# Fuels Products of the LANDFIRE Project

**Matthew C. Reeves**[1], **Jay R. Kost**[2], **and Kevin C. Ryan**[3]

***Abstract***—*The LANDFIRE project is a collaborative interagency effort designed to provide seamless, nationally consistent, locally relevant geographic information systems (GIS) data layers depicting wildland fuels, vegetation and fire regime characteristics. The LANDFIRE project is the first of its kind and offers new opportunity for fire management and research activities. Here we introduce the LANDFIRE wildland fuels data layers including fire behavior fuel models, canopy bulk density, canopy base height, canopy cover, canopy height and new Fuel Loading Models. Specifically, we focus on the methods and data used to create these layers and present preliminary assessments. These key fuels layers will support fuels and smoke management and fire behavior modeling in addition to providing essential information for evaluating and managing wildland fires, seamlessly and consistently.*

## Introduction

Wildland fuels are critical elements in wildland fire planning and management activities. Wildland fuels are needed to parameterize consumption models, for example First Order Fire Effects Model (FOFEM) and fire behavior models such as NEXUS (Scott 1999), BehavePlus (Andrews 2003) and FARSITE (Finney 1998). These models can be used for two basic but critically important purposes; prioritizing fuel treatments and assessing fire behavior and effects in wildland fire suppression activities. Data to drive these models are lacking for most federal lands. These issues led the Wildland Fire Leadership Council, a group of senior administration executives representing all land management agencies in the country, to charter the LANDFIRE Project. The LANDFIRE project is currently mapping or developing geospatial data to meet the need for continuous, consistent, unbiased and scientifically produced fuels layers. In particular, LANDFIRE produces the fuels layers needed to run FARSITE including fire behavior fuel models, both the Anderson (1982) models (13 fire behavior fuel models) and the relatively newer Scott and Burgan (2005) set, canopy cover, canopy height, canopy bulk density and canopy base height. For fire effects analysis, a new set of Fuel Loading Models is being developed that focus on providing the necessary inputs to run FOFEM spatially. This paper explains methods and tools employed by LANDFIRE to map each of these fuel products.

---

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Fuels team leader and GIS specialist for the LANDFIRE program, Fire Sciences Lab, 5Missoula, MT, mreeves@fs.fed.us

[2] Senior Scientist at the USGS Center for Earth Resource Observation and Science (EROS), Science Applications International Corporation (SAIC), Technical Support Services at the USGS National Center for Earth Resources Observation & Science Sioux Falls, SD.

[3] LANDFIRE Program Manager, Fire Sciences Lab, Missoula, MT.

# Methods

## *Upstream Products*

The fuels layers rely on previously produced LANDFIRE layers and ancillary data (fig. 1) including existing vegetation type (EVT), canopy cover (CC), canopy height (CH), environmental site potential (ESP), Enhanced Thematic Mapper (ETM) imagery, digital elevation model (DEM) and associated derivatives and biophysical gradients. A brief explanation of these data is required so that the fuels mapping process can be discussed and understood with clarity.

**Reference Database**—The LANDFIRE reference database forms the foundation for nearly all LANDFIRE deliverables. It is used for developing training sites for imagery classification; validating and testing simulation models; developing vegetation classifications; creating empirical models; determining and archiving data layer attributes and; assessing the accuracy of maps and models (Caratti 2006). The reference database stores all relevant plot level information and provides the means to generate, test, and validate predictive models and LANDFIRE deliverables. Data have been received from a variety of sources in various forms, though the United States Forest Service has been the largest contributor with approximately 56,000 plots (~40% of the total). Roughly 140,000 plots have been archived in the

