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Vegetation dynamics models: a comprehensive set for natural resource assessment and planning in the United States

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Abstract. In the context of widespread ecological changes, land managers and policymakers confront the need to prioritize ecosystem restoration and fuel management activities across large areas to sustain ecosystem services. Reference conditions inform prioritization efforts by providing a baseline from which to measure where and how vegetation and fuels have changed, but until recently the USA lacked a complete set of reference conditions. We describe the ongoing development of a comprehensive set of vegetation reference conditions based on over 900 quantitative vegetation dynamic models and accompanying description documents for terrestrial ecosystems in the USA. These models and description documents, collaboratively developed by more than 800 experts around the country through the interagency LANDFIRE Program, synthesize fundamental ecological information about ecosystem dynamics, structure, composition, and disturbance regimes before European-American settlement. These products establish the first comprehensive national baseline for measuring vegetation change in the USA, providing land managers and policymakers with a tool to support vegetation restoration and fuel management activities at regional to national scales. Users have applied these products to support a variety of land management needs including exploring ecosystem dynamics, assessing current and desired conditions, and simulating the effects of management actions. In an era of rapid ecological change, these products provide land managers with an adaptable tool for understanding ecosystems and predicting possible future conditions.

Key words: collaboration; conservation planning; disturbance; historical range of variability; land management; modeling; natural resource management; reference conditions; state-and-transition; succession; vegetation dynamics.

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Introduction

Unprecedented global changes have reduced the ability of many ecosystems to provide the services on which human communities depend (Millennium Ecosystem Assessment 2005) and prompted the United Nations to declare a Decade on Ecosystem Restoration (2021–2030; https://www.decadeonrestoration.org/about-un-decade). In the USA, negative effects of altered fire regimes have led to calls for increasing the pace and scale of vegetation restoration and fuel management activities so as to maintain ecosystem services and reduce wildfire risk (Davies et al. 2011, USDA Forest Service 2012, Stephens et al. 2020). These demands leave land managers and policymakers to confront a critical question:

How should society prioritize ecosystem restoration and fuel management activities at regional and national scales? In addition to social and economic considerations, prioritization requires a baseline, or reference condition, from which to measure where and how vegetation and fuel conditions have changed. A reference condition describes the range of ecosystem composition, structure, and ecological processes for a given place and time period (Morgan et al. 1994, Moore et al. 1999). The historical range of variability (HRV) is frequently used as a baseline because it encompasses the full range of conditions and processes with which native species evolved and to which they have adapted (Landres et al. 1999). For the USA, HRV is often developed from the pre-European-American settlement era, which had substantial differences from the current time frame including an anomalous cold period, known at the Little Ice Age (Millar and Woolfenden 1999). Despite its limitations (Keane et al. 2009, Millar 2014), managers have found the HRV useful in supporting a number of land management objectives including establishing restoration goals, understanding current conditions, informing desired conditions, and characterizing resilience (Hessburg et al. 2015, DeMeo et al. 2018, Keane et al. 2018, McGarigal et al. 2018, Donato et al. 2020). Beyond these applications, HRV provides context for understanding current landscapes and offers insight into the drivers of ecosystem change over time and space (Fulé 2008, Keane et al. 2009, Higgs et al. 2014, Millar 2014).

Many projects have defined historical reference conditions for individual management units or regions (e.g., Quigley and Arbelbide 1997, Pollock et al. 2012, McGarigal et al. 2018), but only a few offer broader coverage. Schmidt et al. (2002) defined historical natural fire regimes for the conterminous USA but did not define vegetation reference conditions. An interagency collaboration to produce Ecological Site Descriptions has led to the development of many conceptual models that define reference states for vegetation communities at the time of European-American settlement (RIESM 2010), but the effort is ongoing and the reference states are not quantitatively defined (Twidwell et al. 2013, Bestelmeyer 2015). From 2002 to 2005, the interagency Fire Regime Condition Class (FRCC) project produced quantitative reference condition models for 186 vegetation communities in the conterminous USA (Barrett et al. 2010). The FRCC models provided an initial baseline for many ecosystems, but a comprehensive set of reference conditions was still needed to measure vegetation change and prioritize management activities in the USA.

To address this deficit and to build on the FRCC project, we led a collaborative effort to create a complete, quantitative, and consistent set of vegetation dynamic models to estimate historical reference conditions for terrestrial vegetation systems and fire regimes in the USA through the LANDFIRE Program (Box 1, Fig. 1). We stratified vegetation systems according to LANDFIRE's Biophysical Setting (BpS) classification system (Rollins 2009). Models for each BpS and their accompanying description documents (collectively referred to as the BpS model library) synthesize fundamental ecological information about ecosystem dynamics, structure, composition, and disturbance regimes. The BpS model library has been widely applied to a variety of land management needs such as National Forest planning (Nantahala and Pisgah National Forests 2020), regional assessments (DeMeo et al. 2018), evaluating management scenarios (Costanza et al. 2015*a*), and supporting stakeholder-driven planning efforts (Low et al. 2010). These products create the first comprehensive, nation-wide baseline for assessing current vegetation conditions, and, to our knowledge, represent the largest participatory ecological modeling effort (e.g., Voinov et al. 2018) completed in the USA. Our goal with this paper is to provide users with an understanding of the history and development of the LANDFIRE BpS model library and to promote its effective and appropriate use. Specifically, we describe the BpS model library and the collaborative process used to develop it, highlight its range of applications in land management, and discuss its limitations and future enhancements.

Building a National Vegetation Dynamics Model Library

The BpS model library—developed collaboratively by more than 800 experts—includes over 900 vegetation dynamic models and associated BpS descriptions for different terrestrial vegetation communities covering the USA and its territories (LANDFIRE 2020*a*). In this section, we

Box 1.
What is LANDFIRE?

