 000 ha and 2232 homes in southern California;
- In 2004, over 3 million hectares burned in Alaska, the largest fire season in Alaska's history;
- Most recently, the 2006 and 2007 fire seasons burned nearly 8 million hectares in the United States with suppression costs of nearly US$3 billion.

There were 164 wildland fire-related fatalities between 2000 and 2006 (National Interagency Fire Center 2007*b*).

Nationwide, comprehensive geospatial data describing wildland fuel and fire regimes are critical for tactical decision-making during wildland fire incidents, strategic planning focussed on mitigating levels of hazardous fuel across broad landscapes, and for planning the restoration of sustainable landscapes for areas at significant risk of catastrophic wildland fire. Although maps of wildland fuel and fire regimes support effective wildland fire management and ecological restoration, these data exist for relatively few broad areas and standardized methods for economically and efficiently creating these maps have not existed (Keane *et al*. 2001; Morgan *et al*. 2001; Rollins *et al*. 2004). Mapping wildland fuel and fire regimes across broad areas generally requires advanced geospatial applications, in-depth knowledge of wildland fire science, and complex statistical analyses. The difficulty of creating these maps is compounded by complex spatial and temporal dynamics of wildland fire (Rollins *et al*. 2004; Finney 2005). A combined approach to wildland fuel and fire regime mapping that integrates extensive field-referenced databases, multiple sources of fire history information, remote-sensing technologies, and biophysical modelling to map wildland fuels and historical fire regimes has proved to be effective (Keane *et al*. 2001, 2002*b*; Morgan *et al*. 2001; Rollins *et al*. 2004, 2006). The present paper describes the methods and applications of LANDFIRE, a national-level project to provide geospatial data products needed to implement federal wildland fire policy at regional to local levels and to fill critical knowledge gaps in wildland fire management planning. Many of the LANDFIRE methods were

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developed during a 3-year prototype effort completed in 2005 (Rollins *et al*. 2006).

Background

Responding to the increasing severity of wildland fire in the United States, the United States Secretaries of Agriculture and Interior developed the National Fire Plan, which focusses on: (1) ensuring sufficient wildland firefighting capacity in the future; (2) rehabilitating landscapes affected by wildland fire; (3) reducing hazardous wildland fuel; and (4) providing assistance to rural communities affected by severe wildland fires (US General Accounting Office 1999, 2001, 2002*a*; US Department of Agriculture and US Department of Interior 2001*a*). Along with the state governments of the western United States, federal agencies developed a 10-year Joint Cohesive Strategy for National Fire Plan Implementation (US Department of Agriculture and US Department of Interior 2001*b*). In order to implement these plans, the USDA Forest Service and Department of Interior have developed both independent and interagency management strategies from local to national levels with primary objectives focussed on public and firefighter safety, hazardous fuel reduction, wildland fire hazard mitigation, and restoration of ecosystem sustainability on fire-adapted landscapes. The implementation focusses on prioritization of landscapes and communities at risk, appropriate management response, adaptive planning, restoration, and maintenance of sustainable landscapes (USDA Forest Service and US Department of Interior 2006*a*).

Nationwide, comprehensive, consistent, integrated, and accurate data are critical for prioritizing, planning, monitoring, and allocating resources for implementation of the National Fire Plan (US General Accounting Office 2002*a*, 2002*b*, 2003*a*, 2003*b*). In 2000, the US Department of Agriculture (USDA) Forest Service Missoula Fire Sciences Laboratory developed coarse-scale (1-km spatial grain) maps of historical fire regimes and ecological departure from historical conditions for the lower 48 United States (Hardy *et al*. 2001; Schmidt *et al*. 2002). These data were designed to assist wildland fire management at regional scales (e.g. millions of hectares) and to facilitate comparison of fire hazard and risk between regions and states (Hardy *et al*. 2001). These data products included mapped potential natural vegetation groups, current cover types, historical natural fire regimes, Fire Regime Condition Class (FRCC), national fire occurrence (1986–96), potential fire characteristics, and wildland fire risk to flammable structures (Schmidt *et al*. 2002). These data rapidly became the foundation for national-level strategic wildfire planning and for responding to political concerns regarding the risk of catastrophic fire. Fire Regime Condition Class became a key factor for inferring risk to both communities and landscapes across the United States (US Congress 2003).

While generally well accepted and valuable for comparative analyses at national levels, the 1999 coarse-scale data products lacked resolution for regional-to-local planning and for prioritization and guidance for mid-level applications. Subsequent reports from the US Government Accountability Office (known as the General Accounting Office previous to 2004) revealed that, despite the existence of the coarse-scale FRCC data, federal land management agencies lacked adequate data for making decisions and measuring progress in hazardous fuel reduction (US General Accounting Office 2002*b*). Government Accountability Office reports over the last several years have emphasized several shortcomings in wildland fire management planning as well as documenting progress towards mitigating these shortcomings: in 1999–2004, General Accounting Office reports focussed on: (1) many federal lands lacked fire management plans that adequately addressed wildland fire risk to landscapes, communities, and firefighters; (2) federal agencies lacked a framework to ensure that funds for hazardous fuel reduction were spent in an efficient, effective, and timely manner; (3) federal agencies lacked performance measures or consistent baselines for evaluating successes; (4) federal agencies lacked consistent, comprehensive geospatial data for identifying and prioritizing landscapes that are at high risk from wildland fires; (5) federal agencies lacked adequate field-based reference data for expediting the project planning process; (6) federal agencies lacked comprehensive and consistent monitoring approaches for measuring the effectiveness of efforts to mitigate hazardous fuel build-up; and (7) federal agencies have lacked a specific strategy for focussing mitigation efforts on landscapes adjacent to communities at risk (US General Accounting Office 1999, 2002*a*, 2002*b*, 2003*a*). In recent years (2005–07), the Government Accountability Office has noted that important progress has been made towards a more comprehensive and consistent framework for addressing wildland fire risk, implementation of specific performance measures, focussing on communities at risk, and implementing consistent wildland fire and fuel monitoring programs (US Government Accountability Office 2005, 2006, 2007).