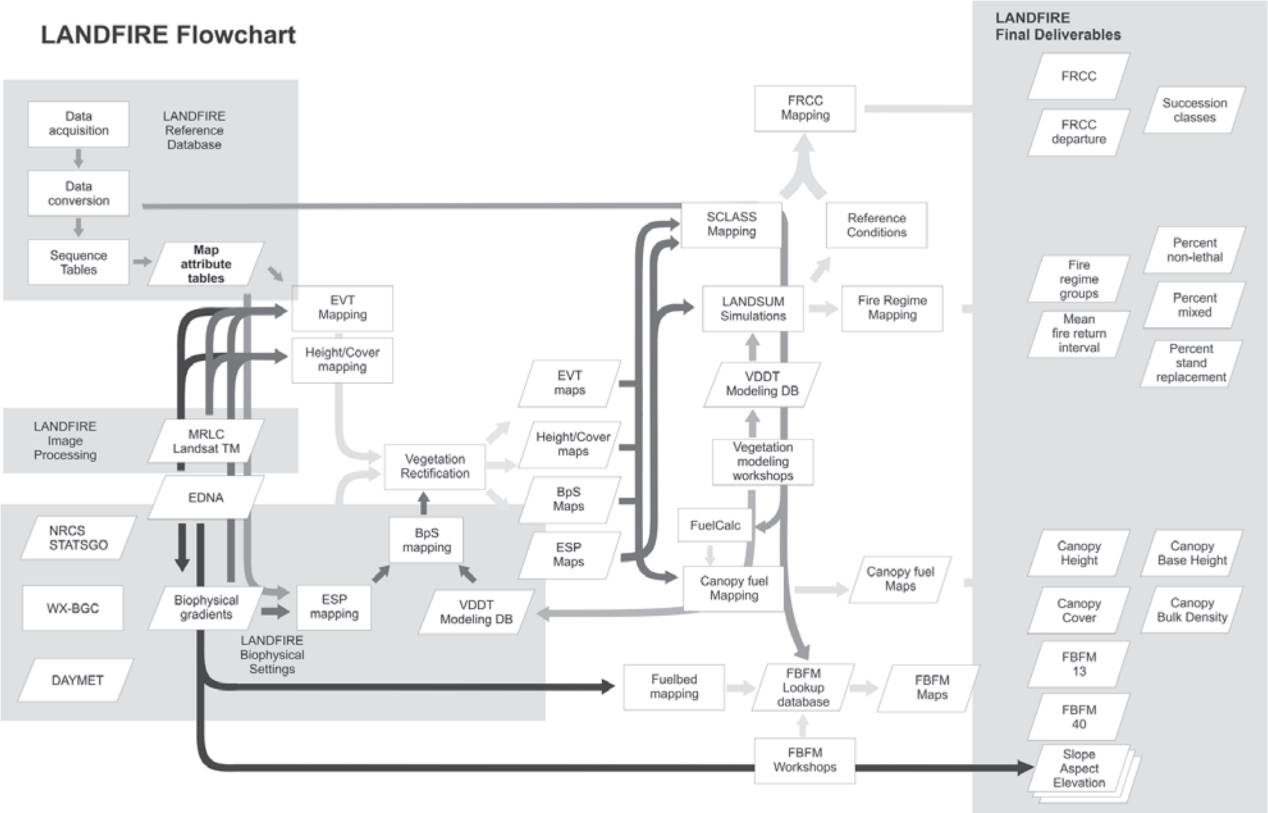

**Figure 1**—Flow of data, data processing and final products of the LANDFIRE project. Note the dependency of the fuels products on upstream LANDFIRE layers.

reference database for the first 16 mapping zones (fig. 2). Once each plot is converted to a common format, it is keyed to an existing vegetation type (EVT) and environmental site potential (ESP) using sequence table classifiers based solely on floristic composition. A main feature of the reference database for fuels mapping is the inclusion of a suite of predictor variables. These predictor variables form the basis for the landscape prediction models developed for mapping canopy fuels.

Predictor variables fall into one of four categories including; 1) imagery, 2) DEM and associated derivatives, 3) biophysical gradients, and 4) other LANDFIRE layers.

The LANDFIRE program uses the satellite imagery from the Multi-Resolution Land Characterization (MRLC) 2001 project (Homer and others 2004). This system divides the nation into separate mapping zones (fig. 2). There are two key elements resulting from this study that are used by LANDFIRE. First, the LANDFIRE project uses the same mapping zones as those created in the MRLC 2001 project. Second, LANDFIRE uses the satellite imagery that was painstakingly mosaicked for each zone for the conterminous U.S. The essential characteristics of this satellite imagery database are; 1) image dates (time of acquisition) range from 1999 – 2003; 2) imagery is supplied by the ETM sensor, and 3) each mapping zone has three sets of associated imagery including leaf-on, spring and leaf-off. A full description of these data is available in Zhu and others (2006).

The biophysical gradients are derived from WXBGC (Keane and others 2002), a modified version of the ecosystem simulation model, BiomeBGC (Running and Gower 1991; Thornton and others 2002). The meteorological data used to drive WXBGC come from the DAYMET meteorological database, which comprises interpolated surfaces of daily meteorology observations (Thornton and others 2002). In addition to these gradients, a suite of terrain variables such as DEM, slope and aspect are used.

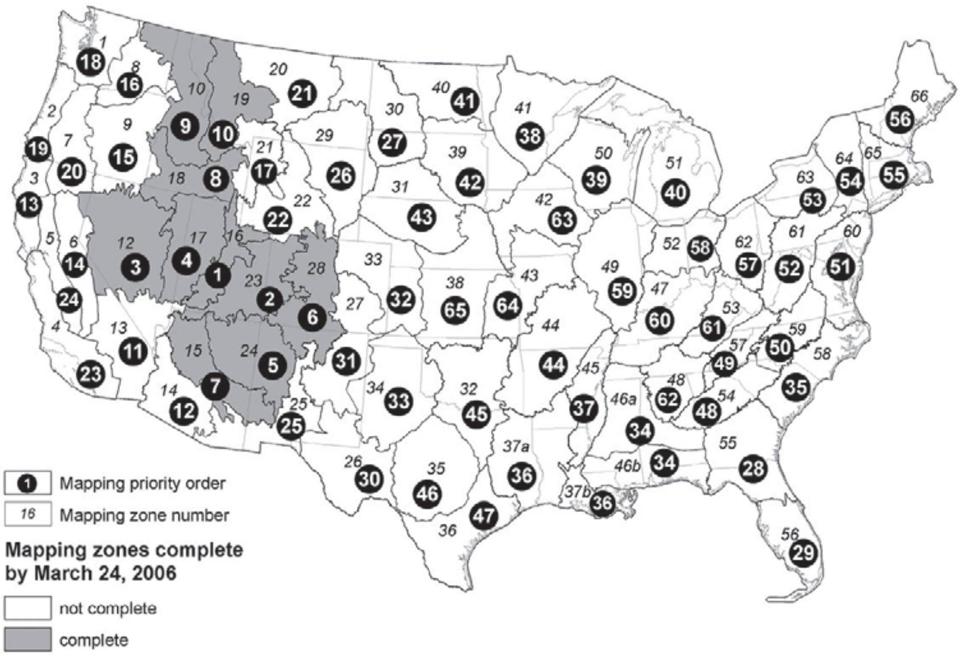

**Figure 2**—Multi-Resolution Land Characterization (MRLC) mapping zones used by LANDFIRE. Numbers in bold circles represent zones completed as of 5 April, 2006.