The Landscape Fire and Resource Management Planning Tools program, or LANDFIRE, was initiated in 2002 in response to concerns about the costs and impacts of wildfire and the need for consistent, cross-boundary data to support fuel and fire management planning and activities (Rollins 2009, Ryan and Opperman 2013). LANDFIRE supports the implementation of federal fire policies and other land management activities by producing more than 20 geospatial products, databases, and ecological models representing current and potential vegetation, wildland fuels, fire regimes, and vegetation conditions for all-lands in the USA. In accordance with its charter, LANDFIRE products are comprehensive for the nation, produced using consistent methods, compatible with one another, and as current as possible. The Program developed through several major phases, described in more detail later in this paper, beginning with a small prototype (Rollins and Frame 2006) in the western USA and expanding in subsequent phases to provide products for the entire USA and its territories. Selected applications of Program products include the following: evaluation and prioritization of fuel treatment projects (Valliant and Reinhard 2017, Barros et al. 2019), assessing ecological conditions (Comer et al. 2013, Cleland et al. 2017) and conservation status (Swaty et al. 2011), analyses of wildfire risk (Scott et al. 2013, 2020) and hazard (Dillon et al. 2015), wildfire incident decision support (Wildland Fire Decision Support System, https://wfdss.usgs.gov/), and quantification of carbon stocks (Zhu et al. 2011). LANDFIRE is a shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior.

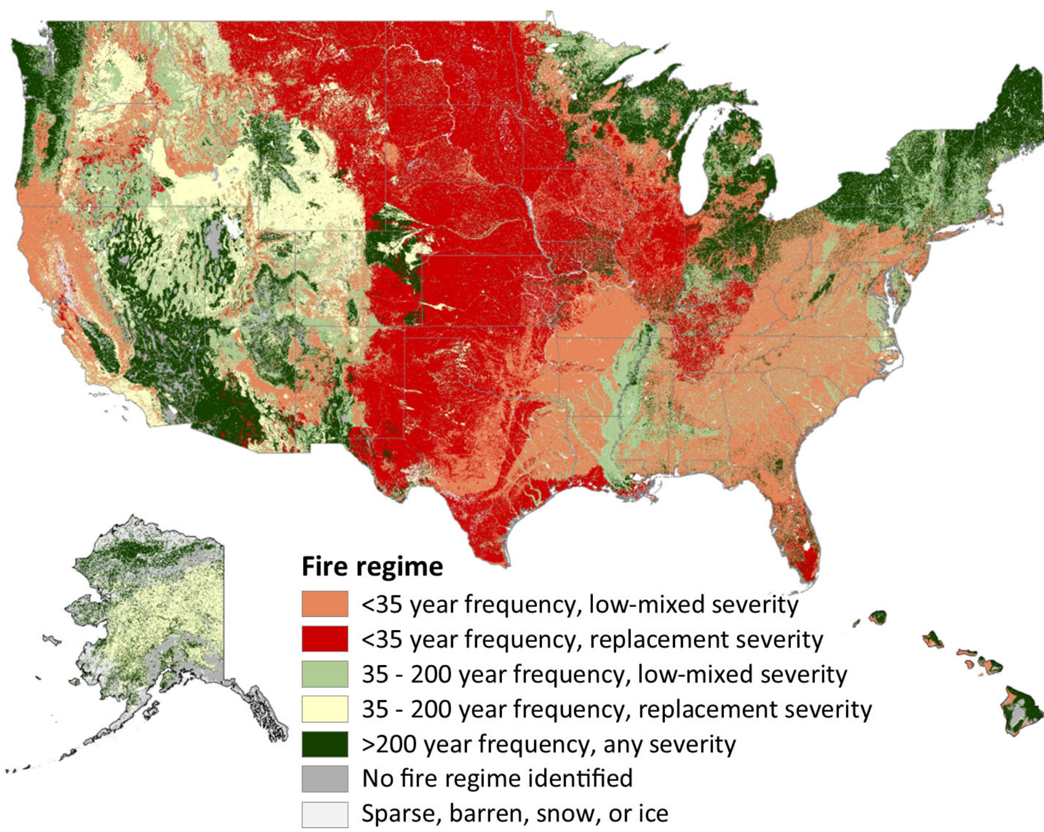

Fig. 1. The LANDFIRE fire regime group geospatial product (LANDFIRE Fire Regime Groups 2019) classifies fire regimes based on reference fire frequency and severity.

describe the BpS model library, focusing on the model development framework, modeling units, and key aspects of how the products are currently parameterized. In a later section, we explore the evolution of the BpS model library including multiple phases of development and refinement over nearly two decades. Due to the adaptive process of testing and updating the products, the current structure and format of the BpS model library described below differs slightly from earlier versions.

Model development framework

To support the goal of providing data to prioritize fire and fuel management activities, LANDFIRE developed historical reference conditions for vegetation composition and fire regimes using a simulation modeling approach. While the details of the approach varied slightly between different Program development phases, vegetation dynamic models, called state-and-transition simulation models (STSMs), were a key component of all phases (Appendix S1). STSMs divide an ecosystem into discrete states linked by pathways that define the rates of growth and frequency and effects of disturbances (Daniel et al. 2016). LANDFIRE used STSMs to estimate reference fire regime and vegetation conditions. Then using a similarity index, called vegetation condition class (Barrett et al. 2010), the Program measured the difference between its modeled historical vegetation reference conditions and current conditions mapped from satellite imagery (Rollins 2009). LANDFIRE defined reference conditions for the time period prior to European-American settlement (pre-settlement hereafter) and at the scale of National Land Cover Database map zones, which vary in size from approximately three million to more than 20 million hectares (Appendix S2).

During the initial phase of Program development, known as the Prototype, the reference time period was defined as 1600–1900 AD (Keane and Rollins 2006), but as BpS model library development expanded geographically, the time period was changed to simply pre-settlement. Recognizing that the timing of settlement varied and finding limited data for many ecosystems, LANDFIRE used the best available information even if it fell outside of the set time frame. Inherent in the pre-settlement reference period was the influence of Native Americans and Polynesians, with whom ecosystems evolved over millennia. The Program recognized that the choice to assume pre-settlement vegetation conditions as a benchmark could be considered overly simplistic in light of climate change and other anthropogenic drivers (Keane et al. 2007). We return to this topic later in the context of applications (see *Applying Models to Land Management*). While imperfect, LANDFIRE chose this benchmark because of the availability of long-term datasets on fire return intervals and other disturbance patterns that could help parameterize the STSMs (Keane et al. 2007).

Engaging experts

Because literature alone was insufficient to fully parameterize a set of STSMs that could represent the breadth of ecosystems across the USA (Long et al. 2006), LANDFIRE chose an expert-based approach to develop the BpS model library. The Program identified a set of modeling leaders, including the authors, to coordinate the effort. We invited experienced land and fire managers, natural resource specialists, biologists, ecologists, and others with knowledge of ecosystem composition, structure, and disturbance regimes to collaborate and co-create a national BpS model library. These individuals (model developers hereafter) had both the interest and the supervisory approval to participate in the effort. While they were generally not compensated, LANDFIRE allocated a small amount to pay for travel to the workshops and time to develop or review STSMs and BpS descriptions in some cases.