In response to comments from the General Accounting Office, the Wildland Fire Leadership Council (www.forestsandrangelands.gov/leadership/index.shtml, accessed 22 April 2009) chartered the LANDFIRE project in 2004 (US Department of Agriculture and US Department of Interior 2004). LANDFIRE is a 5-year project producing consistent and comprehensive maps and data describing vegetation, wildland fuel, fire regimes, and ecological departure from historical conditions for the United States (Table 1). It is a shared project between the wildland fire management programs of the USDA Forest Service and US Department of the Interior. LANDFIRE methodologies are open-source, fully repeatable, and include extensive field-referenced data and image catalogues. LANDFIRE differs from previous and ongoing regional mapping programs in that it is a comprehensive (all 50 states) assessment conducted using repeatable methodologies. Areas mapped in the south-eastern United States may be directly compared with areas in the north-western United States. The repeatable and open-source character of LANDFIRE methodologies enables local product refinement and the development of innovations based on LANDFIRE products. LANDFIRE data products are designed to facilitate national- and regional-level strategic planning and reporting of wildfire management activities. The comprehensive, consistent, and integrated qualities of LANDFIRE data products allow comparison of different wildfire management strategies, wildfire season scenarios and ecosystem restoration strategies. LANDFIRE data products are produced at a 30-m grid cell resolution; there is no minimum mapping unit for LANDFIRE data products. This design criterion was intended to maximize opportunities for aggregations of LANDFIRE data for applications

Table 1. The LANDFIRE data products
Abbreviations are: FBFM, Fire Behaviour Fuel Model; FRCC, Fire Regime Condition Class. For access, see www.landfire.gov

Fire behaviour data products	Fire regime data products	Vegetation data products
13 Anderson FBFMs	FRCC	Environmental site potential
40 Scott and Burgan FBFMs	FRCC departure index	Biophysical settings
Canopy bulk density	Fire regime groups	Existing vegetation type
Canopy base height	Mean fire return interval	Existing vegetation height
Canopy height	Percentage low-severity fire	Existing vegetation cover
Canopy cover	Percentage mixed-severity fire	Vegetation dynamics models
	Percentage replacement-severity fire	
	Succession classes	

across spatial scales. Although designed for national to regional applications, the 30-m grid resolution may be useful for prioritizing and planning specific hazardous fuel reduction and ecosystem restoration projects at local levels. However, the applicability of data products varies by location and specific use. Data products may need to be adjusted by end-users to ensure that they are appropriate for local application. Where possible, LANDFIRE has used definitions and guidelines provided in the USDA Forest Service Existing Vegetation Classification and Mapping Technical Guide (Brohman and Bryant 2005). In the context of this guide, the LANDFIRE data products are considered 'broad-level' data.

LANDFIRE includes tools and guidance to ensure that local fire and fuels information may be substituted for the LANDFIRE layers if higher quality data exist and are perceived as having more utility than the LANDFIRE products (see www.landfire.gov, accessed 22 April 2009). Currently, LANDFIRE data products are used as part of a decision support framework for developing wildland fire suppression strategies by rapidly identifying and quantifying the significant resource values most likely to be threatened by wildland fire incidents (USDA Forest Service and US Department of Interior 2006*b*). The LANDFIRE wildland fuel data products were used for tactical planning and decision support for 168 wildland fire incidents in the United States during the 2007 fire season. Additionally, LANDFIRE data products have been used for long-term risk assessments and fuel treatment strategies in Region 3 of the USDA Forest Service, for wildland fire use in large western wilderness areas, and for habitat assessments for bighorn sheep in central Idaho and grizzly bears in the northern Rocky Mountains (see www.landfire.gov).

Overview

Many sequential and interdependent tasks must be completed to create the suite of databases, geospatial data layers, and models needed to develop the final LANDFIRE data products (Fig. 1; Table 1; Rollins *et al*. 2006). First, the LANDFIRE reference database (LFRDB) is compiled from existing field reference databases from both government and non-government sources. Second, field referenced plots in the LFRDB are assigned vegetation map units based on sequence tables produced for LANDFIRE by NatureServe (www.natureserve.org, accessed 22 April 2009). Third, biophysical gradients, Landsat imagery, and training databases from the LFRDB are used in a predictive landscape modelling environment to create maps of potential vegetation (PVT), existing vegetation composition (EVT), and existing vegetation height and canopy cover (EVH and EVC). Fourth, vegetation dynamics models and the LANDSUM landscape simulation model (Holsinger *et al.* 2006*b*) are used to simulate vegetation dynamics over time in order to quantify the range of historical variation in fire regime and vegetation characteristics (e.g. historical vegetation reference conditions, fire severity, and fire interval) needed for estimating current ecological departure from historic conditions. Fifth, surface and canopy fuel characteristics are mapped using information derived from the LFRDB (e.g. field referenced canopy base height and canopy bulk density), biophysical gradients, EVT, EVH, and EVC. The following sections describe the LANDFIRE methodologies in detail.

LANDFIRE field-referenced database

The LFRDB is a compilation of all existing georeferenced field data available for the United States, including USDA Forest Service Forest Inventory and Analysis data (Gillespie 1999; USDA Forest Service 2007*a*), Natural Resource Inventory data (USDA Forest Service 2007*b*), National Park Service fire monitoring data (US Department of Interior 2003), and data from the US Geological Survey Gap Analysis Program (GAP) (US Geological Survey 2007). Field-referenced data compiled in the LFRDB form a critical foundation for most tasks in the LANDFIRE project.

All LANDFIRE data must be georeferenced. The data must quantify or relate to at least one LANDFIRE mapping attribute (e.g. EVT, EVC, or fuel characteristics). All acquired data are evaluated for suitability and assigned quality control indices based on summary satellite image overlay, logic checking, associated metadata, and digital photographs if available. The database is designed in Microsoft Access database software (Microsoft Corp., Redmond, WA, USA) and has a four-tiered, hierarchical structure (Caratti 2006). Data from Level I and Level II of the LFRDB are used to develop and test the quality of most LANDFIRE data products. Level IV, the lowest level, consists of acquired georeferenced data in their native format. Level III consists of data converted from raw format to the architecture of the fire effects monitoring system (FIREMON) database structure (Lutes *et al*. 2002). Level II data are summaries of Level III data to the LANDFIRE attribute database. Level II data include but are not limited to: unique

