Modeling on the Grand Scale: LANDFIRE Lessons Learned

Kori Blankenship, Jim Smith, Randy Swaty, Ayn J. Shlisky, Jeannie Patton, and Sarah Hagen

Authors

Kori Blankenship is a fire ecologist, The Nature Conservancy, Bend, OR, kblankenship@tnc.org. **Jim Smith** is a LANDFIRE project lead, The Nature Conservancy, Jacksonville, FL, jim_smith@tnc.org. **Randy Swaty** is an ecologist, The Nature Conservancy, 101 S. Front St, Marquette, MI 49855, rswaty@tnc.org. **Ayn J. Shlisky** is a regional forest planning analyst, Pacific Northwest Region, USDA Forest Service, 333 SW First Ave., Portland, OR 97204, ajshlisky@fs.fed.us. **Jeannie Patton** is a program coordinator, The Nature Conservancy, 2424 Spruce St., Boulder, CO 80302, jpatton@tnc.org. S**arah Hagen** is a GIS analyst, The Nature Conservancy, 1101 West River Parkway, Suite 200, Minneapolis, MN 554, shagen@tnc.org.

Abstract

Between 2004 and 2009, the LANDFIRE project facilitated the creation of approximately 1,200 unique state-and-transition models (STMs) for all major ecosystems in the United States. The primary goal of the modeling effort was to create a consistent and comprehensive set of STMs describing reference conditions and to inform the mapping of a subset of LANDFIRE's spatial products. STMs were created by more than 700 experts through a series of modeling workshops, individual meetings and web conferences hosted around the country. While model- building speed, efficiency and consistency may have been enhanced by using a small group of project employees to develop STMs, our participatory approach to model development encouraged early engagement in the LANDFIRE project as a whole, helped to incorporate a broad spectrum of knowledge into the STMs and built modeling capacity. The depth and breadth of the LANDFIRE modeling effort provides an opportunity to learn about expert-based modeling efforts. In this paper we reflect on that effort and, based on our collective experience facilitating the development of the LANDFIRE STMs, we offer 10 lessons learned: (1) create a flexible modeling process, (2) incorporate a learn-by-doing method, but know that it takes work, (3) engage a broad spectrum of experts from the start, (4) agree on what is being modeled, (5) implement procedures to maintain quality control, (6) if possible, build from existing models, (7) thoroughly document results, (8) never forget the modeling purpose, (9) set realistic modeling goals, and (10) model to document known ecological information and identify gaps in understanding. In this paper, we discuss these lessons in detail and offer observations and examples from our experience to help others efficiently build more useful models for land management and planning efforts in the future.

Keywords: pre-settlement, vegetation ecology, vegetation dynamics, state-and-transition model, LANDFIRE, experts, VDDT, Vegetation Condition Class.

Introduction and Background

Between 2004 and 2009, the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE; http://www.landfire.gov) developed state-and-transition models (STMs) for all major Ecological Systems (Comer et al. 2003) in the United States through an expert-based model development process (Rollins 2009). LANDFIRE (now the LANDFIRE Program) is a shared program between the U.S. Department of Agriculture Forest Service and the U.S. Department of the Interior that is chartered to develop a suite of more than 20 vegetation, fire and fuel related products (table 1) that support fire and land management activities at regional and national levels. The datasets were created using consistent methods and cover all lands, public and private, in the United States (Rollins 2009).

LANDFIRE developed STMs to estimate pre-settlement reference conditions and to inform the mapping of a subset of its spatial products (table 1). Pre-settlement reference conditions as applied in LANDFIRE refer to the estimated percent of the landscape within given seral stages for

Table 1—LANDFIRE created and is continually updating its suite of more than 20 related fuel, vegetation and fire regime products. The STMs (called Vegetation Dynamics Models) are used directly and indirectly to create a subset of the spatial products

Fuel products	Vegetation products	Fire regime products
13 fire behavior fuel models[a]	Existing vegetation type[a]	Fire regime groups[b]
40 fire behavior fuel models[a]	Existing vegetation cover	Mean fire return interval[b]
Canadian forest fire danger rating system	Existing vegetation height	Percent low-severity fire[b]
Fuel characteristic classification system fuelbeds	Biophysical settings[a]	Percent mixed-severity fire[b]
Fuel loading models	Vegetation dynamics models	Percent replacement-severity fire[b]
Forest canopy cover	Environmental site potential	Vegetation condition class[b,c]
Forest canopy height		Vegetation departure[b,d]
Forest canopy bulk density		Succession classes[e]
Forest canopy base height		

[a] Products that were developed using STMs and associated description documents as an ancillary data source.
[b] Products that were generated directly by STMs in all versions of LANDFIRE except LANDFIRE National where they were used as inputs to the LANDSUM model (Keane et al. 2006) which generated these products.
[c] Vegetation Condition Class was formerly called Fire Regime Condition Class.
[d] Vegetation Departure was formerly called Fire Regime Condition Class Departure Index.
[e] Product that was generated using rule sets in the STM description document.