Between 2004 and 2009, modeling leaders hosted dozens of workshops across the USA to orient model developers to basic principles and objectives of BpS model library development. Using scientific literature, local data (e.g., inventory and monitoring data), and expert judgment, we worked with model developers to create and refine STSMs and BpS descriptions. In these workshops, we encouraged an iterative approach to the model development task and helped participants select and test the impact of various model parameters and obtain peer review from other workshop participants. Model developers were encouraged to document all sources of information used to build, refine, and review

STSMs and BpS descriptions, and to record their assumptions and any disagreements among them. Following initial development, we used a model review process to gather additional feedback on the STSMs and BpS descriptions to ensure that they incorporated the knowledge of a wide spectrum of experts and the best available literature. We documented instances when developers or reviewers provided conflicting information or opinions, and then sought additional input, performed literature review, and used sensitivity tests to finalize STSM parameters. Even though multiple model developers were involved in producing STSMs, a single consensus model was created for each ecosystem.

Modeling units

Each LANDFIRE STSM and its accompanying narrative represents a BpS—a potential vegetation concept reflecting the native vegetation community that was likely to have existed in the pre-settlement reference period, based on an approximation of historical disturbance regimes and the current biophysical environment (Rollins 2009). LANDFIRE used the Ecological Systems classification (Comer et al. 2003) as a starting point for BpS modeling and mapping units (Rollins 2009). Ecological Systems delineate existing terrestrial vegetation communities influenced by similar processes and found along similar environmental gradients (Comer et al. 2003). The Ecological Systems were suitable for initiating BpS because they encompassed concepts of vegetation dynamics, including succession and disturbance, which could be modeled as transitions between vegetation states. LANDFIRE mapped BpS as non-overlapping, discrete spatial units in its BpS geospatial product (Rollins 2009) effectively linking each STSM and BpS description to a ground location.

Model leaders and developers refined the Ecological Systems as needed to better characterize the potential natural vegetation communities represented by the BpS concepts. We separated or combined Ecological Systems as needed for STSM creation based on geography, biophysical gradients, or disturbance regimes. For example, we separated the Mediterranean California Mixed-Evergreen Forest Ecological System (which spans wide environmental gradients in precipitation, temperature, and topography) into a maritime influenced coastal variant characterized by a mixed-severity, moderate frequency fire regime (LANDFIRE 2020*b*) and an interior variant characterized by a low-severity, high-frequency fire regime (LANDFIRE 2020*c*). In other cases, we combined systems for modeling because model developers indicated that they had similar disturbance regimes, one system was a successional state of another, or knowledge gaps existed about the dynamics of co-occurring systems. For example, despite recognizing Western North American Boreal White Spruce Forest and Western North American Boreal White Spruce-Hardwood Forest as distinct existing vegetation communities, model developers combined them for STSM creation because they could not describe distinct biophysical environments for each system.

Conceiving and modeling vegetation dynamics

In workshops and follow-up efforts, modeling leaders and developers conceived an STSM for each BpS by dividing it into states (also called succession classes) and defining the causes and rates of transitions between them (Fig. 2). Models were initially developed in the Vegetation Dynamics Development Tool (ESSA 2007) and later in SyncroSim's ST-Sim package (ApexRMS 2019; Appendix S1). Both are flexible and free software platforms for developing STSMs. In a LANDFIRE STSM, a state represents a distinct vegetation development stage defined by a unique combination of cover type and structural stage for the dominant vegetation. Model developers used five or fewer states to attribute each BpS and assigned each state an age range. Ages were typically based on ontogenetic shifts (e.g., when a dominant tree changed from juvenile to reproductive status) or changes in other key characteristics, such as the closure of a forest canopy or the development of shrubs in a grassland.

To describe how vegetation transitioned among the various states, model developers defined growth and disturbance pathways for each STSM and represented these processes as deterministic or probabilistic transitions. Model developers used deterministic transitions to represent growth or successional trajectories and probabilistic transitions to represent disturbances. Given LANDFIRE's use of the STSMs to define reference fire regimes, we asked model developers to further specify fire transitions by

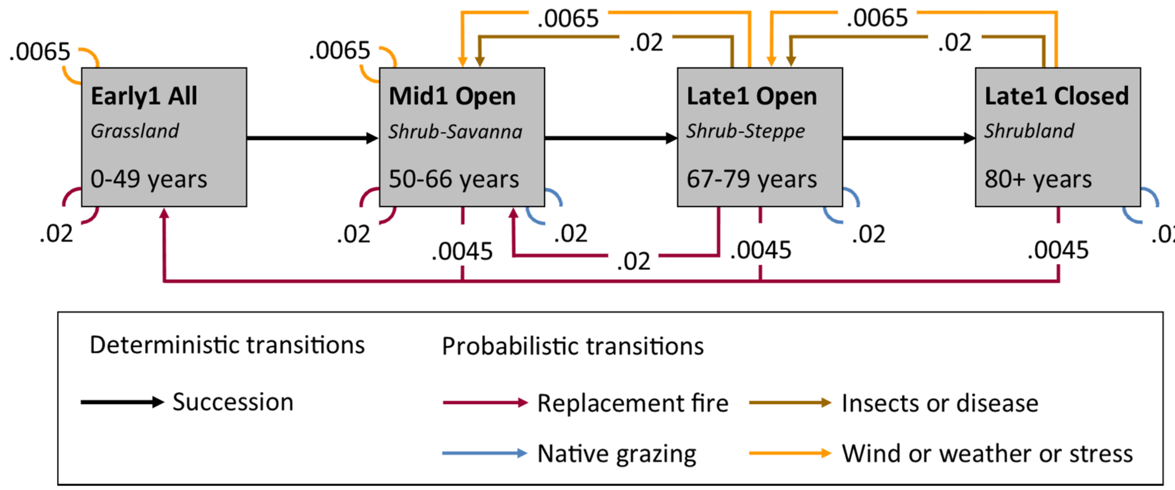

Fig. 2. A LANDFIRE STSM represents the vegetation dynamics of a BpS. This graphic representation of the Inter-Mountain Basins Big Sagebrush Steppe BpS STSM (LANDFIRE 2020*d*) shows the rate of growth between states and the frequency and impact of disturbances. Each state represents a discrete developmental stage defined by its vegetation cover, structure, and age range. The impact and frequency of disturbances is described by the starting and ending state and an annual probability of occurrence indicated by the value associated with each probabilistic transition pathway. All fires in this STSM are considered replacement fires following LANDFIRE's definition because over 75% of the dominant herbaceous and shrub species in this BpS are top-killed by fire.

severity class based on the percent top-kill of the upper vegetation canopy: 0–25% for surface, 25–75% for mixed, and greater than 75% for replacement severity. Model developers included all important system drivers, such as those that could have delayed natural succession or caused a transition to a new state as they built and tested their STSMs.