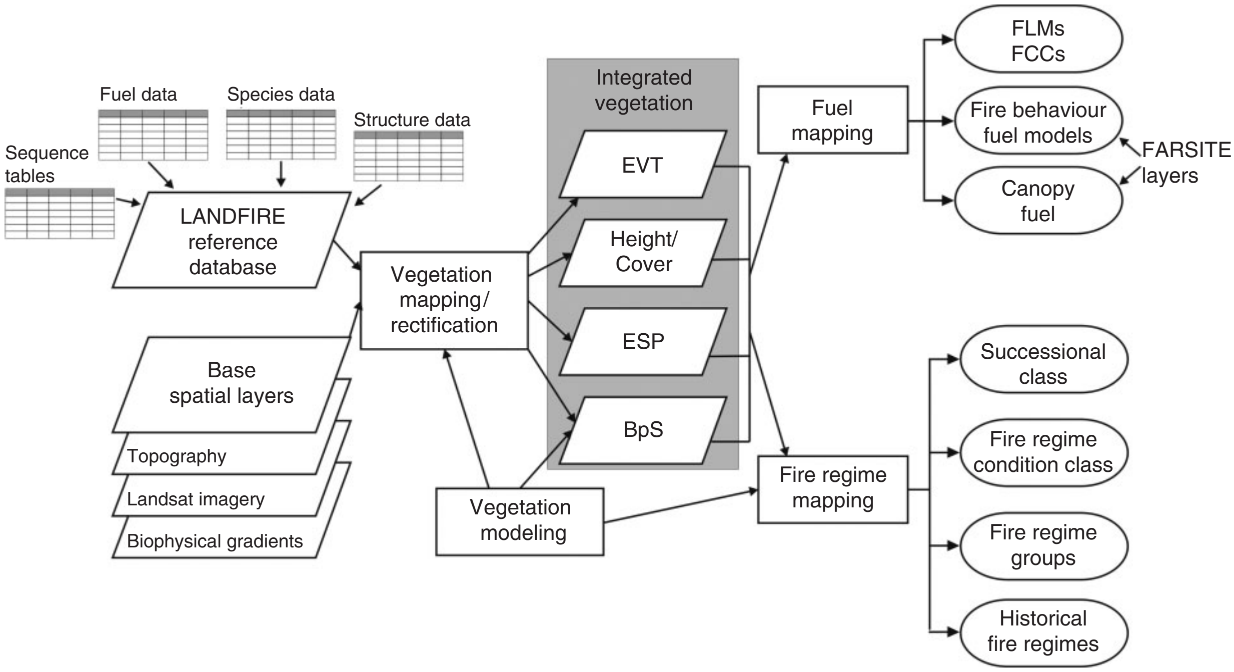

Fig. 1. An overview of the LANDFIRE production procedures. LANDFIRE mapping processes begin with the creation of the LANDFIRE reference database, which comprises a set of all available georeferenced plot information from within each mapping zone. The reference and spatial databases are used in a classification and regression tree-based framework for creating maps of environmental site potential (ESP) and biophysical setting (BpS), existing vegetation type (EVT) and structure (canopy height, EVH and cover, EVC). 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 surface and canopy fuel for simulation of fire behaviour and effects. LANDFIRE fire effects data products include Fuel Loading Models (FLMs) and Fuel Characterization Classes (FCCs).

identification codes or keys for the plot, species lists, fuel inventories, range condition, sampling date, size of plot, ancillary information about sampling methodologies, and digital photographs. Vegetation composition data at Level II are used to classify existing and potential vegetation communities, for evaluation and quantification of model parameters, and for evaluating the quality of existing spatial layers. Level I data are summaries of the LANDFIRE attribute database to a LANDFIRE mapping database. Level I data are used as training information in predictive landscape models used to develop PVT, EVT, EVC, and EVH data products. Level I data also include information used for quality assurance and control of LANDFIRE data products. This includes digital photos, if available, and distance to roads and water bodies. LANDFIRE compiled and applied over 500 000 field-referenced plots for 24 map zones in the western United States (Fig. 2).

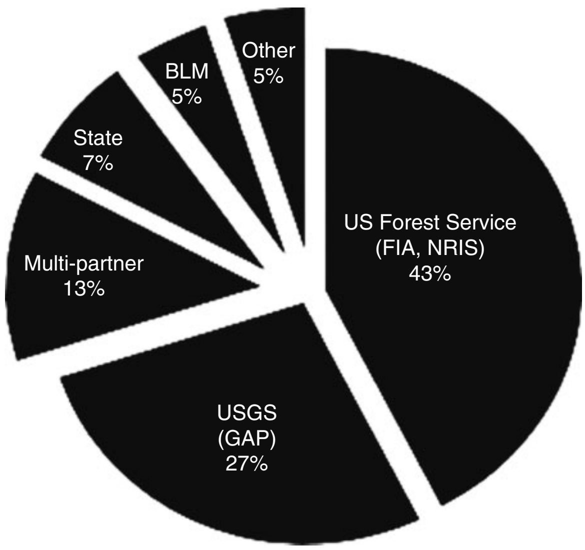

Fig. 2. Distribution, by source, of data included in the LANDFIRE reference database. Abbreviations clockwise from noon are as follows: US Forest Service, United States Forest Service; FIA, forest inventory and analysis national program; NRIS, natural resource information system; USGS, United States Geological Survey; GAP, Gap Analysis Program; and BLM, Bureau of Land Management.

LANDFIRE vegetation map units

Developing the LANDFIRE vegetation, wildland fuel, and fire regime data products depends on implementing nationally available map unit classifications (map unit legends) that meet strict guidelines required by the interagency wildland fire management, resource management staffs, and the myriad of technical requirements for LANDFIRE data products (US Department of

Agriculture and US Department of Interior 2004; Long *et al*. 2006*b*).

LANDFIRE's vegetation map unit legends originate conceptually from NatureServe's Ecological Systems classification, which is a nationally consistent set of mid-scale ecological units. Ecological Systems are defined as groups of vegetative associations that tend to co-occur within landscapes with similar ecological processes, substrates, and environmental gradients (Comer *et al*. 2003). LANDFIRE uses the qualitative descriptions of ecological systems as baseline information for creating the map unit legends for existing vegetation and two types of potential vegetation data products: environmental site potential (ESP; climate-constrained potential vegetation) and biophysical settings (BpS; potential vegetation constrained by climate and historical disturbance regimes). Development of the LANDFIRE vegetation data products is described in following sections.

Initially, plots in the LFRDB are assigned to existing vegetation map units (EVTs) using sequence tables developed by NatureServe. These sequence tables were developed during regional workshops attended by vegetation ecologists to produce the dominant types or communities used to assign plots to LANDFIRE EVT map units based on information contained in the LFRDB. Each row in a sequence table is similar to a branch in a dichotomous key, with the presence and abundance of indicator species serving as primary discriminating criteria. Geographic or environmental parameters are included as secondary discriminating criteria. Existing vegetation map units are arranged in a specific sequence in the table, just as branches in a dichotomous key would be. The final EVT vegetation map units are a mixture of the following: ecological systems (as described in Comer *et al*. 2003), aggregations of some ecological systems for LANDFIRE purposes (e.g. riparian systems or sparsely vegetated systems), and US National Vegetation Classification (NVC) alliances (Grossman *et al*. 1998) where they occur in large enough patches to be mapped. Although used primarily for wildland fire behaviour effects mapping applications, the LANDFIRE map units were designed to be useful for a variety of non-wildland fire applications such as habitat analysis and sustainable natural resource planning.

Foundational geospatial databases

Developing the LANDFIRE data products requires high-quality foundational spatial data to serve as predictor variables over the entire study area (Franklin 1995; Keane *et al*. 2001, 2002*b*; Morgan *et al*. 2001; Rollins *et al*. 2004). In addition to Landsat imagery, these include geospatial data describing gradients of topography, soils, weather, and ecological gradients. LANDFIRE selected sources for these data that ensured both high quality and national availability.