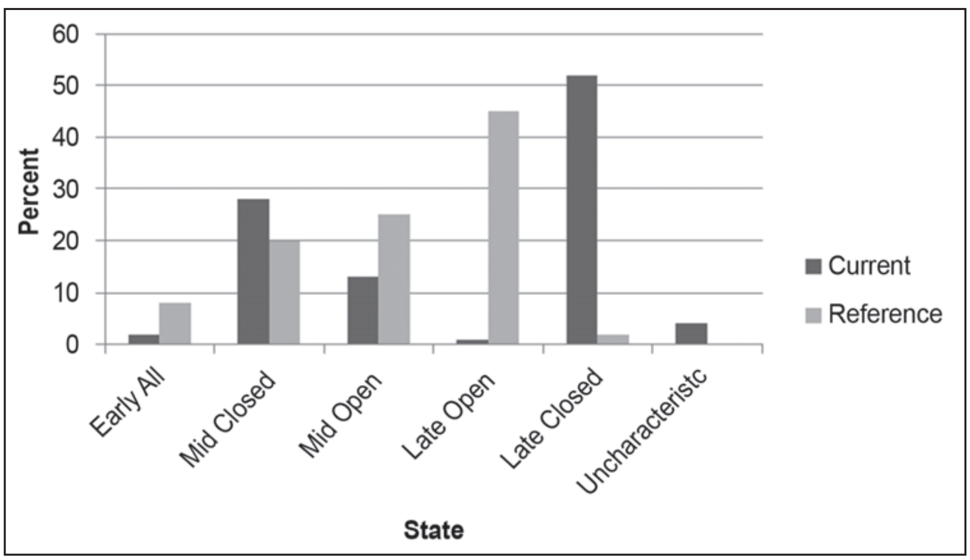


Figure 1—The primary use of STMs by LANDFIRE was to compare reference and current conditions to calculate Vegetation Condition Class. This example compares reference conditions estimated from the Ozark-Ouachita Dry Oak Woodland STM (LANDFIRE 2012a) to current conditions (LANDFIRE 2012b) in Map Zone 44—Ozark and Ouachita Mountains.

an ecosystem that would have occurred prior to European settlement. The reference period included both the influence of Native Americans (e.g., use of fire) throughout much of the continental U.S. and the influence of Polynesian settlers (e.g., agriculture) in the Hawaiian Islands. The primary use of the STM generated reference conditions by LANDFIRE was to calculate Vegetation Condition Class (formerly referred to as Fire Regime Condition Class or FRCC; Barrett et al. 2010), a metric which quantifies the difference in vegetation cover, height and type between reference and current conditions (fig. 1). The model documentation and model outputs for the reference scenario were also used directly to provide mapping rule sets for developing the Fire Regime Group, Succession Class, Fire Frequency and Fire Severity spatial layers and as an ancillary data source for mapping Biophysical Settings, Existing Vegetation Type and Fire Behavior Fuel Models (Rollins 2009; table 1).

The primary objective of the LANDFIRE modeling effort was to create a consistent and comprehensive set of STMs describing reference conditions for every ecosystem mapped by LANDFIRE. In addition, we wanted to:

- create a STM library as a foundation for future modeling efforts,
- develop a sense of buy-in and ownership by the community of potential LANDFIRE data users,
- train participants in the concepts and applications of STMs, and
- provide a forum for scientific and land management networking.

These objectives guided the model development process and modeling rules. The process we implemented served to market the LANDFIRE project as a whole, taking it from a top, own effort that delivered maps and models built by a small team of project employees to a participatory effort where user input was incorporated directly to build a subset of the products. While the former approach would probably have led to greater consistency in the STMs, it would have likely compromised training, outreach and networking objectives.

Each LANDFIRE STM represents a single ecosystem called a Biophysical Setting (BpS). A BpS is a vegetation concept mapped by LANDFIRE, based on the Ecological Systems classification (Comer et al. 2003), which represents the potential vegetation community that could exist on the landscape given the current biophysical environment (e.g. soils and precipitation) and an approximation of the historical disturbance regime (e.g. fire return interval and flooding frequency). A LANDFIRE STM consists of two related parts (fig. 2):

1. a quantitative state-and-transition model developed with the Vegetation Dynamics Development Tool (VDDT; ESSA Technologies Ltd. 2007) and
2. a description document developed in the Model Tracker Database (MTDB).

VDDT was used to attribute each state within a BpS with an age range and probabilities for deterministic (i.e. succession) and probabilistic (i.e. disturbance) transitions. VDDT was then run for 1,000 years to estimate reference conditions (i.e. the percent of the landscape in each state) and the frequency of fire and other disturbances. VDDT was chosen as the modeling platform by LANDFIRE because it is in the public domain, relatively user-friendly, compatible with related spatial models and capable of running multiple iterations quickly. VDDT is also supported by some federal and state agencies as a land management planning tool.

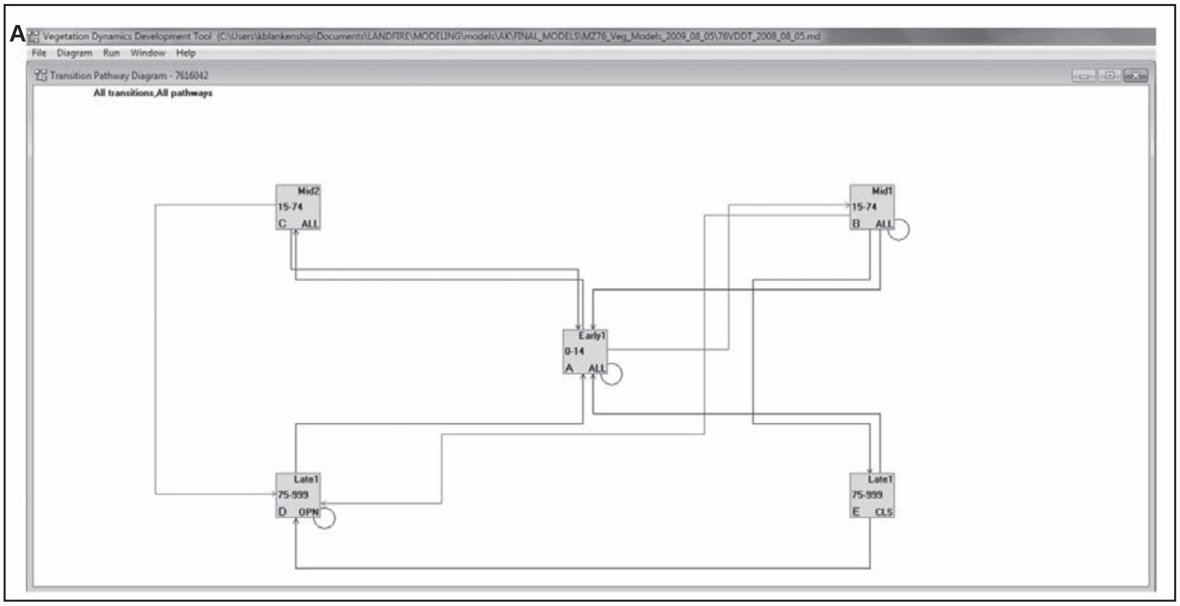
MTDB is a Microsoft Access database designed by LANDFIRE to document model development (fig. 3). The database was used by modelers to record:

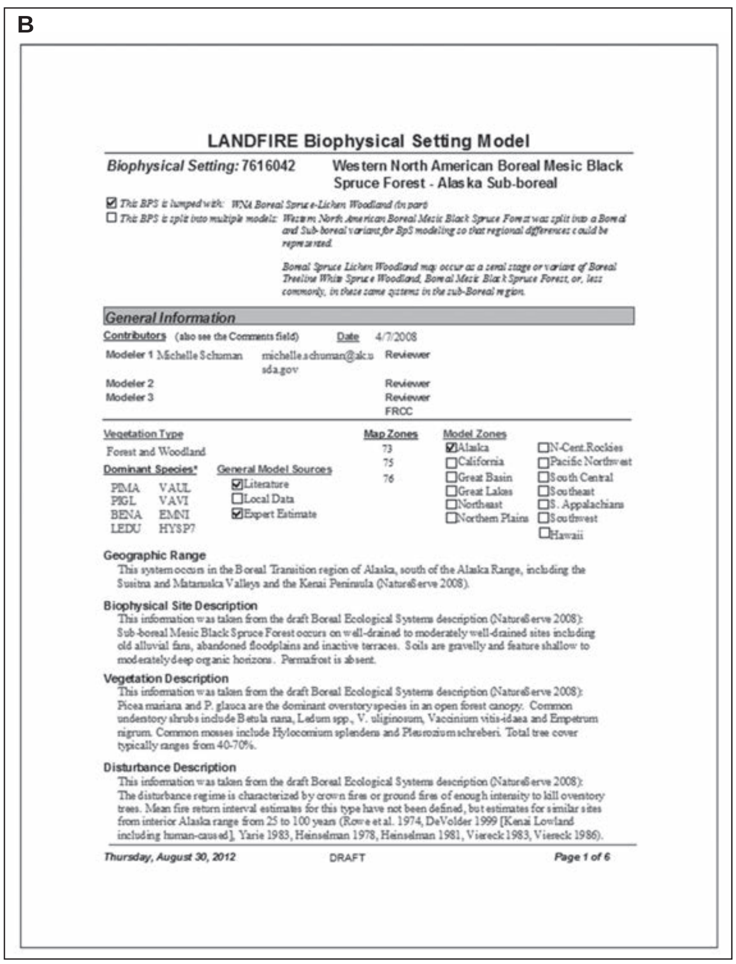
- a description of the modeled ecosystem including geographic range, biophysical setting, disturbance regime, vegetation characteristics and dominant species,
- mapping rules for each state (called s-class or succession class by LANDFIRE) in the STM,
- STM results including the estimated reference condition (i.e. the percent of ecosystem in the various states) and the fire frequency and severity, and
- relevant literature, model contributors, model reviewers and modeling assumptions.

A report was generated from the MTDB which became the description document (metadata) that accompanies each STM.

Modeling rules were established to ensure that the models would be consistent and comparable across the country and could be used to develop map products. For example, LANDFIRE models are consistent in resolution (they have five or fewer states), capture the main successional pathway without gaps or overlap in age and use a pre-defined subset of VDDT functions including:

- a standardized set of definitions for cover types, structural stages, transition types and transition groups,




B

LANDFIRE Biophysical Setting Model

Biophysical Setting: 7616042 — Western North American Boreal Mesic Black Spruce Forest - Alaska Sub-boreal

☑ *This BPS is lumped with:* *WNA Boreal Spruce-Lichen Woodland (in part)*

☐ *This BPS is split into multiple models:* *Western North American Boreal Mesic Black Spruce Forest was split into a Boreal and Sub-boreal variant for BpS modeling so that regional differences could be represented.*

Boreal Spruce Lichen Woodland may occur as a seral stage or variant of Boreal Treeline White Spruce Woodland, Boreal Mesic Black Spruce Forest, or, less commonly, in these same systems in the sub-Boreal region.

General Information

Contributors (also see the Comments field) **Date** 4/7/2008

Modeler 1 Michelle Schuman michelle.schuman@ak.usda.gov **Reviewer**

Modeler 2 **Reviewer**

Modeler 3 **Reviewer**

FRCC

Vegetation Type
Forest and Woodland

Dominant Species*
PIMA VAUL
PIGL VAVI
BENA EMNI
LEDU HYSP7

General Model Sources
☑ Literature
☐ Local Data
☑ Expert Estimate

Map Zones
73
75
76

Model Zones
☑ Alaska
☐ California
☐ Great Basin
☐ Great Lakes
☐ Northeast
☐ Northern Plains
☐ N-Cent.Rockies
☐ Pacific Northwest
☐ South Central
☐ Southeast
☐ S. Appalachians
☐ Southwest
☐ Hawaii

Geographic Range
This system occurs in the Boreal Transition region of Alaska, south of the Alaska Range, including the Susitna and Matanuska Valleys and the Kenai Peninsula (NatureServe 2008).