Model developers used multiple sources of information to develop disturbance probabilities for STSMs. Modeling leaders advised model developers to define the average, annual probability of a disturbance occurring at a given point on a landscape. Data on fire frequency, especially the fire return interval, were by far the most common type of disturbance information available for parameterizing STSMs. Model developers translated mean fire return intervals into annual probabilities and adjusted the values as needed to represent the average probability of fire for the BpS at the map zone scale. When disturbance frequency data were lacking or incomplete, we advised model developers to estimate the parameters. Model developers tested the disturbance parameters and compared the results to available data, observed conditions, and/or expert judgment. This process typically involved many rounds of iteration and revision before a consensus on input values was reached by the model developers.

Model developers ran each STSM to estimate how the set of states and transitions they had specified for a BpS resulted in an equilibrium state distribution and fire regime under pre-settlement conditions (i.e., the LANDFIRE reference condition). We initiated each STSM with 1000 simulation cells equally divided among all states within a BpS and ran ten Monte Carlo realizations of 1000 timesteps each. These parameters, determined by modeling leaders through sensitivity testing, balanced the need to rapidly simulate the STSMs with the desire to reduce stochasticity. We discarded the first 500 timesteps of the simulation results to allow for model initialization and to reduce the impact of starting conditions. Using the final 500 timesteps for each of ten Monte Carlo realizations, we calculated LANDFIRE's reference conditions for each BpS, including:

1. the average proportion of states (Fig. 3),
2. the average fire frequency by fire severity class and for all fire severity classes combined (referred to as the "all fire" frequency), and

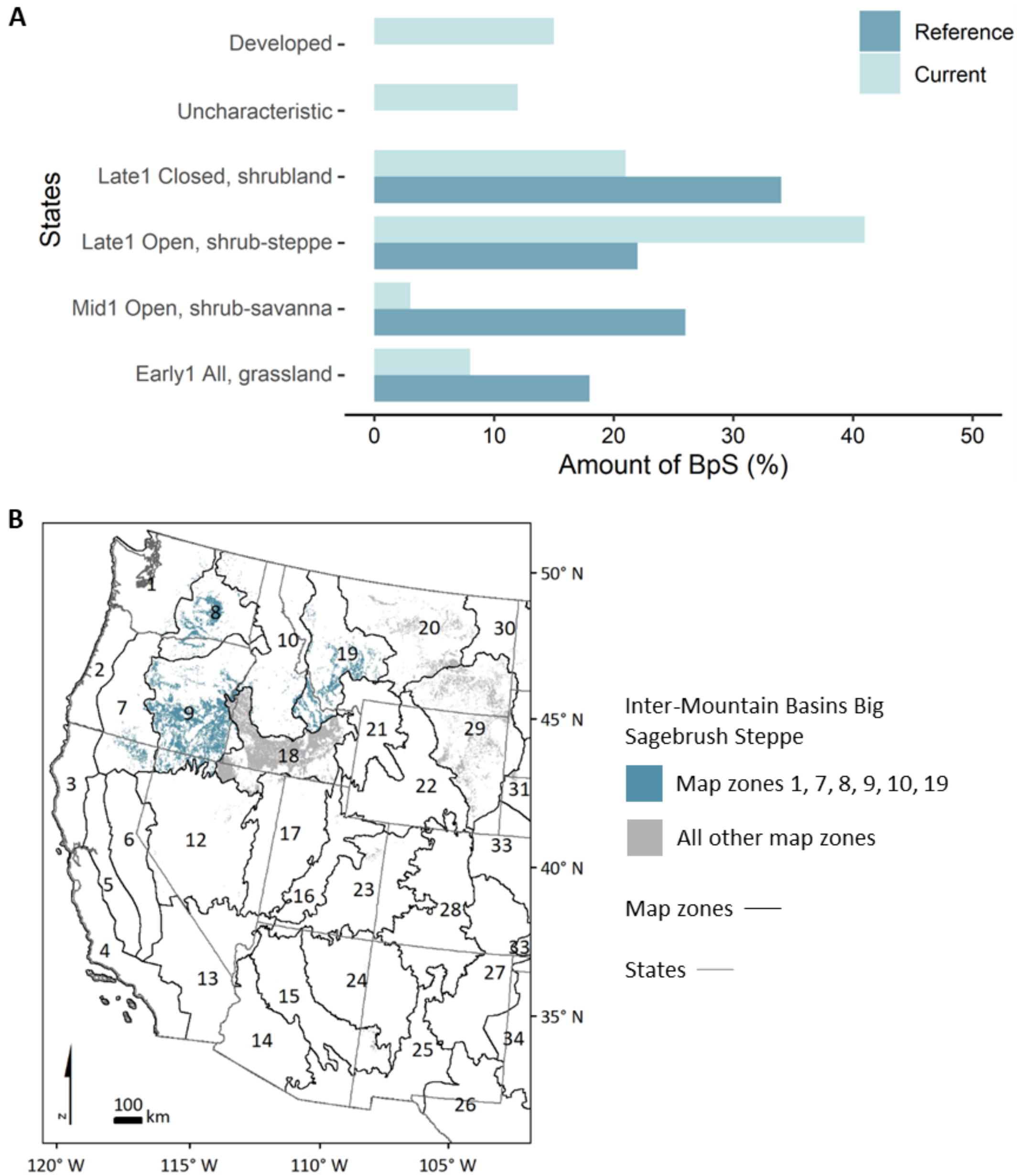

Fig. 3. LANDFIRE calculated reference conditions from STSM results. (A) In this example, vegetation reference conditions for the Inter-Mountain Basins Big Sagebrush Steppe BpS (LANDFIRE 2020*d*) are compared to the current state amount calculated from the succession class geospatial product (LANDFIRE Succession Classes 2020). Current conditions include developed and uncharacteristic (e.g., exotic species) states that were not present in the reference condition. (B) This BpS is found throughout the west, but reference conditions shown here are for the northwesternmost extent of its range (map zones 1, 7, 8, 9, 10, and 19).