**Other LANDFIRE Layers**—The fuels mapping process relies extensively upon EVT, existing vegetation cover, height and, to a lesser degree, ESP. The EVT and associated structural attributes are produced by Earth Resources Observation Systems (EROS), a United States Geological Survey LANDFIRE partner, while ESP is created at the Missoula Fire Sciences Laboratory.

The EVT depicts the dominant Ecological System (Comer and others 2003) currently present at each 30 m pixel. Each field plot is assigned a life-form and ecological system class, and this information is then used to train decision tree models (Quinlan 1993) using imagery, topographic, and biophysical data (Zhu and others 2006).

Existing vegetation canopy cover, as defined in the LANDFIRE project, represents the average percentage of dominant life-form, non-overlapping canopy cover for each 30 m pixel. A life-form stratification is used to develop independent canopy cover for tree, shrub, and herbaceous life-forms. Canopy cover for the shrub and herbaceous life-forms is developed through use of field plot information in the reference database combined with imagery, topographic, and biophysical data to train regression tree models (Quinlan 1993), while tree canopy cover is developed by procedures employed for the National Land Cover Dataset (NLCD) effort (Homer and others 2004). The final existing vegetation cover dataset is comprised of nine, 10 percent incremental classes ranging from 10 to 100 percent.

Existing vegetation height represents the average height of the dominant life-form for each 30 m pixel. Field plot height measurements, in addition to Landsat imagery, topographic, and biophysical spatial data, are used to train decision tree models that predict existing vegetation height. Continuous tree, shrub, and herbaceous height field data are grouped into 3 to 5 discrete classes, depending on plot height ranges and data availability, prior to being modeled. Prior to dissemination on the National Map (http://nationalmap.gov [last visited 24 March, 2006]) as fuels layers, existing vegetation height and cover are converted to the canopy height (CH) and canopy cover (CC) products. These differ from the existing vegetation height and cover products because the thematic classes are converted to ordinal, biologically meaningful values so that they can be used directly in a fire behavior processor (Finney 1998; Scott 1999). In addition, the CH and CC products only represent cover and height of forested systems, as all herbaceous and shrub areas are coded as 0.

The environmental site potential (ESP) represents the vegetation that could be supported at a site based on the biophysical environment. Map units are named according to NatureServe's Ecological Systems classification (Comer and others 2003). As used in LANDFIRE, map unit names represent the natural plant communities that would become established at late or climax stages of successional development in the absence of disturbance. The ESP is similar in concept to other potential vegetation classifications in the western United States, including habitat types (for example, Daubenmire 1968; Pfister and others 1977).

## *Fuels Mapping*

**Fire Behavior Fuel Models**—Prior to creating maps of fire behavior fuel models (here referred to as FBFM), LANDFIRE fuelbeds are created using the spatial intersection of EVT/CC/CH/ESP. Every unique combination identified during this process is assigned a fire behavior fuel model. Use of these four variables for identifying fuelbeds is appropriate because it enables maps of fire behavior fuel models to be inferred from vegetation. Existing vegetation type yields information about the type of litter and ultimately, the vegetation that will most likely carry the fire. Canopy cover permits inference of the nature of the understory. For example, in more open canopy situations a greater preponderance of understory vegetation, such as shrubs and herbs is expected. Canopy height can further help the distinction between FBFM's. For example, a grass existing vegetation type will probably burn more like a fire behavior model 1 (Anderson 1982) if it is short, whereas if the grass is tall and dense, for example ≥ 1 m, it will likely be categorized as a FBFM 3 (Anderson 1982). The environmental site potential is infrequently used to distinguish relatively more xeric fuelbeds from those that are relatively more mesic.

Using this information, rules can be created that divide these ranges of possibilities into several categories for each EVT based on expected fire behavior. For example, the assumption can be made that there are two general kinds of fire behavior typically observed in a Great Basin pinyon-juniper environment. The first is a creeping fire with low flame length and rate of spread. This situation often occurs on relatively more dense stands with high canopy cover and low fuel moistures. The other type of fire behavior is more active, with higher rates of spread and flame lengths. This type of behavior is typically observed in relatively more open stands, in high winds, where herbaceous species are denser and shrubs such as sagebrush are interspersed with the larger pinyon pine and juniper.

With this logic, several rulesets can be derived from our example stand of pinyon-juniper (table 1). Each ruleset is subsequently assigned two fire behavior fuel models; one from Anderson (1982) and one from Scott and Burgan (2005). After these preliminary assignments are made they are refined and reviewed by local fire and fuel managers during fire behavior fuel model assignment workshops. After fuelbeds are reviewed, they are linked to a layer in a GIS and fuel model maps are created. After each fuel model map is created it goes through a separate cycle of review by local fire and fuel specialists with revision as appropriate. This second revision process differs from the assignment workshops because it focuses on the spatial expression of the rulesets created by experts during the assignment process. These workshops are a critical part of the LANDFIRE process because they permit collaboration between specialists, with knowledge about their area, and LANDFIRE scientists.

**Canopy Base Height and Bulk Density**—Canopy base height (CBH) is defined as the lowest point in the canopy at which there is sufficient available fuel for propagating the fire vertically, while canopy bulk density (CBD)

**Table 1**—Example LANDFIRE fuelbed assignments from a Great Basin Pinyon-Juniper Existing Vegetation Type. ESP is Environmental Site Potential.

| Fuelbed # | Cover (%) | Height (m) | ESP | FBFM13[1] | FBFM40 |
|---|---|---|---|---|---|
| 1 | 0 - 50 | Any | Xeric | 6 | SH1 |
| 2 | 0 - 50 | Any | Mesic | 2 | GS2 |
| 3 | 50 - 100 | ≥ 3 | Any | 8 | TL1 |
| 4 | 50 - 100 | ≤ 3 | Any | 6 | SH1 |

[1] FBFM13 and FBFM40 are fire behavior fuel models from Anderson (1982) and Scott and Burgan (2005) respectively.

refers to the mass of available canopy fuel per unit canopy volume (Scott and Reinhardt 2001). These canopy characteristics are most often used to determine expected crown fire activity for a stand or larger landscape.