Biophysical Site Description
This information was taken from the draft Boreal Ecological Systems description (NatureServe 2008): Sub-boreal Mesic Black Spruce Forest occurs on well-drained to moderately well-drained sites including old alluvial fans, abandoned floodplains and inactive terraces. Soils are gravelly and feature shallow to moderately deep organic horizons. Permafrost is absent.

Vegetation Description
This information was taken from the draft Boreal Ecological Systems description (NatureServe 2008): Picea mariana and P. glauca are the dominant overstory species in an open forest canopy. Common understory shrubs include Betula nana, Ledum spp., V. uliginosum, Vaccinium vitis-idaea and Empetrum nigrum. Common mosses include Hylocomium splendens and Pleurozium schreberi. Total tree cover typically ranges from 40-70%.

Disturbance Description
This information was taken from the draft Boreal Ecological Systems description (NatureServe 2008): The disturbance regime is characterized by crown fires or ground fires of enough intensity to kill overstory trees. Mean fire return interval estimates for this type have not been defined, but estimates for similar sites from interior Alaska range from 25 to 100 years (Rowe et al. 1974, DeVolder 1999 [Kenai Lowland including human-caused], Yarie 1983, Heinselman 1978, Heinselman 1981, Viereck 1983, Viereck 1986).

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Figure 2—A LANDFIRE model consists of a STM developed in VDDT (A) and a description document developed in the MTDB (B).

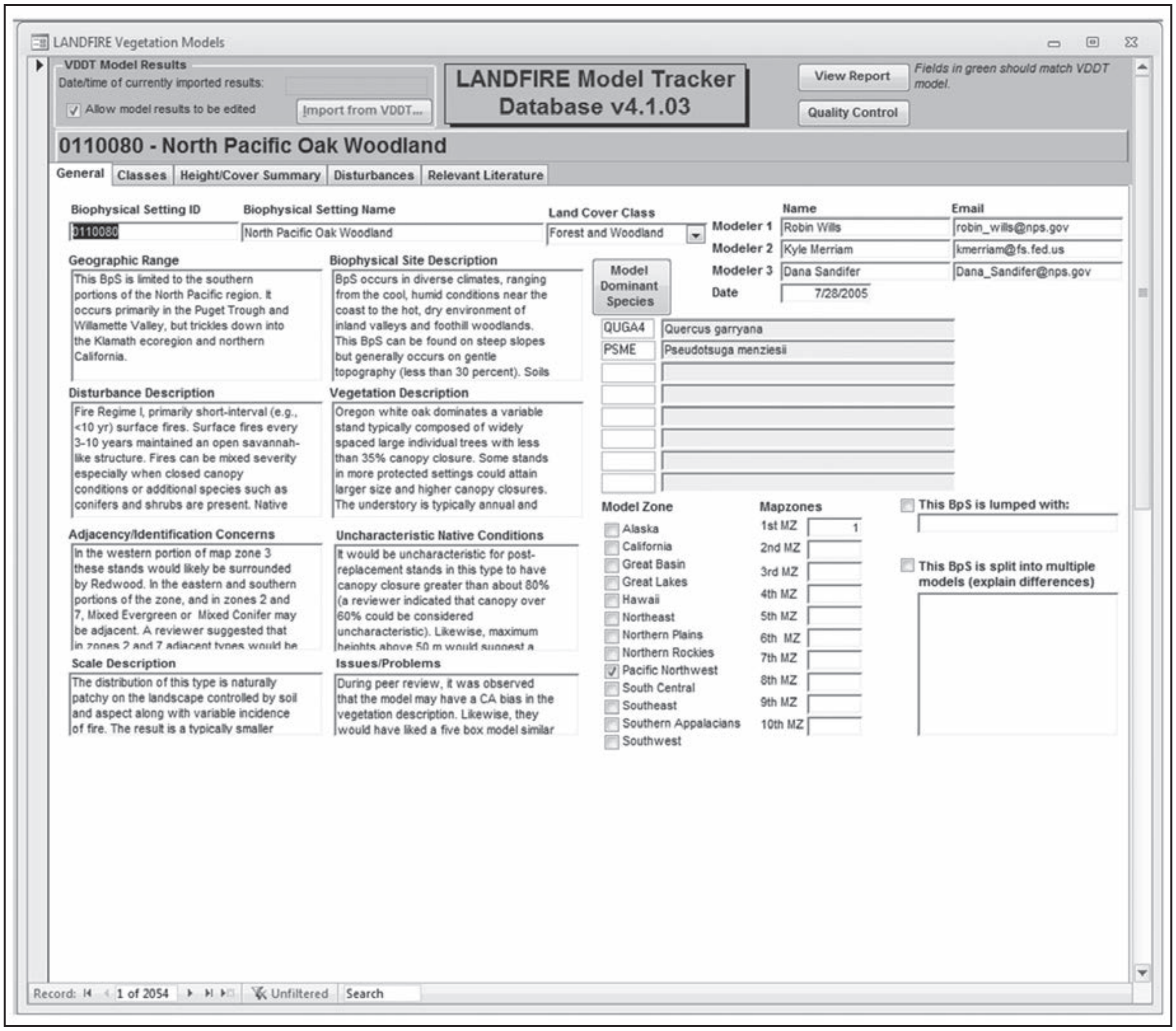

Figure 3—MTDB is Microsoft Access tool developed by LANDFIRE to document the modeling process.

- use of Time Since Disturbance (TSD) only with alternate succession pathways, and
- use of relative Age (RelAge) limited to replacement severity disturbances occurring in the initial state (normally state A in LANDFIRE).

These modeling rules created a number of weaknesses, including:

- the need to develop crosswalks between differing vegetation classifications,
- the potential loss of information available at resolutions finer than the project objectives, and
- constraint of expert modelers to a select suite of model functions, sometimes below their skill level.

Another limitation was imposed by the project schedule which limited the time available for STM development and review. During the National phase of the project, LANDFIRE developed, reviewed and revised seven unique STMs each week on average for 183 weeks.