3. the percent fire severity for every fire severity class (for a detailed description of reference condition calculations, see Appendix S3).

Given the intent of using the BpS model library in-part to inform regional and national scale assessments, we needed to promote consistency between STSMs. To do this, we developed a standard set of STSM definitions for model developers to attribute cover types (e.g., late development) and structural stages (e.g., open), and to characterize the probabilistic transitions (e.g., native grazing; Appendix S4). While the cover and structure categories were standardized, their specific definitions varied by BpS; model developers explicitly defined them in the BpS description. For example, model developers distinguished open and closed states for the Southern Rocky Mountain Ponderosa Pine BpS using a tree canopy cover break of 50% for the wetter, more productive northern extent of the BpS (e.g., map zones 20 and 29), decreasing to 30% at the more moisture limited southern extent (e.g., map zones 13, 14, 15, 25, and 26).

To produce a set of STSMs with comparable levels of detail across the country and to ensure compatibility with other LANDFIRE products, we designed modeling rules, such as restricting model developers to defining five or fewer states (Appendix S5: Table S1). In addition, we standardized and constrained the software functions available to model developers to help ensure consistency in outputs and facilitate quality checking hundreds of STSMs (Appendix S5: Table S2). Advanced modeling functions, such as simulating temporal variability in disturbance regimes, were prohibited because they required additional data that were unavailable for most locations and disturbance types.

Describing and documenting vegetation dynamics

Model leaders and developers wrote BpS descriptions to accompany each of the STSMs. The primary purpose of the accompanying narrative was to explain the BpS concept, describe the modeled states, and provide the scientific evidence and rationale underlying each STSM (see an example BpS description in Appendix S6). BpS descriptions were comprised of four primary sections.

1. *Overview.* Model developers listed all individuals who contributed to the development of the STSM and BpS description, and described the BpS concept, its geographic range, plant species composition, biophysical site characteristics (e.g., soils, moisture regime), and disturbance regimes, including the fire frequency and severity reference conditions calculated from the STSM results. Importantly, modeling leaders used the overview section to chronicle changes in the STSM over time, report reviewer comments, record modeling issues and assumptions, and note uncertainty about the degree of scientific support and agreement underlying the STSM.
2. *Succession classes*. Model developers described each state in the STSM including its indicator species and reference amount calculated from the STSM results. Model developers further defined each state with a complete and mutually exclusive set of cover, height, and life-form (i.e., herb, shrub, tree) attributes. In some cases, model developers also used composition (based on existing vegetation type) or leaf-form (i.e., broadleaf, conifer, or mixed conifer and broadleaf) attributes to help distinguish classes. These attributes provided a rule set for mapping the current location of the states in the LANDFIRE succession class geospatial product (LANDFIRE Succession Classes 2020; Appendix S7), a required input for mapping vegetation departure from reference conditions in the vegetation condition class geospatial product (LANDFIRE Vegetation Condition Class 2019). In some cases, model developers were constrained in STSM development by what LANDFIRE could map based on classification of satellite imagery. For example, while model developers included key understory plant species in the narrative, we discouraged them from distinguishing states based on understory species that could not be detected on remotely sensed imagery.
3. *Model parameters*. This section presents a table of information that we imported from ST-Sim containing the definitions of all modeled states and transitions, including disturbance intervals.
4. *References*. Model developers included literature citations referenced in the BpS description and related to the BpS. Reflecting the state of ecological science, the number of citations in the references section varied from one or two for ecosystems with little research to more than 30 for well-studied types.

Multiple Phases of Collaborative Development

LANDFIRE's charge—to produce nationwide, comprehensive data to support fire and land management activities—demanded sustained effort to produce current, high-quality datasets. The Program improved the usability of its products and specifically the BpS model library through four major production phases: Prototype, Rapid Assessment, National Implementation, and Remap and BpS Model Library Review (Fig. 4). LANDFIRE's modeling effort was preceded by the Interior Columbia Basin Ecosystem Management Project (Quigley and Arbelbide 1997) and the Fire Regime Condition Class (FRCC) project (Barrett et al. 2010) which together established a conceptual framework and an initial set of STSMs from which the BpS model library was built. From this foundation, we worked with model developers to refine existing FRCC models, expand the number of modeled ecosystems, incorporate new science, and apply the products. In this section, we describe this sustained, collaborative process of creating, testing, refining, and supporting the application of the BpS model library, describe the principles that guided our approach to collaborative model development (Box 2), and reflect on lessons learned in the process (Box 3).

Prototype

The LANDFIRE Prototype was designed to test methods for the nation-wide implementation of the Program. During the Prototype, modeling leaders created STSMs for the Central Utah Highlands and the Northern Rocky Mountains