The canopy fuels mapping process begins by attributing each plot with estimates of CBH and CBD. These canopy characteristics are computed using FuelCalc (Reinhardt and others 2006, this proceedings). The inputs required by FuelCalc include species, diameter at breast height (d.b.h), canopy height, height to live crown, crown class and trees per acre. These tree lists used as input to FuelCalc are simple attributes to collect but not often recorded in the field with the exception of the Forest Inventory and Analysis (FIA) program. Indeed, 84% of all plots used thus far in the LANDFIRE fuels mapping effort come from FIA data. The FIA data used for this effort range in date from 1978 to 2005, and therefore were obtained using different field methods and plot designs (Bechtold and Scott 2005).

These tree lists are ingested by FuelCalc and canopy biomass is computed by linking d.b.h. with total canopy biomass using species allometric equations. Using these equations, total crown biomass is computed and crown fuel is estimated to be that portion of the crown biomass that may be consumed by the flaming front of a passing fire (≤ 0.6 cm. [¼ in.] dia.). This fuel biomass is apportioned through the canopy of the stand according to the nature of the stand being investigated. From this CBD profile the maximum value is chosen to represent the stand. Likewise, the CBH is defined as the lowest layer in the canopy at which the CBD is ≥ 0.012 kg $m^{-3}$ (0.0007 lb $ft^{-3}$).

The goal of the canopy fuels mapping effort is to predict CBH and CBD across each LANDFIRE mapping zone by relating these attributes to the plethora of predictor variables available for each zone. These predictions derived in this manner are referred to as the FuelCalc — derived estimates of canopy characteristics. This distinction is significant to later discussions.

The statistical models used to spatially predict CBD and CBH are formulated using the commercially available regression tree, machine-learning algorithm, Cubist (© Rulequest Research 2004) (Quinlan 1993; Rulequest Research 2006). Cubist offers a fast, efficient and relatively accurate approach for building regression tree models that can be applied to large areas (Huang and others 2001; Xian and others 2002). Other salient features of Cubist are discussed in Zhu and others (2006) and Keane and others (2006).

The CBH and CBD regression tree models are evaluated using a 10-fold cross validation procedure (Shao 1993). Different combinations of variables are tested until a consistently low cross validation error rate is observed. Once a suitable regression tree model has been formulated, it is applied spatially using a suite of tools developed in support of the NLCD project (Homer and others 2004; Vogelman and others 2001). These tools were specifically designed to integrate and interpret regression trees formulated using Cubist with the ERDAS Imagine image processing system (Erdas Imagine 2006) (© ERDAS, Inc. 2001).

The landscape predictions of CBH and CBD are then subsequently qualitatively and quantitatively evaluated. Quantitative evaluations include comparisons of CBD with the LANDFIRE canopy cover and satellite imagery. Canopy bulk density is strongly related to canopy cover (fig. 3). Thus, logical relationships between canopy bulk density and canopy cover should be observed in the LANDFIRE products. To evaluate these relationships, zonal statistics are performed such that the mean CBD is computed for each canopy cover class. In a similar manner CBH is evaluated against canopy height for each mapping zone.

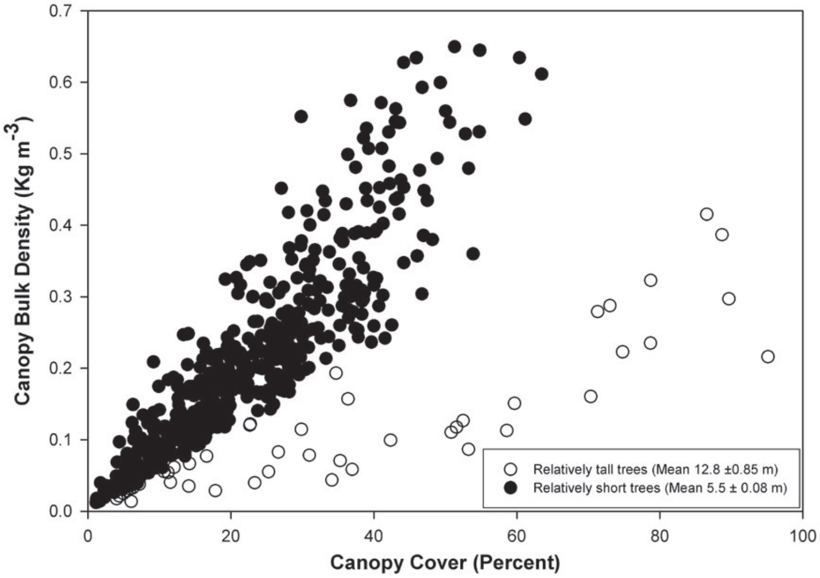

**Figure 3**—Relationship between estimated canopy bulk density (kg $m^{-3}$) and canopy cover (percent) from FuelCalc for Mapping Zone 12. Black dots represent relatively short trees (average of 5.5 m with standard error of ± 0.08 m) (usually *Juniperus* spp.), while open circles represent relatively taller trees (average of 12.8 m with standard error of ± 0.85 m).

Other quantitative methods of evaluating the canopy fuel products include comparisons between the frequency of CBH and CBD from the plot data with that of the predicted values in each layer. One might expect a consistent pattern in the numerical distribution between plot and image data, provided that the field plots sufficiently cover the range of variability observed in a mapping zone. For example, if 50 percent of the field plots fell below a bulk density 0.12 kg $m^{-3}$, then a similar finding in the predicted values for a mapping zone would be expected.