The STMs were developed through a series of more than 40 expert workshops held around the country, some 35 web conferences and many more individual meetings. A modeling leader was designated for each of 13 geographic regions and provided funding for STM development activities in their area. LANDFIRE modeling leaders cast a wide net for experts in the fields of vegetation, fire and landscape ecology as well as land managers and stewards—in short, anyone with the training and/or experience necessary to

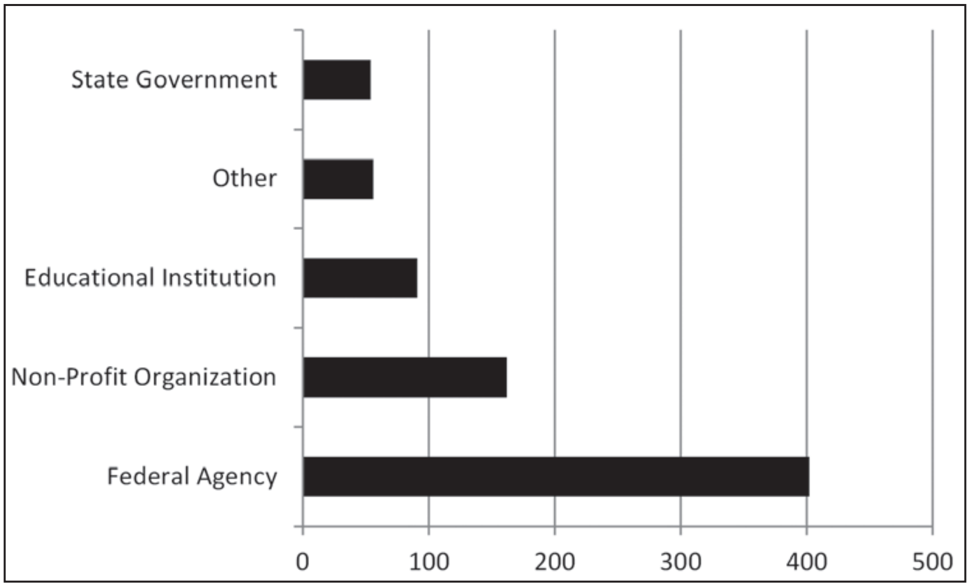

Figure 4—More than 700 individuals from the government, non-profit and private sectors contributed to the development of LANDFIRE STMs. The category "Other" refers to individuals who did not affiliate with any group or organization, such as independent contractors and consultants.

Table 2—LANDFIRE created two sets of STMs: 1) Rapid Assessment models which were coarser scale and covered the conterminous U.S. and 2) National models which were finer scale and covered the entire United State including Alaska and Hawaii. The relationship between types mapped and types modeled is one-to-many because in some cases multiple STMs were needed to represent the geographic variation in widespread vegetation types. Of the 2,426 total LANDFIRE STMs, about 1,200 are unique because in some cases one STM was used to represent the same BpS in different Map Zones

Project phase	Vegetation types mapped	Vegetation types modeled
LANDFIRE Rapid Assessment	242	262
LANDFIRE National	541	2,164
TOTAL	783	2,426

populate the ecological information in a STM, and who had supervisory support and funding for engagement in the project. Workshops were open to all interested individuals, and a modest amount of funds were available to support travel for a portion of participants. Model parameters were developed based on literature, local data and professional judgment. When disagreements occurred regarding model inputs, LANDFIRE modeling leaders consulted additional experts, reviewed the literature, performed sensitivity analysis and ultimately made the final decision about the parameters. Both the decision-making process and all the opinions were thoroughly documented in MTDB to ensure transparency. Written and verbal evaluations were solicited at each workshop to fuel to facilitate adaptive workshop planning.

During the Rapid Assessment phase of the project, 262 coarse-scale STMs representing 242 BpS units mapped in the conterminous U.S. were developed. These STMs were then refined during the LANDFIRE National phase of the project to create 2,164 STMs representing 541 mid-scale (ranging from 10–1000's of hectares in size) BpS units mapped in the U.S., including Alaska and Hawaii. In total, LANDFIRE engaged more than 700 experts from various sectors (fig. 4) to create 2,426 STMs (approximately 1,200 of which were unique) representing 783 vegetation units in the U.S. (table 2). Not all of the STMs were unique because in some cases, based one expert feedback, one STM was used to represent the same BpS in different Map Zones (National Landcover Database Map Zones). However, the associated documentation in MTDB may have been adjusted to better represent the geographic variation in plant species or environmental gradients so a unique record was maintained for each Map Zone even when quantitative information in the STM was not changed. In some cases, the opposite situation occurred—a given BpS had multiple STMs associated with it to represent the geographic variation across Map Zones with quantitative changes in the model. For example, the Inter-Mountain Basins Big Sagebrush Shrubland BpS occured in 20 Map Zones and had at least three distinct STMs associated with it to represent the variability in successional rates and disturbance probabilities throughout its extensive range.

In this paper we offer 10 lessons learned based on our collective experience facilitating the development of LANDFIRE's STM library. We discuss lessons related to all aspects of model building including developing a modeling process, eliciting expert input, defining modeling units, checking for model errors, documenting model results and setting appropriate expectations. These lessons may help others build more useful models for land management and planning in the future.

Lesson 1: Create a Flexible Modeling Process

Imagine embarking on a project to develop thousands of structurally-consistent, scientifically-sound vegetation STMs while also engaging hundreds of people with diverse knowledge, skills and personalities. Together these objectives necessitate a relatively large degree of flexibility in approach (e.g., to address a diversity of learning styles), while there may also exist many constraints on the modeling mechanics (e.g., to ensure each model is built at the appropriate scale of resolution). Being flexible in the modeling approach does not necessarily mean scientific quality will suffer; scientific quality may in fact be enhanced when the approach allows a greater diversity of experts to contribute their knowledge and skills. Flexibility in approach provides the wiggle-room necessary to work with individuals or organizations that have different styles or processes.