Landsat imagery

Accurate portrayal of existing vegetation and structure is critical to LANDFIRE. Vegetation data forms the foundation for characterizing wildland fuel and for describing current conditions for comparison with historical reference conditions for calculations of FRCC. Existing vegetation type and vegetation structure (i.e. canopy closure and height) layers are derived using Landsat images acquired from the Multi-Resolution Land Characteristics (MRLC) Consortium (Vogelmann *et al*. 2001; Homer *et al*. 2004). Landsat images were acquired for three different dates for the entire United States over the time period between 1999 and 2001 to capture vegetation dynamics of a growing season and to maximize land-cover type separability (Yang *et al*. 2001). Georeferencing is performed using a terrain correction approach using 1-arc second topographic data from the National Elevation Dataset (US Geological Survey 2006*a*). Raw Landsat digital numbers are converted to at-sensor reflectance for the six Landsat reflective bands, and to at-sensor temperature for the thermal band according to Markham and Barker (1986) and the Landsat 7 Science Data User's Handbook (Irish 2000). Reflectance-based spectral coefficients are used to derive tasseled-cap brightness, greenness and wetness, which have been found useful for vegetation characterization (Cohen *et al*. 1998; Huang *et al*. 2002*a*).

Topography

LANDFIRE uses topographic products from the Elevation Derivatives for National Applications (EDNA) dataset (US Geological Survey 2006*b*). These topographic data are derived from the National Elevation Dataset, which comprises merged 7.5-min quadrangle topographic data, resulting in a high-quality, consistent elevation dataset that spans the entire United States. EDNA products have been hydrologically conditioned for improved hydrologic flow representation, making them more immediately applicable to LANDFIRE's mapping and modelling needs. For example, many of the intermediate EDNA products such as flow accumulation and flow direction are used in the vegetation mapping processes and to delineate riparian areas.

Soils

For the western United States, LANDFIRE used STATSGO soils data for calculating soil texture and soil depth for mapping and modelling purposes. Soil texture was derived using the State Soil Geographic (STATSGO) database, which is composed of digitized polygons from 1 : 250 000 scale state soil maps (US Department of Agriculture 1995*a*). Initially, LANDFIRE technical staff explored the finer-scale Soil Survey Geographic (SSURGO) database, but found that incomplete SSURGO coverage would not provide sufficient soils information for the national LANDFIRE mapping effort. STATSGO data structure consists of soil polygons, where each polygon has associated descriptions of soil sequence and soil layers in tabular format. Soil sequence represents the dominant kinds of soils (up to three taxonomic classes) contained in a polygon. Geospatial data for soil textures and soil depth were derived from the STATSGO database based on methods described in Holsinger *et al*. (2006*a*). In the eastern United States, it was determined that that the SSURGO soil database (US Department of Agriculture 1995*b*) would be complete enough to use in LANDFIRE applications. Like STATSGO, SSURGO data are composed of many map attributes assigned to polygons. Information was extracted from the SSURGO database in very much the same way as with the STATSGO data. In areas where SSURGO data were incomplete, LANDFIRE used an image segmentation and imputation approach to assign SSURGO information from known areas to areas with similar topography and biophysical settings.

Biophysical gradients

Using direct and functional gradients has been shown to improve the accuracy of vegetation and fuel maps (Franklin 1995; Müller 1998; Ohmann and Gregory 2002; Rollins *et al*. 2004). We used an ecosystem simulation approach to create geospatial data layers that describe important environmental gradients that directly influence the distribution of vegetation and wildland fire across broad landscapes (Rollins *et al*. 2004). The simulation model WXBGC was developed for LANDFIRE specifically for the purpose of employing standardized and repeatable modelling methods to derive landscape-level weather and ecological gradients for predictions of landscape characteristics such as vegetation and fuel. It was an evolution of the WXFIRE application (Keane *et al*. 2002*b*; Rollins *et al*. 2004; Holsinger *et al*. 2006*a*; Keane and Holsinger 2006). WXBGC was designed to simulate biophysical gradients using spatially interpolated daily weather information in addition to mapped soils and terrain data (Thornton *et al.* 1997). 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 WXBGC required the three following steps: (1) develop simulation units (the smallest unit of resolution in WXBCG), (2) compile mapped daily weather, and (3) execute the model (Holsinger *et al*. 2006*a*). Thirty-eight output variables from WXBGC 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 *et al*. 2006*a*). Specifically, these layers were used as a basis for mapping PVT, EVT, EVC, and EVH (Frescino and Rollins 2006; Zhu *et al*. 2006) and for mapping both surface and canopy wildland fuel (Keane *et al*. 2006*a*). Additionally, biophysical gradient layers facilitated comparison of map units across mapping zones during the map unit development. For example, an equivalent EVT in two different mapping zones should have similar biophysical characteristics. Large differences in biophysical characteristics may indicate that a new EVT should be developed.

Potential vegetation mapping

LANDFIRE uses the ecological concept of potential vegetation (Küchler 1964; Daubenmire 1968; Pfister and Arno 1980) to stratify or compartmentalize the landscape for simulating historical vegetation and wildland fire dynamics, for summarizing FRCC and for mapping wildland fuel (both surface and canopy). There are two LANDFIRE potential vegetation data products: (1) ESP and (2) BpS. ESP is used as an environmental stratification for wildland fuel mapping and as a precursor to the BpS mapping process. Biophysical settings serve as a spatial template for simulating the ecological processes of succession and disturbance that are modelled aspatially using the vegetation dynamics development tool (VDDT). It is important to note that the utility of the concept of 'potential vegetation' for evaluating successional trajectories and vegetation community development is debated among vegetation ecologists; this is especially true for ecosystems where landscapes are permanently altered by land-use and other human perturbations (e.g. the eastern United States). This debate can be exacerbated when considering landscape function, structure, and composition in the context of a changing climate. In areas where landscapes have been permanently altered, particularly in the eastern United States, LANDFIRE developed custom existing map units that, along with the vegetation dynamics models described below, accounted for permanently altered landscapes. LANDFIRE uses potential vegetation maps for stratification for wildland fuel and fire regime mapping. Using the concept of potential vegetation in this context does not imply that historical landscapes are always a management target or a desired future condition for natural resource management.

LANDFIRE potential vegetation data products have been used along with existing vegetation in USDA Forest Service Region 3 to refine local plans for allocating resources for hazardous fuel reduction. These data were refined by local managers and incorporated into assessments that crossed administrative boundaries and facilitated an integrated assessment involving federal, state, and private land ownership. The integrated nature of the LANDFIRE data products allowed for the combination of wildland fire behaviour and effects simulation results, wildland–urban interface information, and habitat evaluations for Mexican spotted owl into the final assessment.

Environmental site potential

The LANDFIRE ESP map represents vegetation that could be supported at a given site based on the biophysical environment. It reflects information about the current climate, substrate, and topography, as well as the competitive potential of native plant species. Map units are named according to NatureServe's Ecological Systems map unit classification, which is a nationally consistent set of mid-scale ecological units (Comer *et al*. 2003). As used in the ESP map, map unit labels represent the natural plant communities that could occur at late or climax stages of successional development in the absence of disturbance. The map unit classification for ESP is closely linked to the existing vegetation map unit classification (EVT sequence table), but does not include units that represent early seral or non-native conditions.