These quantitative methods are combined with extensive visual inspections for obvious errors. While not statistically rigorous, these methods yield valuable guidance and insight as to the appropriate predictor variables and subsequent regression tree formulations that should be used. As a result of these processes, a predictive regression tree model may undergo significant revision for a mapping zone prior to completion of the final product.

**Identifying and Filling Areas of Snow, Cloud and Shadow**—Although the MRLC project carefully selected scenes of imagery to eliminate clouds, there are still a few small areas where it was not possible to get a totally cloud free scene. Areas contaminated by snow, cloud and shadow are identified in each mapping zone using maximum likelihood supervised classification techniques implemented in Erdas Imagine. Any pixel in a mapping zone dominated by snow, clouds or shadow will be filled using one of two values. These "fill" values are generated using plot data by computing mean CBH and CBD for each EVT/ESP (Stage 1) and EVT (Stage 2) combination. The "filling" process occurs in two stages. Stage 1 filling draws from the database of mean CBH and CBD for each EVT/ESP combination. Use of Stage 1 filling is preferable because it maintains more spatial heterogeneity than the stage 2 filling. However, it is not always possible to use Stage 1 filling because not every EVT/ESP combination on the landscape has plot data with which to compute a mean CBH or CBD. In these instances, the simpler, mean CBH or CBD by EVT is used. Finally, if there is an EVT found in a mapping zone for which there are no plot data to compute a mean CBH or CBD, then the prediction is not altered from its original state (as computed using regression tree formulae) regardless of the error associated with that prediction.

**Obtaining Canopy Base Height From an Expert System**—Canopy base height is used to aid in predicting surface to crown fire transition. Thus, it is a critical parameter for accurate simulation of crown fire activity. For maximum effectiveness, however, canopy fuels should not be developed independently of surface fuels or illogical combinations might occur (Keane and others 2001). In recognition of the need to convolve CBH estimates with each LANDFIRE fuelbed, an expert system was developed to crosswalk these entities to permit crown fire simulation.

To accomplish this task a series of fire behavior and fire management experts were asked to estimate conditions under which each appropriate LANDFIRE fuelbed would transition from a surface to a crown fire. The expert panel was shown a picture and a description of each fuelbed and then asked to identify specific environmental criteria under which, in their experience, they had observed transitions from surface to crown fire. These fuelbeds combined with the environmental criteria obtained from the experts were fed into a spreadsheet analysis system with the appropriate functions from FARSITE (Finney 1998) programmed into it. The necessary CBH to permit passive crown fire was computed from this analytical spreadsheet. This dataset is separate from the FuelCalc — derived estimates of CBH described above. Indeed, these expert system canopy base height estimates are specifically designed to be used with LANDFIRE data in fire behavior processors and should not be construed as biologically relevant predictions of CBH across the landscape. Instead, this CBH layer simply represents a model parameter that is estimated in the context of each LANDFIRE fuelbed.

**Fuel Loading Models**—The Fuel Loading Models (FLM) represent a unique surface fuels classification that incorporates the variability of fuel loading within and across fuel components. The model classification uses surface components including fine and coarse woody debris (FWD ≤ 7.62 cm [3 in.] and CWD ≥ 7.62 cm respectively), duff and litter. Fuel loading models were created using four generalized steps: 1) collection of fuels data, 2) compute fire effects from fuels data, 3) cluster fire effects predictions into "Effects Groups" (EG), and 4) classify effects groups to create FLM's. Roughly 4,000 plots were used to create these FLM's spanning a large geographic range.

Using these plots, fire effects were estimated using the First Order Fire Effects Model (FOFEM) (Keane and others 1994; Reinhardt and others 1997). Each fuels plot was subsequently clustered into one of ten effects groups based on total $PM_{2.5}$ emissions and maximum surface soil heating (fig. 4). Classification tree analysis was then used to build a rule set to predict each of these effects groups based on FWD, CWD and duff and litter. These FLM's will eventually be spatially mapped through vicarious linkages with vegetation and fuels attributes from the LANDFIRE project. These mapped FLM's will contain the necessary data to parameterize fire effects models such as FOFEM in a spatial manner.