Goals for developing STMs for LANDFIRE included engagement of a large diversity of experts for the purposes of compiling the best available science on ecosystem structure and function, and capacity-building for the future application of completed models. Some modeling participants were interested in learning how to build and apply the STMs, as well as providing and/or compiling the best available science for translation into a STM format. Other participants were primarily focused on compiling the best available information and were not interested in being able to use the STMs themselves. Workshop participants also differed in learning styles. The "experiential learners" needed to run the models in a hands-on manner to understand how they worked; while others were "abstract learners" and could understand enough about the modeling process through lectures to meet the project objectives.

While LANDFIRE, in part, aimed to build applied modeling capacity in each modeling participant, the diversity of learning styles and participant motivations necessitated a flexible approach. For example, we learned that if a small group of experts was expected to build a STM, it must include at least one person willing to listen openly and patiently to others and run the model software while also incorporating their own expert knowledge in an unbiased manner. If a group of experts lacked the skills and desire to build a STM in VDDT, they had to be provided more abstract methods to document the best available science on model parameters (e.g., flipcharts or forms where experts could fill-in tables of transition probabilities, or draw box-and-arrow diagrams) so that the STM could be built later. If experiential learners were willing to build STMs, but no other experts were available to assist, they had to be comfortable working individually, or be provided one-on-one support throughout the model-building process. In general, based on written workshop evaluations by participants, most LANDFIRE modelers appreciated the in-person, facilitated workshop approach and the opportunity to interact with other experts. However, where time, travel budgets, modeling skills and/or a desire for increased modeling capacity was lacking, first iteration "straw man" models were built by LANDFIRE staff which could be reviewed individually by experts on their own time.

We suggest holding in-person workshops and one-on-one meetings whenever possible, using techniques that the modeling leaders and modelers are comfortable with. We used multiple techniques to build models often within the same workshop, including:

- facilitated modeling using flip charts and/or VDDT software,
- modeling individually or in small groups,
- modeling by pairing an expert with a VDDT "driver" who could run the software but did not necessarily understand the ecology, and
- LANDFIRE staff creating straw man models which were later critiqued by experts during or outside a workshop event.

Online web conferences can be effective when in-person meetings are not feasible.

Essentially, the need to build structurally consistent STMs using the best available science (see Lesson 5) does not preclude taking a flexible modeling approach. A flexible modeling approach facilitates engaging the broadest suite of learning styles and personal motivations possible.

Lesson 2: Incorporate a Learn-By-Doing Method, but Know That it Takes Work

Building STMs requires a general understanding of modeling concepts and specific knowledge of modeling tools such as VDDT. While these concepts and tools can be taught through a didactic approach, we found that an experiential learning approach, where users learned directly by doing, facilitated two of our project objectives: building many STMs in a short amount of time and building modeling capacity within our expert community. While this constructivist-guided approach is well documented (two publications by Jean Piaget, attributed as "father" of constructivism, have over 7,000 citations in Google Scholar), it requires (1) teamwork, (2) motivation, and (3) preparation on the part of the facilitator.

Team learning , such as building STMs in small groups as was done at most LANDFIRE workshops, has proven to be valuable in virtually every educational setting (Daniels and Walker 2001). Team situations provide opportunities for reflective observation (i.e., asking "why?"), and further, learning is often motivated by conflict (Kolb 1993). The teams in the LANDFIRE modeling effort were selected for expertise, not necessarily for agreement in learning styles, age or type of experience. In one example from a LANDFIRE modeling workshop in Michigan, a young college professor was paired with an older ecologist from The Nature Conservancy. The professor was very comfortable with both the modeling software and the ecosystem from literature review, whereas The Nature Conservancy ecologist was relatively uncomfortable with the software but had decades of field experience. The two experts often questioned each other—the ecologist questioning how the professor ran the model; the professor questioning the ecologist's field-based observations. The tension forced both modelers to alternate between the four modes of experimental learning: reflection, action, feeling and thinking (Daniels and Walker 2001). We did not test the experts, but both stayed engaged with LANDFIRE, built a nuanced and complete model and most importantly, commented that they "learned a lot" from the experience.

Addressing the built-in tensions between people, the challenges of quantifying ecosystem processes with substantial levels of uncertainty, high expectations and simply "being away from the office" required motivation. Motivation was both internal to the experts and created on site during workshops and meetings. The simple fact that experts prioritized their work to be involved often indicated that there was motivation and that the topic at hand had immediate relevance. However, some experts may have been directed to attend by a supervisor, for example. It is important that leaders do not assume adequate motivation among participants. In the LANDFIRE modeling process, motivation was developed through several means: (1) immediate engagement (e.g. minimizing lectures and moving quickly to hands-on modeling), (2) creation of a "safe" environment where risks of questioning and being questioned were kept to a minimum, (3) accountability based on STM review and (4) fun (see below).

Working with many people of varied backgrounds requires structure and preparation. Corroborating many of Vella's 12 fundamental principles of adult learning (Vella 1994), we found that for the processes to be effective there had to be physical comfort (plenty of food, quiet location, etc.), clear expectations and clear, but evolving roles. In LANDFIRE workshops, the facilitator took on the leadership role in establishing the aforementioned "motivational setting," but as the process matured the facilitator would often be replaced as the leader by experts. It was apparent to us that peer-to-peer learning and collaboration increased the value of the workshop approach over STMs being developed by individuals working independently.

Finally, it was helpful to throw in some fun whenever possible. For example, we used an acronym contest, where we learned that TNC, i.e. The Nature Conservancy, also can mean "Totally Non-Confrontational." Administering an "Are you a lumper or a splitter?" quiz to workshop participants not only brought laughter, but helped participants recognize their potential modeling strengths and weaknesses.