Field training plots are assigned to map units using sequence tables. Sequence tables are developed based on input from regional ecologists and field-referenced data in the LANDFIRE reference database. Each row in the table is similar to a branch in a dichotomous key, with the presence and abundance of indicator species serving as the primary discriminating criteria. Geographic parameters are included as secondary discriminating criteria. ESP map units are arranged in a specific sequence in the table, just as branches in a dichotomous key would be. Sequences are based on gradients of ecological amplitude and competitive potential of indicator species. The relative importance of these characteristics in the LANDFIRE sequence tables is determined by geography and ecological regions defined by ECOMAP (Cleland *et al*. 2007), Environmental Protection Agency (EPA) ecoregions (Omernik 1995; Environmental Protection Agency 2007), and LANDFIRE mapping zones. Once plots in the LANDFIRE reference database are keyed to ESP units, they are used as training data in the development of ESP maps. Classification trees are developed using these plot data against a suite of biophysical gradient layers, as described in Holsinger *et al*. (2006*a*) and at www.landfire.gov. An iterative, stratified approach is used where mapping models are created using classification trees and evaluated against field-referenced data.

The LANDFIRE ESP concept is similar to that used in other classifications of potential vegetation, including habitat types (Daubenmire 1968; Pfister *et al*. 1977) and plant associations (Henderson *et al*. 1989). It is important to note here that ESP is an abstract concept and represents neither current nor historical vegetation. The ESP map is very similar in concept to the potential vegetation map created for the LANDFIRE Prototype Project (Frescino and Rollins 2006). The ESP data product is an important precursor to the BpS data product.

Biophysical settings

The LANDFIRE BpS data product represents the vegetation that may have been dominant on the landscape before Euro-American settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime. It is a refinement of the ESP layer; in this refinement, we attempt to incorporate current scientific knowledge regarding the functioning of ecological processes – such as fire – in the centuries preceding non-indigenous human influence. Map units are based on NatureServe's Ecological Systems classification, which is a nationally consistent set of mid-scale ecological units (Comer *et al*. 2003). As used in LANDFIRE, map unit names represent the natural plant communities that may have been present during the reference period. Each BpS map unit is matched with a model of vegetation succession, and both serve as key inputs to the LANDSUM landscape succession model (Keane *et al*. 2002*a*). The LANDFIRE BpS concept is similar to the concept of potential natural vegetation groups used in mapping and modelling efforts related to fire regime condition class (Schmidt *et al*. 2002; www.frcc.gov, accessed 6 May 2009).

The LANDFIRE BpS map evolves from the ESP map. ESP map units are modified to reflect conditions that existed before Euro-American settlement. Fire regime information used to modify ESP map units is acquired from: (1) the qualitative descriptions of Ecological Systems in Comer *et al*. (2003); (2) the LANDFIRE Model Tracker Database (MTDB) compiled through regional workshops held by The Nature Conservancy (described later in this document and at www.landfire.gov); (3) communications and iterative review by local ecologists and fire managers; and (4) existing literature describing the relationships between fire and vegetation dynamics. Modification of ESP map units is based on a combination of plot data, biophysical gradient data, input from vegetation dynamics models, and classification tree models. The modified map units are merged with the original ESP map to create the BpS map. Local datasets are used to develop separate mapping models for BpS for landscapes where existing vegetation is highly departed from historical vegetation and local data exist describing historical vegetation conditions. In this way, available local data are incorporated into the LANDFIRE BpS maps. The BpS data product is similar in concept to the potential natural vegetation groups (PNVG) in previous mapping and modelling efforts related to FRCC (see Schmidt *et al*. 2002; and www.frcc.gov).These mapping efforts were important precursors to the LANDFIRE Project's fire regime products.

Existing vegetation

Maps of existing vegetation composition and structure are principal LANDFIRE data 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 EVT, EVC, and EVH (Fig. 1). In 2007, LANDFIRE existing vegetation data products were used in a regional assessment of grizzly bear habitat in the northern Rocky Mountains (Graves *et al*. 2006). The LANDFIRE existing vegetation data products were updated for wildland fires that had occurred since the initial LANDFIRE mapping, and the existing vegetation maps were updated based on LANDFIRE vegetation dynamics models (described below). This process has served as a prototype for consistently maintaining the currency of the LANDFIRE data products into the future.

Existing vegetation type

The LANDFIRE EVT data product represents the vegetation currently present at a given site. Map units are classified based on the dominant vegetation in plot information contained in the LFRDB. The map unit classification is floristically based and uses the qualitative descriptions of ecological systems as a starting point. Sequence tables for assigning EVT to plots in the LFRDB are developed at workshops held by NatureServe that engage local ecologists to develop an expert system-based classification. The final sequence table is floristically based and defined by the dominance of indicator species for individual ecological systems.

LANDFIRE uses classification and regression tree (CART) algorithms for all vegetation mapping, using Landsat imagery, biophysical gradients, and training databases developed from the LFRDB (Breiman *et al*. 1984; Zhu *et al*. 2006).We selected CART classification methods for the following reasons. First, as a non-parametric classifier, CART is more appropriate for broad-scale mapping than parametric methods (e.g. maximum likelihood estimation or discriminant analysis; Breiman *et al*. 1984). Second, CART-based models may be trained hundreds of times faster than some other non-parametric classifiers like neural networks and support vector machines (Huang *et al*. 2002*b*), yet it is comparable with and performs similarly with regard to accuracy to these methods (Friedl and Brodley 1997; Huang *et al*. 2002*a*; Franklin 2003; Rollins *et al*. 2004). Third, the CART framework explicitly represents logics that can be interpreted and incorporated in expert systems for further analysis, whereas neural networks and support vector machines work like 'black boxes', with classification logics difficult to interpret or simply 'invisible'. Last, CART have been successfully used recently for modelling and mapping vegetation at broad scales in central Utah as part of the LANDFIRE Prototype Project (Huang *et al*. 2001; Homer *et al*. 2004; Zhu *et al*. 2006).

The first step in LANDFIRE EVT mapping is additional, vegetation-specific, quality control and assurance procedures that screen plots for major changes between the date of data collection and imagery acquisition, removing plots that are too close to roads or other developed areas, and visual checking for logical inconsistencies. Once the training databases have been developed, a hierarchical and iterative set of classification models is applied, with the first mapping model separating more general land-cover types and subsequent models separating more detailed cover types. Specifically, lifeform maps are generated, then separate models are developed iteratively for each separate lifeform. Information from the LFRDB, biophysical gradients, other ancillary data layers, and expert local review are used both qualitatively and quantitatively to guide the mapping process.