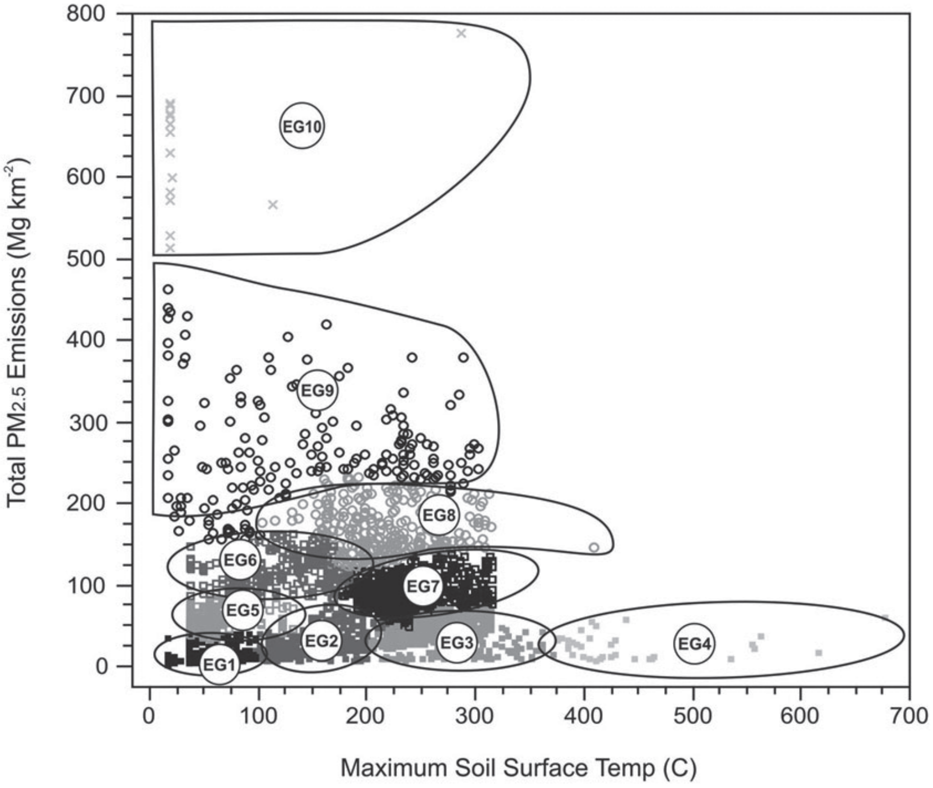

**Figure 4**—Ten effects groups ordinated by $PM_{2.5}$ (Mg $km^{-3}$) emissions and maximum soil surface temperature (C).

# Discussion

## *Fire Behavior Fuel Models*

Approximately 130 fire behavior and fuels specialists have participated in the LANDFIRE fire behavior fuel model assignment and calibration workshops. This has greatly increased the efficacy of the FBFM layers. For example, a common problem identified with the LANDFIRE FBFM layers is the lack of grass models resulting from invasion by *Bromus* spp. (for example, cheatgrass). As a result, we implemented a procedure, which resulted in millions of acres being updated to grass models due to the preponderance of *Bromus* spp. These and other changes have updated LANDFIRE layers to represent local conditions as near as possible given the constraints of mapping consistency and objectivity. It is notable that the LANDFIRE EVT mapping process is not refined enough to detect stands that have been minimally thinned, which result in accumulation of slash. Thus, it is rare to observe any of the slash models in LANDFIRE data, with one exception. Slash models have been assigned to some LANDFIRE fuelbeds in the southwestern United States. Some stands in this region are late successional decedent stands of *Abies concolor* (white fir) where very high fuel loads (> 60 tons $acre^{-1}$) of coarse woody debris are observed and blowdown can be several meters thick. The fire and fuel specialists in these areas felt that the fire behavior under these conditions could only be described by slash models, but these situations are relatively rare.

**Canopy Base Height and Bulk Density**—Examples of the relationships developed during the canopy fuels regression tree analysis are shown in figures 5 and 6. Figures 5 and 6 indicate CBD estimates above 0.4 and CBH estimates above approximately 6 meters are probably not reliable. In general there are not enough plots with large values of CBD or CBH to make a reliable and stable regression tree above these values.

There is an inverse relationship between canopy cover and bulk density in some mapping zones but only in areas of extremely high CC. This nonlinear relationship typically only occurs in stands with relatively high CH. This follows the pattern observed in the plot level estimates of CBD and CC (fig. 3). Figure 3 clearly shows two distinct relationships between CBD and CC; one for tall trees and one for short trees.

In comparison to CBD, CBH is more difficult to interpret, map and identify using field based reconnaissance. This is because CBH is more abstract and is not a definitively measurable feature of a stand. Thus, few techniques exist that can be used to asses the true accuracy of these estimates in LANDFIRE data. This is one primary reason for creating the expert system derived CBH estimates. Examples of these expert system estimates are shown in table 2.

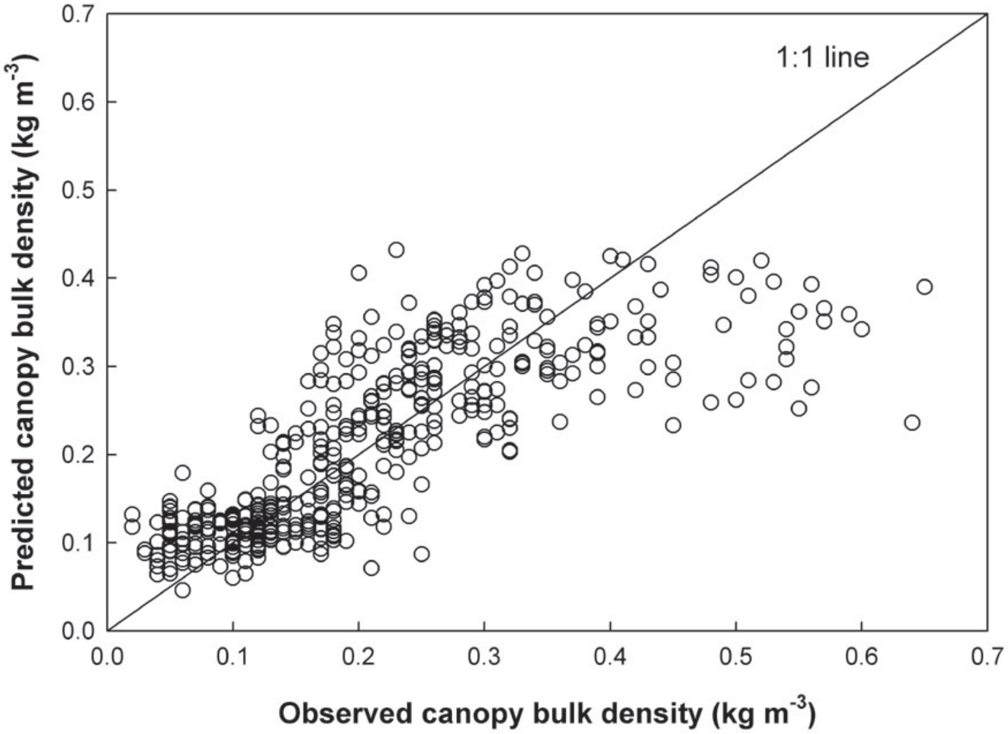

**Figure 5**—Predicted and observed canopy bulk density (kg m$^{-3}$) resulting from a regression tree analysis for Mapping Zone 12. Note the asymptotic feature beginning at approximately 0.4 kg m$^{-3}$.