Lesson 3: Engage a Broad Spectrum of Experts from the Start

We believe that engaging a broad spectrum of experts in the development and review processes results in more robust and useful SMTs. Consider inviting individuals who will be critical to building future support for the use of STMs. Research has shown that experts are the greatest source of variation in the modeling process (Czembor 2011) but for many ecosystems expert knowledge is virtually the only information source available. If variation is inevitable, modeling leaders need to increase the sample size, that is, identify and engage as many experts as possible within time and resource constraints. LANDFIRE modelers included scientists, managers and resource specialists from all the major U.S. land management agencies (e.g., Forest Service and National Park Service), teachers and students from academic institutions and foresters, ecologists, botanists, managers and others from a variety of non-governmental organizations (e.g., The Nature Conservancy and NatureServe; fig. 4).

Once experts are involved, managing their input in constructive ways is the key to successful engagement. Through experience we developed several techniques for responding appropriately to issues encountered when working with a diverse group of experts (table 3). When modeling is complete, it is important to follow up with modeling participants to communicate project results and the importance of their efforts to the success of the project.

Lesson 4: Agree on What is Being Modeled

Defining *what* is being modeled and communicating that explicitly are essential to the modeling process. This includes both the vegetation concept (e.g., BpS) and the individual vegetation units to be modeled (e.g., Alaska Arctic Wet Sedge-Sphagnum Peatland). When explaining the vegetation concept, we found it helpful to discuss it within the context of various other potential vegetation classifications familiar to our experts such as Potential Natural Vegetation Type (e.g., Schmidt et al. 2002), Habitat Type (e.g., Daubenmire 1968, Pfister et al. 1977), Land Type Association (e.g., ECOMAP 1993) and others.

After the modeling concept is defined and understood, the individual modeling units themselves must be examined and modelers must come to agreement on the distinction between related and sometimes overlapping ecosystems. For example, LANDFIRE created STMs for seven California chaparral ecosystems: California Maritime Chaparral, California Mesic Chaparral, California Montane Woodland and Chaparral, California Xeric Serpentine Chaparral, Mediterranean California Mesic Serpentine Woodland and Chaparral, Northern and Central California Dry-Mesic Chaparral and Southern California Dry-Mesic Chaparral. While time consuming, examining similar ecosystems like those listed above before initiating modeling is essential to preventing confusion during model development and later model use.

Lesson 5: Implement Procedures to Maintain Model Quality

Maintaining model quality through standards, rules and error checking are critical when STMs are to be comparable across ecosystems and/or if they are to be used in other software programs (e.g., LANDSUM) or applications (e.g., mapping state classes). LANDFIRE developed modeling

Table 3—Successfully engaging experts and eliciting the information required to build STMs involves developing ways to constructively mange expert input and work with experts with diverse backgrounds and skills

Issue	Potential solution	LANDFIRE example
Working with "lumpers" and "splitters" (i.e., individuals who tend to focus on similarities and define fewer ecosystems vs. those who tend to focus on differences and define more ecosystems)	Illuminate individual tendencies to prevent either over-simplification or wasted time tracking down unnecessary information.	We gave a light-hearted "Are you a lumper or a splitter?" quiz to identify individual tendencies early on in the model development process.
Managing experts with agendas	Respectfully mange their input so as to separate agendas from science.	MTDB provided a place where all opinions could be documented and robust model review helped ensure that the best available science was incorporated into each STM.
Building modeling confidence and capacity	Make sure all participants feel valued and acknowledge that only some experts will be willing to learn modeling tools such as VDDT.	We paired experts who were comfortable modeling with those who were not, and/or provided other devices to record expert input such as flip charts or cheat sheets. We started by eliciting information within the expert's area of interest and worked towards less familiar information.
Limited budget for compensating experts	Payment may increase motivation and timeliness. Use web conferences instead of in-person meetings when budgets are limited.	We used limited financial support to engage key experts and ensure completion of all STMs, especially for rare ecosystems and ecosystems for which little research existed.

standards and rules to maintain the quality and consistency of its STMs and to ensure their compatibility with mapped products. Standards, such as modeling forested ecosystems with a standardized set of state classes including one early, two open and two closed states, create a sense of unity among the LANDFIRE models. While this standard was followed most, but not all, of the time, LANDFIRE had a set of rules that were applied to the entire model set such as using five or fewer states in a STM to create consistency in resolution and prohibition of the use of Monte Carlo multiplier files to capture temporal variation in disturbances. The VDDT software includes functionality for setting the temporal variation in disturbances, but it was not incorporated into the project design because of large gaps in data or knowledge about temporal variation of natural disturbances geographically and for particular disturbance types (see lesson eight).

An automated and a manual set of quality control checks were developed to ensure that LANDFIRE modeling rules were followed and errors were minimized. Keeping models as simple as possible (see lesson nine), makes finding and fixing errors easier. Modeling efforts like LANDFIRE should clearly communicate the benefits of standards or rules such that modelers and reviewers can understand how the rules may work in their favor in the long term.

Lesson 6: If Possible, Build from Existing Models

Starting with an existing STM and modifying it as needed to represent a new ecosystem can promote modeling efficiency and may help build modeling confidence among experts with little modeling experience. Working with a variety of experts we found that most preferred to modify an existing STM rather than start from scratch. This seemed to be particularly helpful for individuals who had no previous modeling experience or who had not used VDDT before—the case for most LANDFIRE modelers.

In addition to helping modelers get started, working from a similar, existing STM aided efficiency by allowing users to focus on the quantitative differences between ecosystems (see lesson seven). For ecosystems with little research from which to develop STM parameters, starting with a related ecosystem's STM and focusing on relative differences in those numbers was an effective strategy. The downside of starting with an existing STM is that, to reveal hidden bias, it becomes extremely important to question the existing model's assumptions within the context of the new ecosystem.