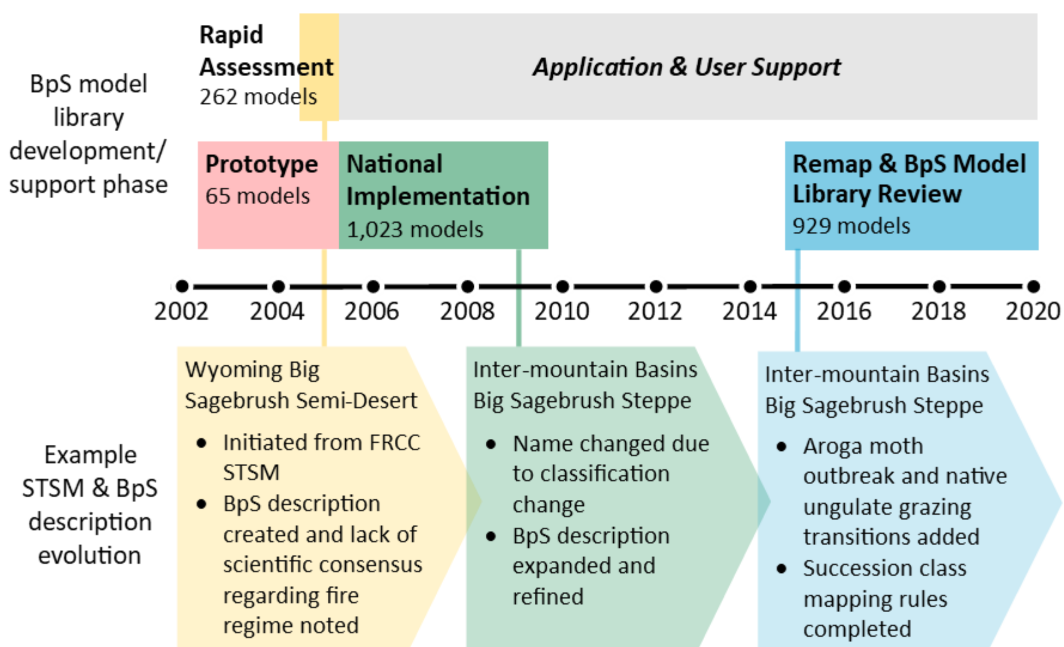

Fig. 4. This timeline tracks LANDFIRE's BpS model library through four phases of development and a phase of application and user support (above the line). Changes in the modeling units, the geographic extent of the effort, and ongoing refinement of the BpS concepts led to expansions and contractions in the number of records in the BpS model library over time. Below the timeline, we demonstrate the evolution of an example STSM and BpS description for the Inter-Mountain Basins Big Sagebrush Steppe BpS (LANDFIRE 2020*d*). The STSM for this BpS was initiated from a Fire Regime Condition Class (FRCC) project STSM and refined in multiple phases. During the Prototype phase, a related Wyoming-Basin Big Sagebrush STSM was created, but it is not included on the timeline because it was not used in subsequent development. Over time, model developers expanded and refined the BpS description and adjusted and added transitions to the STSM.

Box 2.

Guiding principles for LANDFIRE collaborative modeling

The use of an expert-based process to co-develop a national model library presented advantages and challenges. The process allowed LANDFIRE to create STSMs and document ecosystems based on expert knowledge and experience when published data were lacking. In addition, modeling meetings and support efforts provided outreach for the Program, offered training on tools and concepts among the user community, and created a forum where natural resource scientists and managers could network. Challenges to garnering expert input included finding participants and sustaining their engagement, quickly training model developers on STSM concepts and software, and managing disagreements about ecosystem ecology among model developers. Several principles guided our approach to developing the BpS model library (updated from Blankenship et al. 2012).

1. *Collaboration*. We developed an inclusive and collaborative approach for expert engagement and promoted a learn-by-doing method for producing the BpS model library. We sought a broad spectrum of contributors with knowledge and experience of ecosystem structure and function and a willingness to learn about STSMs. Because most model developers had no prior experience creating STSMs, modeling leaders provided training on the concepts and software. Working in teams and using existing STSMs as a starting point for creating new ones helped jump start STSM development for novice modelers. Additionally, LANDFIRE's modeling rules and standards constrained the modeling options and reduced the complexity of the task.
2. *Balanced flexibility and consistency*. We attempted to create a flexible and consistent modeling framework while acknowledging the trade-offs. Modeling leaders applied a variety of approaches to create STSMs such as drafting STSMs on flip-charts, creating "straw" STSMs for model developers to critique, and modeling online when in-person meetings were not possible. This flexibility was countered by constraints on how STSMs could be attributed. For example, we allowed modelers to define five or fewer states per BpS to ensure consistency in resolution across the set of STSMs. While these rules and standards may have limited applications of the products outside of LANDFIRE, they resulted in a product that met the Program's needs.
3. *Scientific transparency*. We promoted transparency to encourage understanding about the products and their appropriate applications. We encouraged model developers to cite all sources used in STSM and BpS description development, record their assumptions, and include a diversity of evidence and expert opinion. Modeling leaders captured all review input and their decisions in the BpS descriptions. This documentation facilitated later evaluation and appropriate use of the BpS model library.
4. *Adaptive learning*. Recognizing the need to adjust models as our understanding of ecosystems evolved and the difficulty of creating so many STSMs and BpS descriptions in a relatively short timeframe, we used an iterative process to incrementally improve the BpS model library over time. During each phase of development, we adjusted our processes in an attempt to improve the quality of the BpS model library and increase expert participation. For example, we used an online process in partial response to limited federal travel budgets during the Remap and BpS Model Library Review phase. We also encouraged model developers to use a heuristic approach to STSM development whereby model parameters were adjusted incrementally and run iteratively to test assumptions and arrive at a final product.

(map zones 16 and 19, respectively; Rollins and Frame 2006). These STSMs pre-dated the modeling guidelines and rules described above (see *Conceiving and modeling vegetation dynamics*), and they typically had more states and transitions than the STSMs developed in later phases. Modeling leaders noted the paucity of information for parameterizing fire frequency and severity for every state within a vegetation community. They recommended that future phases use expert input to estimate these parameters (Long et al. 2006), setting the stage for later collaborative development of the full BpS model library.

Box 3.

Lessons learned from a nation-wide ecological modeling effort

The development of the BpS model library presents a rare learning opportunity, not only about the ecosystems, but also about such a broadscale collaborative process. Blankenship et al. (2012) captured many early lessons learned. Here, we reflect on four additional insights from this ongoing effort.