Canopy cover and height

Methods for mapping and modelling canopy cover and height from satellite imagery include physically based models, spectral mixture models, and empirical models. Though often considered unsophisticated and criticised for lack of focus on mechanistic process, empirical models have been found more successful than the other two groups of models in applications involving large areas (Cihlar 2000; Huang *et al*. 2001). We use regression tree-based methods to model the relationships between field-measured canopy cover and height with spectral information from Landsat imagery. The final LANDFIRE canopy cover layer is a combination of National Land Cover Database (NLCD) forest canopy (Homer *et al*. 2004) cover with individually modelled shrub and herbaceous cover.

Historical fire regime and Fire Regime Condition Class

Vegetation dynamics modelling

The objectives of LANDFIRE vegetation modelling were to (1) describe the myriad of disturbance information and transition times that entrain vegetation patterns over time; (2) to provide vegetation models for modelling historical fire regimes; and (3) to document the ecological assumptions and information behind the development of the models in the LANDFIRE MTDB (www.landfire.gov). Information from the MTDB is used as ancillary data in the mapping of BpS, existing vegetation type, succession classes, and surface and canopy fuels.

Vegetation models in the western US were developed at regional workshops where over 700 regional ecologists and fire managers developed over 1200 vegetation models. At these workshops, vegetation and fire ecology experts synthesized the best available science and local knowledge on disturbance dynamics for the vegetation communities found in their region. Participants were trained in VDDT software (Beukema *et al*. 2003) and worked in groups to develop vegetation models for each BpS in their respective modelling zones. Extensive internal and external review processes followed model development.

Historical vegetation reference conditions and fire regime modelling

LANDFIRE uses the Landscape Succession Model (LANDSUM) to simulate historical reference conditions and historical fire regimes. The LANDSUM simulation model was selected for LANDFIRE over other landscape simulation models based on a balance of (1) minimal input data requirements, (2) ease of parameterization, and (3) computation demands. LANDSUM has been use to estimate historical range and variation of landscape patch dynamics for four watersheds in the northern Rocky Mountains and Cascades (Keane *et al*. 2002*a*). An early version of LANDSUM, called CRBSUM, was used to predict future management scenarios for the Interior Columbia Ecosystem Management Project (Quigley *et al*. 1996).

LANDSUM is a spatially explicit vegetation dynamics simulation program where succession is treated as a deterministic process and disturbances (e.g. fire, insects, and disease) are treated as stochastic processes (Keane *et al*. 2002*a*, 2006*b*; Pratt *et al*. 2006). LANDSUM simulates succession within a patch (adjacent similar pixels) or polygon using the multiple pathway fire succession modelling approach presented by Kessell and Fischer (1981).This approach assumes all pathways of successional development will eventually converge to a stable or climax plant community called a PVT. All disturbances, except fire, are stochastically modelled at the stand level from probabilities specified by the user. Fire ignition is computed from input fire frequency probabilities specified by PVT, cover type, and structural stage categories. Wildfire is spread across the landscape based on simplistic slope and wind factors. The effects of simulated fires are stochastically simulated based on the fire severity types as specified in disturbance input files and vegetation dynamics models described above (Keane *et al*. 2006*b*; Pratt *et al*. 2006). Finally, LANDSUM outputs the area occupied by BpS, vegetation composition and vegetation structure combinations by a user-defined reporting unit and reporting time. These time series of simulated vegetation composition and structure are used to define vegetation reference conditions for creating the FRCC data product. The cumulative simulated fire occurrence and fire severity information is used to create the historical fire regime group data product.

Fire regimes have changed dramatically over the last 200 years. Human settlement and concomitant land use and community development have irrevocably altered the frequency, size, and severity of wildland fires. This is a defining characteristic of the landscapes of the eastern United States. Wildland fire and landscape managers need to accommodate for these permanently altered landscapes. LANDFIRE data products and interagency FRCC guidelines incorporate historical fire regimes into measures of current departure from historical conditions. Using historical conditions as a target for ecological restoration or the management of sustainable systems is likely not desirable from a socioeconomic standpoint. However, these products and metrics provide information on the long-term conditions under which landscape function, structure, and composition have evolved. In management situations, this information must be considered along with information about the current role of fire in ecosystems and the fragmented character of current landscape structure, composition, and ownership.

Fire regime groups

LANDSUM outputs three fire severity maps and one fire frequency map that are then processed to create the final LANDFIRE fire regime data products. Fire severity in LANDSUM is defined as low-severity fire, mixed-severity, and replacement-severity. LANDFIRE produces maps for each of these severity types that display the percentage of fires of the given severity type experienced by a particular pixel. Fire severity is calculated as the total number of fires of the given severity type divided by the total number of fires experienced by that cell multiplied by 100. Values for each map range from 0 to 100 and, for any cell, the sum of the three maps equals 100. The fire frequency map simply reports the simulated fire return interval (in years) and is calculated as the total number of simulation years divided by the total number of fires occurring in that cell. The fire frequency and fire severity data products are integrated to create a map of fire regime groups. These groups are intended to characterize the presumed historical fire regimes within landscapes based on interactions between vegetation dynamics, fire spread, fire effects, and spatial context (Hann *et al*. 2004). There are various definitions for fire regime groups (Hann and Bunnell 2001; Schmidt *et al*. 2002; National Interagency Fire Center 2007*c*). LANDFIRE refined the definition in the Interagency Fire Regime Condition Class Guidebook (Hann *et al*. 2004) to create discrete, mutually exclusive criteria appropriate for use with LANDFIRE's fire frequency and fire severity data products.

Characterizing existing reference conditions: succession class mapping

The LANDFIRE succession class (SClass) map represents the current successional state of vegetation as determined by integrating the LANDFIRE existing vegetation data products (existing vegetation type, cover, and height) with the defined successional composition and structure states in each vegetation dynamics model (Holsinger *et al*. 2006*b*; Long *et al*. 2006*a*). LANDFIRE SClass maps categorize current vegetation composition and structure as five successional states defined for each vegetation dynamics model. Two additional categories define uncharacteristic vegetation. Agriculture and urban areas are removed from analysis of vegetation departure. LANDFIRE SClass maps are similar in concept to those defined in the Interagency Fire Regime Condition Class Guidebook (www.frcc.gov).

Current conditions for each BpS are defined by from the SClass map by computing the percentage of each SClass category within each biophysical setting. Current conditions can then be compared with reference conditions computed at the same scale to obtain a measure of departure as described in the following section.

Fire Regime Condition Class and FRCC departure maps

Tabular vegetation reference conditions simulated using LANDSUM are aggregated to a spatial reporting unit defined for LANDFIRE by ecological subsections (Cleland *et al*. 2007). Although subsections may be composed of one or more distinct polygons, all LANDFIRE FRCC calculations are performed at the level of the entire subsection rather than for each individual polygon within it. It is important to note, however, that subsections may be subdivided by the LANDFIRE mapzone boundaries. In this case, the areas of a subsection in each zone are summarized individually because LANDFIRE data are processed on a mapzone-by-mapzone basis. The tabular simulation results from each simulation reporting unit are added to each subsection that occurs within the unit boundary.