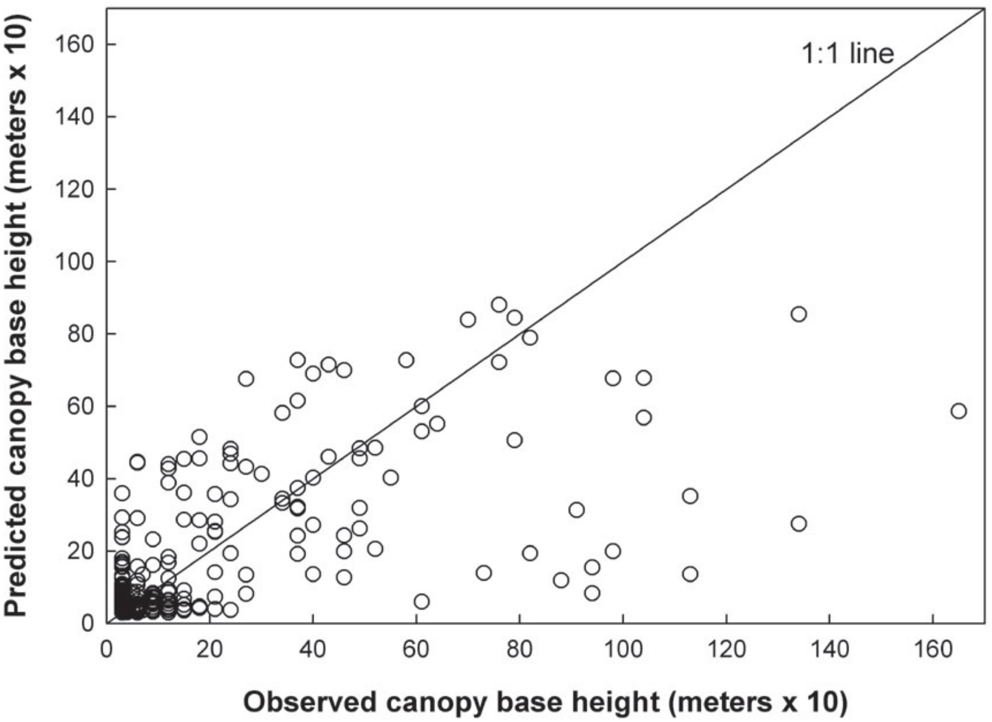

**Figure 6**—Predicted and observed canopy base height (m) resulting from a regression tree analysis for Mapping Zone 23. Predictions above approximately 6.0 meters are unreliable.

**Table 2**—Canopy base heights computed using an analytical spreadsheet informed through an expert system. Note that each fuelbed has both Anderson (1982) (FBFM13) and Scott and Burgan (2005) (FBFM40) fuel models. The environmental criteria for this analysis are as follows: fine dead fuel moistures (1,10 and 100 hr time lag fuels) are 4,5 and 6% moisture content respectively; 20 ft. wind speed was estimated as 20 mph.

| EVT | Cover | Ht | ESP[1] | FBFM13 | FBFM40 | CBH13[2] | CBH40[3] |
|---|---|---|---|---|---|---|---|
| | *(%)* | *(m)* | | | | - - - - - - *(m)*- - - - - - | |
| Northern Rocky Mountain Ponderosa Pine Woodland and Savannah | | | | | | | |
| | ≥50 | ≥ 5 | Any | 9 | TU5 | 0.29 | .71 |
| | < 50 | ≥ 5 | Any | 2 | TU3 | 0.075 | 2.33 |
| | Any | < 5 | Any | 6 | GS2 | N/A | N/A |
| Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland | | | | | | | |
| | ≥ 50 | ≥ 5 | Any | 10 | TU5 | 0.34 | 1 |
| | 30 - 49 | ≥ 5 | Any | 8 | TU1 | 0.25 | 0.23 |
| | < 30 | < 5 | Any | 5 | SH4 | N/A | N/A |

[1] ESP is Environmental Site Potential.

[2] Canopy base heights formulated using the Anderson (1982) fuel model.

[3] Canopy base heights formulated using the Scott and Burgan (2005) fuel model.

### *Use and Limitations of LANDFIRE Fuels Data*

The LANDFIRE fuels data layers can be used for applications at varying scales, including project level planning (for example, < 5000 acres), particularly when higher resolution data are lacking. These data are particularly well suited for comparative analyses within and between regions. Thus, it is the responsibility of the user to determine the appropriate scale and usefulness of LANDFIRE fuels data. These fuels layers span all ownerships, a trait not likely to be found in other fuels data sets. These layers are expected to form the baseline data for interagency planning, while local datasets, which cost more and take longer to produce can be used in place of, or in addition to, LANDFIRE data. However, because of their objective and comprehensive nature LANDFIRE data can be used efficiently for such activities as strategic fuels reduction plans, tactical fire behavior assessment and estimating fire effects. These fuels data are the first of their kind because they will seamlessly cover the nation. Any project with this scope will have tradeoffs between quantity and quality. As a result, there is a need for further research for improving the quality of these layers and for assessing their true efficacy. To meet this need we recommend cohesive, scientific, interagency assessments of LANDFIRE fuels data.