1. *Cultivating the user community*. Experts are key contributors to creating the BpS model library; however, sustaining expert engagement in the effort is challenging. Among the ways, LANDFIRE engages and cultivates its model developer base is supporting users in their applications of the BpS model library and associated LANDFIRE geospatial products. By providing that collaborative assistance, LANDFIRE creates and maintains a knowledgeable user community that contributes to ongoing BpS model library development.
2. *Institutional leadership*. Maintaining a collaborative, nation-wide effort spanning nearly two decades takes commitment. Continuous funding is key, which the U.S. Department of Agriculture and U.S. Department of the Interior have provided, but equally important is institutional support that provides direction, a platform on which to publish the BpS model library (i.e., www.landfire.gov), and flexibility (e.g., allowing us to also develop www.landfirereview.org). The Nature Conservancy is primarily responsible for the development, improvement, and support of the BpS model library. The Conservancy's LANDFIRE Team has been a principal partner in the LANDFIRE Program for 16 years through several, multi-year cooperative agreements with the U.S. Forest Service Fire and Aviation Management branch.
3. *The journey vs. the destination*. While results are important, the process of collaborative modeling yields many insights. In a general discussion of STSMs, Provencher et al. (2016) stated that "the social benefit of model building is that it allows land managers and scientists to explicitly document their understanding and assumptions about ecological processes, management actions, and the interactions between the two" (p. 379). Price et al. (2012) used LANDFIRE STSMs in a collaborative modeling process and noted that the collaboration increased "the validity and transfer of results to those involved in making management and policy decisions affecting landscape conservation" (p. 86).
4. *Demonstrating impact can be a challenge*. Modelers often use the LANDFIRE STSMs early in complex projects, so it is hard to show potential new users where the models played a specific role in decision-making. For example, McGarigal et al. (2018) used modified LANDFIRE STSMs to drive spatial simulations in the Tahoe National Forest, noting that their approach "demonstrates the feasibility of creating detailed, specific, and quantitative desired future conditions, and monitoring progress toward achieving those conditions" (p. 110). While they were one toolset among many, the LANDFIRE STSMs helped support the proof of concept for a key tenet of the 2012 Planning Rule (NFMA 2012 Planning Rule 2015) and associated directives for U.S. National Forest management by setting the stage for adaptive management at a watershed scale (McGarigal et al. 2018).

Rapid Assessment

The goal of the Rapid Assessment was to quickly produce regional-scale vegetation and fire regime geospatial products for the conterminous USA to fill data needs until the National Implementation phase was completed. Following recommendations from the Prototype, we co-developed STSMs and BpS descriptions in collaboration with model developers in a series of 12 regional workshops facilitated by modeling leaders. Model developers used STSMs from the FRCC project as a starting point when appropriate and created many new STSMs and BpS descriptions for vegetation communities that had no analog from the FRCC project. During and after workshops, we solicited review of the draft STSMs and BpS descriptions to garner additional input and ensure the products incorporated the best available science. At this time, we implemented the LANDFIRE modeling rules (Appendix S5: Table S1) and standards (Appendix S5: Table S2) and used a quality

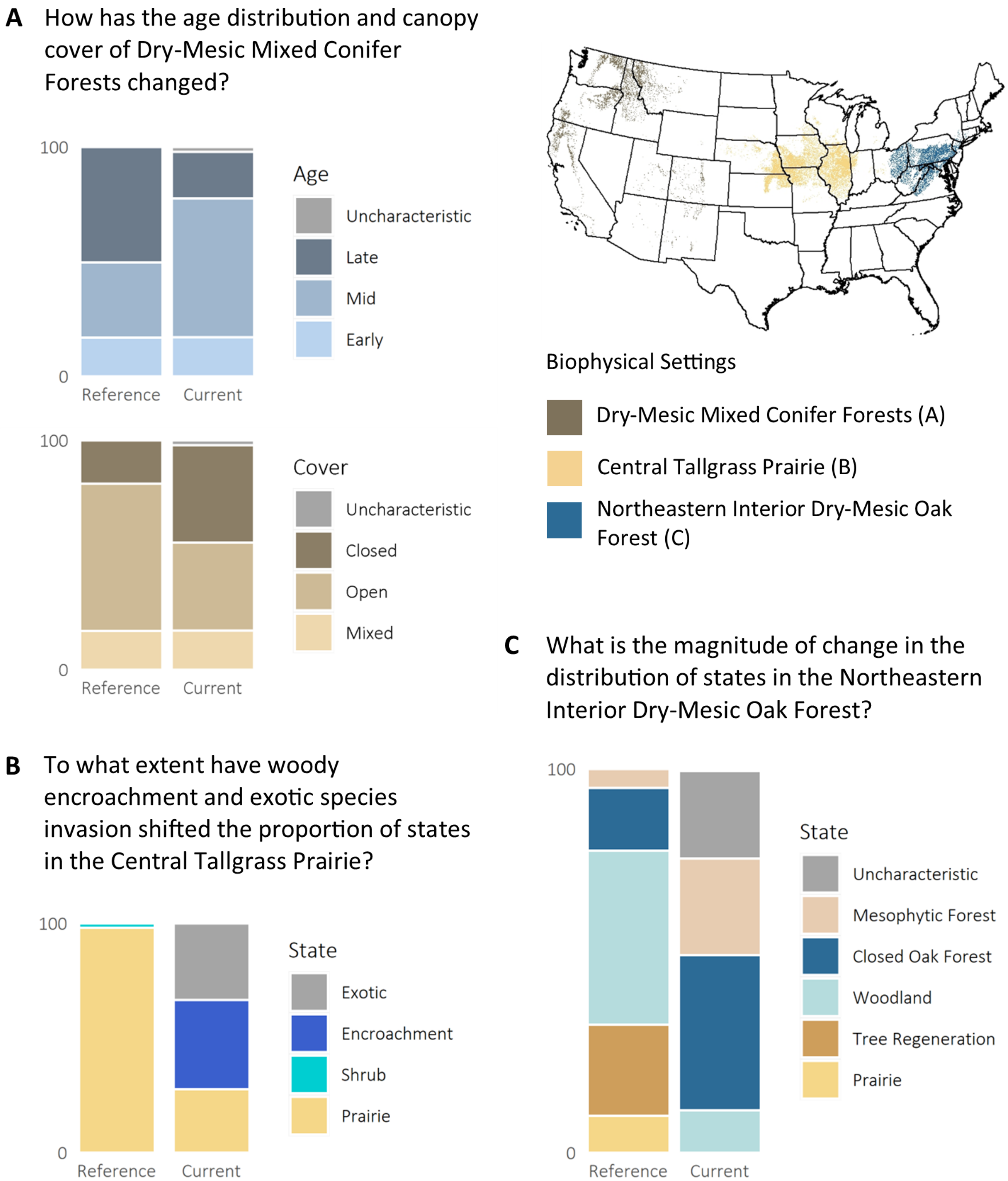

Fig. 5. Using examples from across the USA, we demonstrate the use of the LANDFIRE reference conditions as a baseline for assessing change and providing context for the scale of three distinct land management issues. These charts compare reference conditions, calculated from STSM results as an average of relevant states classes, to current conditions, calculated from the LANDFIRE succession class geospatial product (LANDFIRE Succession Classes 2020). In the charts, the term "uncharacteristic" refers to conditions that are outside of the reference condition such as the presence of ruderal or exotic vegetation. (A) Mediterranean California, Northern Rocky

Fig. 5. *(Continued)*

Mountain, and Southern Rocky Mountain Dry-Mesic Mixed Conifer Forests have shifted from predominantly late (i.e., older) to mid (i.e., younger) age classes and from predominantly open to closed-canopy forest conditions. (B) In the Central Tallgrass Prairie BpS, all of the low cover native shrub and much of the prairie states have been replaced by exotic species and woody encroachment states. (C) In the Northeastern Interior Dry-Mesic Oak BpS, historically dominated by savanna and woodland states, there has been a threefold increase in closed oak and mixed mesophytic forest states compared with reference conditions.

control process to verify that all STSMs and BpS descriptions met them. During this phase, we rapidly trained more than 270 workshop participants in STSM concepts and collaboratively refined and expanded 186 FRCC project STSMs to create a set of 262 STSMs for the conterminous USA.