The yearly percentages contained in each SClass in each BpS in each subsection are then summarized into a normalized median reference condition value for that SClass. A median is calculated from the vegetation time series for each SClass, and this value is normalized across succession classes within a given BpS to ensure that the reference conditions always total 100% of the area in that BpS. The area in each SClass in a given year is mutually exclusive of the other succession classes because a pixel can belong only to one SClass at a time. However, summary metrics applied to the time series of SClass areas are not guaranteed to be mutually exclusive. The normalized median for each SClass is the relative proportion of the raw median for that SClass compared with the sum of raw medians across all succession classes in a given BpS.

Current conditions are derived from spatial summaries of the LANDFIRE SClass layer using the BpS and landscape summary unit data layers. Agriculture, urban, and non-vegetated areas are excluded from calculations of current conditions and FRCC. The current condition of an SClass is the percentage of that SClass in the LANDFIRE within the total area of a given BpS in a given ecological subsection (Holsinger *et al*. 2006*b*).

The reference and current conditions for each BpS are compared in each subsection to calculate FRCC. Only vegetation conditions are used in LANDFIRE FRCC calculations; these calculations do not account for fire regime departure as described in the Interagency Fire Regime Condition Class Guidebook (Hann *et al*. 2004) because of a lack of comprehensive estimates of current fire regimes across the nation. This is important to note because FRCC analyses conducted for local assessments may be required to account for such fire regime departure. In this case, it would be necessary to define the 'current' fire regime (Hann *et al*. 2004).

Detailed methodologies for calculating FRCC may be found in Hann *et al*. (2004) and Holsinger *et al*. (2006*b*). First, similarity is calculated by totaling the smaller of the reference or current conditions for each SClass. This similarity is then subtracted from 100 to determine the departure value. This departure value is then assigned to every pixel in the BpS layer in the subsection to create the LANDFIRE FRCC Departure data product. This departure value is aggregated into the three condition classes to create the LANDFIRE FRCC data product, in which departure values between 0 and 33 are assigned to FRCC I, departure values between 34 and 66 are assigned to FRCC II, and departure values between 67 and 100 are assigned to FRCC III.

Surface and canopy fuel

The objectives of LANDFIRE fuel mapping were to provide fire managers with the data needed for both strategic and tactical planning for wildfire seasons and to support fire behaviour analysis on specific incidents. Both surface and canopy fuel had to be mapped so that they could be used in fire behaviour and fire effects predictive models. Because wildland fuel is highly variable and complex, many fire applications use classifications of fuel as inputs rather than using the actual amounts and configuration of wildland fuel that are measured in the field. Fuel classifications contain fuel units with representative fuel loading for a set of fuel components, and these fuel classes are often referred to as 'fuel models' or 'fire behaviour fuel models'.

To complicate matters, most fire behaviour simulation models require fuel models that are actually abstract representations of expected fire behaviour and therefore cannot be used to simulate fire effects (Anderson 1982; Finney 1998; Keane *et al*. 2001). Moreover, existing fire behaviour fuel models are quite broad and do not match the resolution needed to detect changes in fuel characteristics after fuel treatments (Anderson 1982). Because LANDFIRE design criteria specified that, with the implementation of the National Fire Plan, the LANDFIRE data products must be able to identify changes in hazardous fuel levels, a new set of fire behaviour fuel models and a new classification of fire effects fuel models were developed to ensure that the fuel layers could be used for local to regional assessments and analyses.

A new set of fire behaviour fuel models (FBFMs) was created by Scott and Burgan (2005) independently of (but concurrently with) the LANDFIRE effort. This suite of 40 models represents a significant improvement in detail and resolution over the FBFMs described by Anderson (1982). The new FBFMs were developed to be useful in widely used fire behaviour applications such as BEHAVE (Andrews 1986; Andrews and Bevins 1999) and FARSITE (Finney 1998). Each model has a complete description and includes analyses showing fire behaviour under different fuel moisture and weather conditions.

Surface fuel data products are mapped using a rule-based approach (Keane *et al*. 2001, 2006*a*). The rule-based approach was really the only technique available to map surface fuels for LANDFIRE for three main reasons. First, statistical modelling approaches could not be used because only a small fraction of the LFRDB contained information about wildland fuel characteristics. This meant that CART analysis techniques that were applied in other LANDFIRE mapping tasks could not be used because there were insufficient reference data to build the statistical functions for spatially predicting surface fuel models. This was especially true for the new fuel classification developed by Scott and Burgan (2005), because at the inception of LANDFIRE they had never been applied in the field. Second, there were no rule sets or field keys existing to enable consistent fuel model identification from field-referenced data, such as canopy cover, vegetation type, fuel loadings, and tree densities. It is difficult to objectively describe fuel conditions at a site using generalized fuel model classifications because fuel composition and condition are highly variable in space and time along with probable fire behaviour.

All surface fuel maps were created using similar classification protocols where a fuel model category was directly assigned to an ESP-EVT-EVC-EVH combination (Keane *et al*. 2006*a*). A rule set is a hierarchically nested set of rules that assigns fuel models to categories of LANDFIRE data layers using expert opinion and the LFRDB as the base information for rule set development. This approach allowed the inclusion of additional detail to categorical data by augmenting the ESP-EVT-EVC-EVH stratification with other biophysical and vegetation spatial data where needed. For example, a rule set might assign a specific FBFM to areas with a specific ESP-EVT-EVC-EVH combination on slopes greater than 50% with a specific vapor pressure deficit threshold defined by LANDFIRE biophysical gradient layers. Once draft rule sets and surface fuel data products were developed, they were reviewed and adjusted based on local expert opinion during regional review workshops (see www.landfire.gov for more information on these workshops). To account for areas where landscapes have experienced significant landscape change (e.g. wildland fires, land use, rapid succession), the LANDFIRE program will rely on updates (beginning in 2010) of fuel data products.

Most fire behaviour and effects applications require a quantification of several canopy characteristics to simulate crown fire initiation and propagation (Rothermel 1991; van Wagner 1993; Albini 1999). These characteristics include canopy bulk density, canopy height, canopy base height, and canopy cover. Canopy cover and height were developed as part of the existing vegetation mapping process (Zhu *et al*. 2006). Canopy bulk density and canopy base height were mapped by modelling these two canopy attributes from tree inventory information in the LFRDB using the Fuel Calculation system (*FuelCalc*) application (Reinhardt *et al*. 2006). This program uses tree measurements of species, height, and diameter to compute the vertical distribution of crown biomass from a set of biomass equations. The program also contains an algorithm that computes the canopy base height from the vertical distribution of crown biomass (Reinhardt *et al*. 2006). These two canopy characteristics are then mapped using a classification tree approach along with Landsat imagery and LANDFIRE biophysical gradient layers (Keane *et al*. 2006*a*). The canopy fuel data layers are then reviewed and adjusted based on local expert opinion during regional review workshops (see www.landfire.gov for more information on these workshops).