## Summary

This paper provides a general overview of the LANDFIRE fuels mapping procedures and highlights their interdependency on multiple data sources including other LANDFIRE layers. Fire behavior fuel models are linked with vegetation type and structural attributes based on rulesets devised by local fire and fuel experts. In turn, the spatial expression of these rulesets is evaluated and critiqued in a series of local calibration efforts. Canopy fuels are mapped using predictive landscape modeling by relating a multitude of predictor variables to CBH and CBD in regression trees. These regression trees are subsequently applied across the landscape. Given the nebulous nature of CBH and the dependence on this variable by fire behavior processors, we have devised a strategy to map canopy base height across the landscape using an expert system approach. At national and regional scales LANDFIRE will provide valuable insight for modelers, fire scientists and managers. Finally, we recognize the need for cohesive efforts to assess the efficacy of all LANDFIRE fuels data and hope to initiate this process in the future.

## Acknowledgments

We acknowledge Robert E. Keane, Mark A. Finney, Charles McHugh, and Joe Scott for their thoughtful contributions to LANDFIRE methods. A large national project could not succeed without a business management team. We therefore also acknowledge Henry Bastian, Daniel Crittenden, Bruce Jeske, and Timothy Melchert for their professional business support. Finally, we wish to thank the participants of the various fuels workshops. Their local expertise has dramatically improved the LANDFIRE fuels layers.

# Literature Cited

Anderson, H. 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report GTR INT-122. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Andrews, P.L., and C.D., B. 2003. BehavePlus fire modeling system, version 2.0: overview. Proceedings of the Second International Wildland Fire Ecology and Fire Management Congress and Fifth Symposium on Fire and Forest Meteorology. November 16-20, 2003. Orlando, FL: American Meteorological Society. pp. 5-11.

Bechtold, W.A., and Scott, C.T. 2005. The forest inventory and analysis plot design. In: Bechtold, W.A.; Patterson, P.L., eds. The enhanced forest inventory and analysis program — national sampling design and estimation procedures. General Technical Report GTR - SRS80. U.S. Department of Agriculture, Forest Service, Southern Research Station: Asheville, N.C.

Caratti, J.F. 2006. In press. The LANDFIRE Reference Database. In: The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data and tools for wildland fire management. General Technical Report RMRS-GTR-XXX. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Comer, P., Faber-Langendoen, D., Evans, R., Gawler, S., Josse, C., Kittel, G., Menard, S., Pyne, M., Reid, M., Schulz, K., Snow, K., and Teague, J. 2003. Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems. Arlington, VA.

Daubenmire, R. 1968. A textbook of plant synecology. Harper and Row, New York, New York.

Erdas Imagine 2006. http://gis.leica-geosystems.com/default.aspx. Last Visited 22 March, 2006.

Finney, M.A. 1998. FARSITE: Fire area simulator. — model development and evaluation. RMRS-RP-4. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Homer, C., Huang, C., Yang, L., Wylie, B., and Coan, M. 2004. Development of a 2001 National Land-Cover Database for the United States. Photogrammetric Engineering & Remote Sensing 70:829-840.

Huang, C., Yang, L., and Wylie, B.C. 2001. A Strategy for Estimating Tree Canopy Density Using Landsat 7 ETM+ and High Resolution Images Over Large Areas. Third International Conference on Geospatial Information in Agriculture and Forestry:CD-ROM. Disk 1.

Keane, R.E., Reinhardt, E.D., and Brown, J.K. 1994. FOFEM — A first order fire effects model for predicting the immediate consequences of wildland fire in the United States. In: Proceedings of the 12th Conference of Fire and Forest Meteorology: 628-632.

Keane, R.E., Burgan, R., and Wagtendonk, J.V. 2001. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. International Journal of Wildland Fire 10:301-319.

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

Keane, R.E., Reinhardt, E.D., Scott, J., Gray, K., and Reardon, J. 2005. Estimating forest canopy bulk density using six indirect methods. Canadian Journal of Forest Research 35:724-739.

Pfister, R.D., Kovalchik, B.L., Arno, S.F., and Presby, R.C. 1977. Forest Habitat-types of Montana. General Technical Report. GTR-INT-34. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Quinlan, J.R. 1993. Combining instance-based and mode-based learning. 10th International conference on machine learning. Amherst MD:236-243.

Reinhardt, E.D., Keane, R.E., and Brown, J.K. 1997. First Order Fire Effects Model: FOFEM 4.0 Users's Guide. General Technical Report. INT-GTR-344. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Rulequest Research. 2006. Data mining tools. http://www.rulequest.com/ [Online] (verified 22 March, 2006).

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

Scott, J.H. 1999. NEXUS: A System for Assessing Crown Fire Hazard. Fire Management Notes (2) 59:20-24.

Scott, J.H., and Burgan, R.E. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Shao, J. 1993. Linear model selection by cross-validation. Journal of the American Statistical Association 88:486-484.

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

Vogelman, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and Van Driel, J.N. 2001. Completion of the 1990's National Land Cover Data Set for the conterminous United States. Photogrammetric Engineering & Remote Sensing 67:650-662.

Xian, G.K., Zhu, Z., Hoppus, M., and Flemming., M. 2002. Application of decision tree techniques to forest group and basal area mapping using satellite imagery and forest inventory data. I/FIEOS Conference, Pecora 15/Land Satellite information IV/ISPRS Commision.

Zhu, Z., Ohlen, D., Kost, J., Chen, X., and Tolk, B. 2006. In press. Mapping existing vegetation composition and structure for the LANDFIRE Prototype project. In: The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data and tools for wildland fire management. General Technical Report RMRS-GTR-XXX. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.