Lesson 7: Thoroughly Document Results

Documenting model results promotes later evaluation, understanding and application of the model set by identifying information sources, stating assumptions and identifying knowledge gaps. The use of LANDFIRE's MTDB as a place to document this information promoted transparency in the modeling process, which supported scientific confidence in the STMs. This was particularly important in cases where there was disagreement between experts on model parameters and/or where there was little research from which to glean succession and disturbance rates. In addition to its use internally, documentation makes models more transferable and readily useable by others. When a modeler starts with an existing model (see lesson 6), and understands its assumptions, documentation of new model parameters can be facilitated by merely editing existing documentation.

Lesson 8: Never Forget the Modeling Purpose

Modeling is generally undertaken to achieve a specific objective and this objective should help guide modeling decisions. The LANDFIRE project used its STMs primarily to estimate reference conditions and to assist with mapping vegetation and fuel spatial products. Keeping these goals in mind allowed us to focus on the required outputs and minimize issues that did not impact the results the project needed. For example, we found it was often difficult to quantify infrequent disturbances (with return intervals of 1,000 years or more such as severe insect outbreaks or weather events) without the use of Monte Carlo multipliers, a VDDT function not used in LANDFIRE STMs (see lesson five). Without the use of multipliers, disturbances with long return intervals occur in the model more frequently (because at every time step there is a probability of their occurrence) but at a lower intensity (i.e., the disturbance affects fewer pixels or landscape area) at any given time than would be expected by the real world event. For short duration simulations, the loss of variability could have a significant effect on the results but by running the STMs for a long time period (1,000 years) and, taking the average of the outputs for that period, the impact on the results needed by LANDFIRE was minimal so we could document our assumptions and move on without delay. However, this example illustrates the trade-offs between modeling rules set in place by the project for consistency and the ability to model some complex ecological phenomena. The modeling purpose impacts the modeling rules; it can help determine what to include and what to leave out of a model.

Lesson 9: Set Realistic Modeling Goals

As a matter of practicality and philosophy, we recommend keeping STMs as simple as they can be while still meeting the project goals. Philosophically, modelers must remember that every model is an intentional simplification of reality, and that it is the modeler's responsibility to decide how much simplification is appropriate to meet his or her objectives. Practically, modelers should remember that STMs must be parameterized and understood to be useful, and the more complex the STM, the more difficult both these tasks are. There are at least two levels of simplification that we recommend, what to model and how to model.

To decide *what* to model, identify those things that are important to your project. For instance, in LANDFIRE, the significance of fire and fire regime was paramount, although not exclusive. When the list of BpS to be modeled was defined by the experts involved, we asked them to "lump" and "split" modeling units intelligently based upon LANDFIRE's needs. If two vegetation systems were very similar ecologically and had very similar fire regimes, such as riparian types, the distinction between them was not critical to LANDFIRE, so we asked them to "lump" the two BpS into a single STM. If a BpS occurred in two variants that had significantly different fire regimes, such as Douglas-fir at different elevations or on different aspects, we asked the experts to “split” the system into two distinct STMs. Within the context of the modeling objectives, the simpler the model, the easier it is to maintain model quality.

There are many reasons to keep the content and structure of each STM as simple as possible, such as parameter specification, model over-specification and model exploration. A vegetation STM is composed of states, transitions and transition parameters (frequency and destination at minimum). A STM with five states and five transitions has at least 50 potential parameters to specify, and each transition has five possible destinations. Imagine a second STM with 10 states and 10 transitions. This STM has 100 or more potential parameters to specify, and each transition has 10 possible destinations that must be sorted out. Often the reference information or experience that is needed to specify all these model parameters is not substantial, and is spread very thin indeed for more complex models. It is also possible to over-specify a STM. Consider a system with two types of flooding disturbances: one has a return interval of 50 years and the other’s is 500 years. It is highly likely that the second type of flooding disturbance may not add useful information to a STM being used in a 100-year planning process. Finally, it is much easier to understand and explore a simpler STM. By minimizing the number of states and transitions in a STM, errors are found and diagnosed more quickly, and the interpretation process is more thorough and efficient.

Lesson 10: Model to Document Known Ecological Information and Identify Gaps in Understanding

The process of quantitatively modeling every mid-scale ecosystem in the United States helped us identify the many gaps in our collective ecological understanding. We found that ecosystems with commercial value such as ponderosa pine and longleaf pine forests tend to have more research associated with them, allowing for more robust estimates of succession and disturbance rates. In contrast, noncommercial and/or rare ecosystems such as California chaparral or Great Lakes alvar (limestone plains with sparse vegetation) have comparatively less information from which to build quantitative models. Our efforts highlighted research needs in many ecosystems.

The modeling process was often as beneficial as the STM results. For example, the process allowed us to:

- document what is known about ecosystems,
- identify areas where information is lacking about ecosystems,
- test assumptions about ecosystem function,
- look at relative differences between ecosystems,
- create a shared understanding about ecosystem function, and
- stimulate collaborative learning.

These were valuable outcomes of the modeling process above and beyond the creation of STMs.

The creation of a comprehensive, national STM library led by LANDFIRE in collaboration with hundreds of experts across the country represents a significant contribution to the understanding and synthesis of information related to pre-settlement ecosystems across the entire U.S. In addition to their use in understanding and setting reference conditions, the models can be adapted to represent current or desired conditions, to predict future conditions and/or test land management strategies (sensu Low et al. 2010, Pohl et al. 2001, Shlisky et al. 2005, Shlisky and Vandendriesche 2012, Weisz et al. 2009). The LANDFIRE STMs combined with these lessons learned can serve as a solid foundation for future model development efforts related to land management and planning in the United States.

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