The LANDFIRE fuel data products have been incorporated into the Wildland Fire Decision Support System (WFDSS). This new system has been applied extensively during the 2006 and 2007 fire seasons (Fig. 3). WFDSS is a spatially explicit, web-based decision support application that facilitates tactical decisions during wildland fire events. The system comprises a set of models that determine the probability of individual wildfire spread and severity and the probability that fires will affect communities and infrastructure. The LANDFIRE fuel data products are the main inputs to the wildland fire simulations in WFDSS. The WFDSS project, when completed, will replace many of the applications used during the management and suppression of wildland fires in the United States (see https://wfdss.usgs.gov, accessed 22 April 2009). Scope includes re-engineering the existing Wildland Fire Situation Analysis (WFSA) and Wildland Fire Implementation Plan (WFIP) processes and supporting applications. For longer-term strategic planning, the LANDFIRE fuel data products are used in the Fire Program Analysis (FPA) application. FPA is a program that supports wildland planning, informs budget development and implementation, and identifies cost-effective wildland fire programs (www.fpa.nifc.gov, accessed 22 April 2009). In FPA, the LANDFIRE data products are used as inputs to fire probability simulations that evaluate initial response options, prevention options, and fuel treatment options to support decisions about the allocation of fire and fuel management resources across the United States.

Conclusion

As of November 2007, data products have been completed for 428 966 780 ha of the United States by the LANDFIRE project at

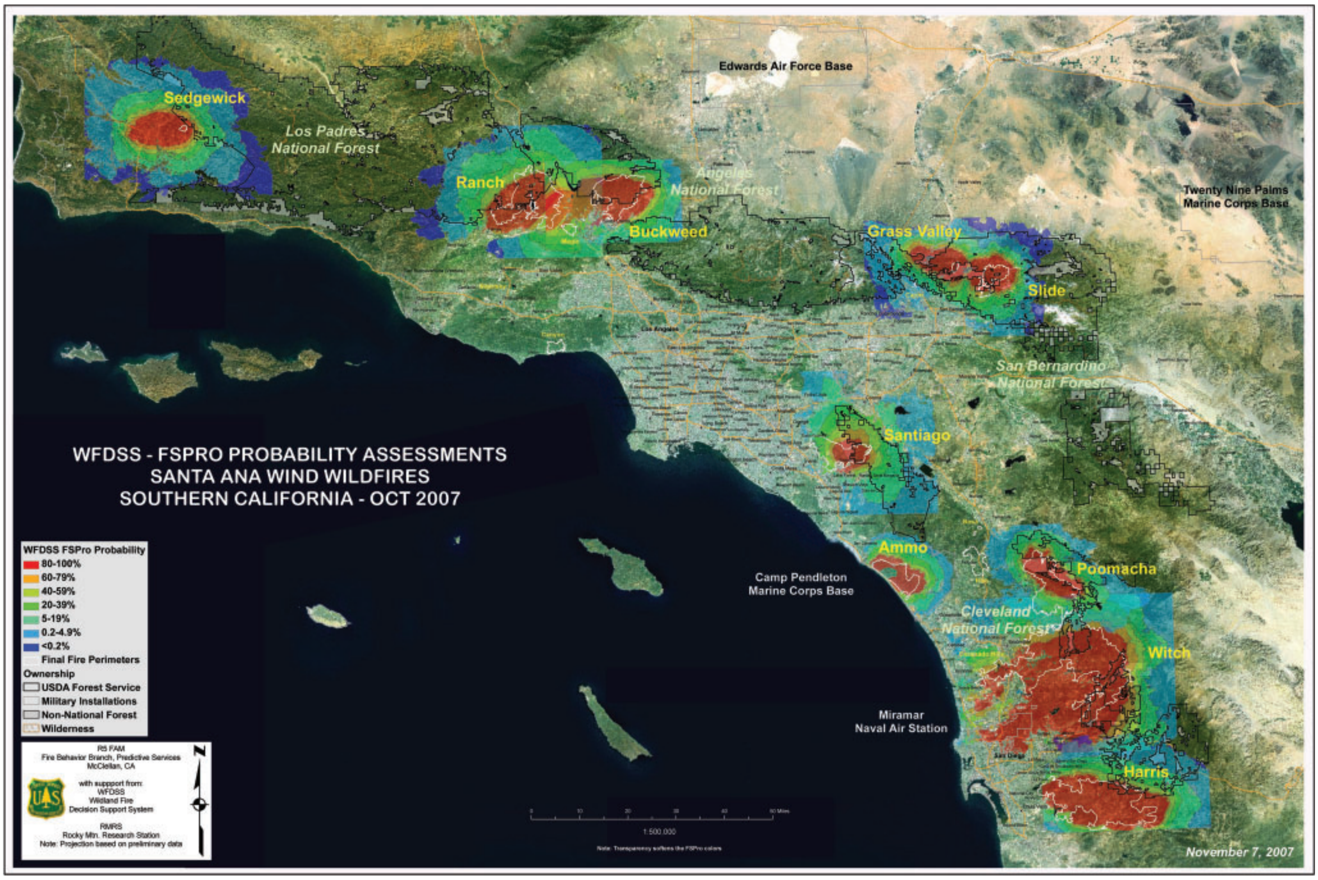

Fig. 3. Planning map prepared for wildland fire predictive services in southern California for several severe wildland fires in October 2007. The Wildland Fire Decision Support system was applied across the geographic area to predict where wildland fires were likely to spread under a scenario with continued Santa Ana winds from the north-east.

an approximate cost of US6 cents per hectare for all 24 geospatial data products. Over the last several years, LANDFIRE data products have been used in strategic and tactical wildfire management planning and numerous other applications from national forest plan revision to wildlife habitat mapping. The main strengths of the LANDFIRE project include:

- a standardized, open-source, repeatable method for developing consistent and comprehensive data products for wildland fire and natural resource management;
- comprehensive coverage across all administrative boundaries and ownerships;
- the use of field-referenced databases from a variety of existing government and non-government sources;
- the combination of remote sensing, ecosystem simulation, and biophysical gradient modelling to map existing and potential vegetation, wildland fuel, fire regimes, and fire regime condition class;
- a robust, straightforward, biophysically driven statistical approach;
- a multistep, qualitative and quantitative accuracy assessment;
- automation of individual LANDIFRE tasks and processing steps;
- a seamless, Geographic Information System (GIS)-based data product dissemination tool.

The comprehensive, consistent, and automated methods developed through the LANDFIRE project complement an integrated approach to wildland fire management and facilitate comparison of potential treatment areas using equivalent databases across the entire United States.

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