National Implementation

The goal of the National Implementation phase was to complete the nation-wide mapping of LANDFIRE's complete suite of geospatial products along with a comprehensive set of STSMs for setting reference conditions, calculating vegetation conditions, and mapping historical fire regimes. Changes such as implementing the Ecological Systems classification as a starting point for BpS and the use of individual map zones as model summary units prompted the expansion and refinement of the BpS model library. In many small workshops, model developers refined the Rapid Assessment BpS model library and created new STSMs and BpS descriptions to represent ecosystems that were not modeled previously. This included all vegetation communities in Hawaii and many in Alaska. As before, we sought peer review and quality checked all STSMs and BpS descriptions. This phase resulted in the development of the first complete, comprehensive, and quantitative set of 1023 STSMs and BpS descriptions for the USA, representing the contributions of more than 700 individuals (including both Rapid Assessment and National Implementation model developers).

Application and user support

Feedback from the users of the BpS model library and LANDFIRE geospatial products was a key driver of continued product development and refinement. LANDFIRE began outreach and engagement with users following the Rapid Assessment, and user support was the primary focus of modeling leaders between the National Implementation and Remap and BpS Model Library Review phases (described below). We raised awareness about the products, their utility, strengths, and limitations through conference presentations, webinars, and interactions with colleagues in our professional networks. We also supported a wide range of applications of the BpS model library and LANDFIRE geospatial products such as regional-scale assessments of vegetation conditions, fire and fuels planning, forest plan revision, conservation planning and prioritization, and teaching natural resource-related laboratory exercises in partnership with academic researchers. These applications and engagement activities provided valuable feedback that helped us improve the BpS model library and expand its usability. For instance:

1. While supporting the mapping of STSM states in the succession class geospatial product, we found that the succession class mapping rules (Appendix S7) covered the most common, rather than every possible, mapped expression of the states. As a result, we developed a complete succession class mapping rule set during the Remap and BpS Model Library Review phase.
2. Several users of the fire regime group geospatial product identified situations where they felt that the fire regime (which was classified based on the fire frequency and severity of the STSM) was inappropriate. We flagged this input for later review.
3. As a result of a partnership between LANDFIRE and the Fire Effects Information System (FEIS; Smith 2010), FEIS staff provided feedback on approximately 80 BpS descriptions based on their review of the fire effect literature. We used this information during

the Remap and BpS Model Library Review phase to ensure that BpS descriptions incorporated a broad spectrum of literature and that the STSM parameters reflected that information.

Remap and BpS Model Library Review

The goals of the Remap and BpS Model Library Review phase were to update LANDFIRE geospatial products using new imagery (Picotte et al. 2019) and to update and improve the BpS model library with new science and feedback gleaned via our user support work. We engaged experts and conducted the review primarily through an online process supplemented with a few workshops for larger groups and many one-on-one meetings. We used literature and expert judgment to support the hands-on examination and testing of STSMs and the refinement of the BpS descriptions. During this phase, modeling leaders modified the existing succession class mapping rules to create a mutually exclusive and exhaustive rule set and incorporated other feedback gleaned from the application and user support work described above. Feedback from more than 90 individuals allowed us to update and refine 279 STSMs and BpS descriptions during this phase. The resulting BpS model library, composed of 929 records, was slightly smaller than the National Implementation version because some records were combined based on reviewer comments and where STSMs and BpS descriptions were nearly identical across map zones. The most recent BpS model library is freely available from the LANDFIRE website (https://www.landfire.gov/bps-models.php), and users can access the STSMs through the landfirevegmodels SyncroSim package.

Applying Models to Land Management

By documenting the collective understanding of hundreds of experts about the pre-settlement structure and function of all major terrestrial ecosystems in the USA, the BpS model library offers land managers a baseline for measuring change (Fig. 5), a tool for understanding ecosystem dynamics, and information for developing desired future conditions. Unlike static datasets, the BpS model library integrates multiple drivers of vegetation change, allowing users to actively learn and test assumptions about how changes in key drivers may have influenced landscape structure. The comprehensive nature of the BpS model library facilitates cross-boundary applications, and the internal consistency and relative simplicity (e.g., no more than five states) of the STSMs reduce the user's learning curve. While the BpS model library was developed to meet the specific needs of LANDFIRE (Fig. 6), it has been widely applied for other purposes, either as delivered or after local review and modification by researchers and land managers. In this section, we describe the application of the BpS model library to resource management and present selected examples of its use.

Supporting understanding of ecosystem dynamics

LANDFIRE recognized the need for a national set of reference conditions despite the caveats associated with choosing a particular reference time period where the range of vegetation drivers did not include many current stressors, such as exotic invasive species, human land use, and climate change (Keane et al. 2007). Despite these limitations, depictions of the relative proportion of different vegetation classes under historical conditions (or HRV) have been promoted in the resource management field as a reference for understanding patterns of degradation, and as a tool for informing restoration goals (Keane et al. 2007, Haugo et al. 2015, Donato et al. 2020). While historical ecological information does not provide a prescription for restoration or a blueprint for desired conditions, it offers insight into the spatial and temporal variability of processes that have shaped ecosystems, which can support land management planning (Millar 1997, Keane et al. 2009), even under a changing climate (Fulé 2008, Stephens et al. 2013, Higgs et al. 2014). By documenting the drivers of vegetation change and the impacts of various disturbances, and considering disturbances as foundational ecosystem processes, the BpS model library offers manager context for current landscape conditions and how those conditions might change in the future.

Our work with academic researchers, land managers, and conservation practitioners suggests that the BpS model library provides a helpful foundation for exploring the ecological

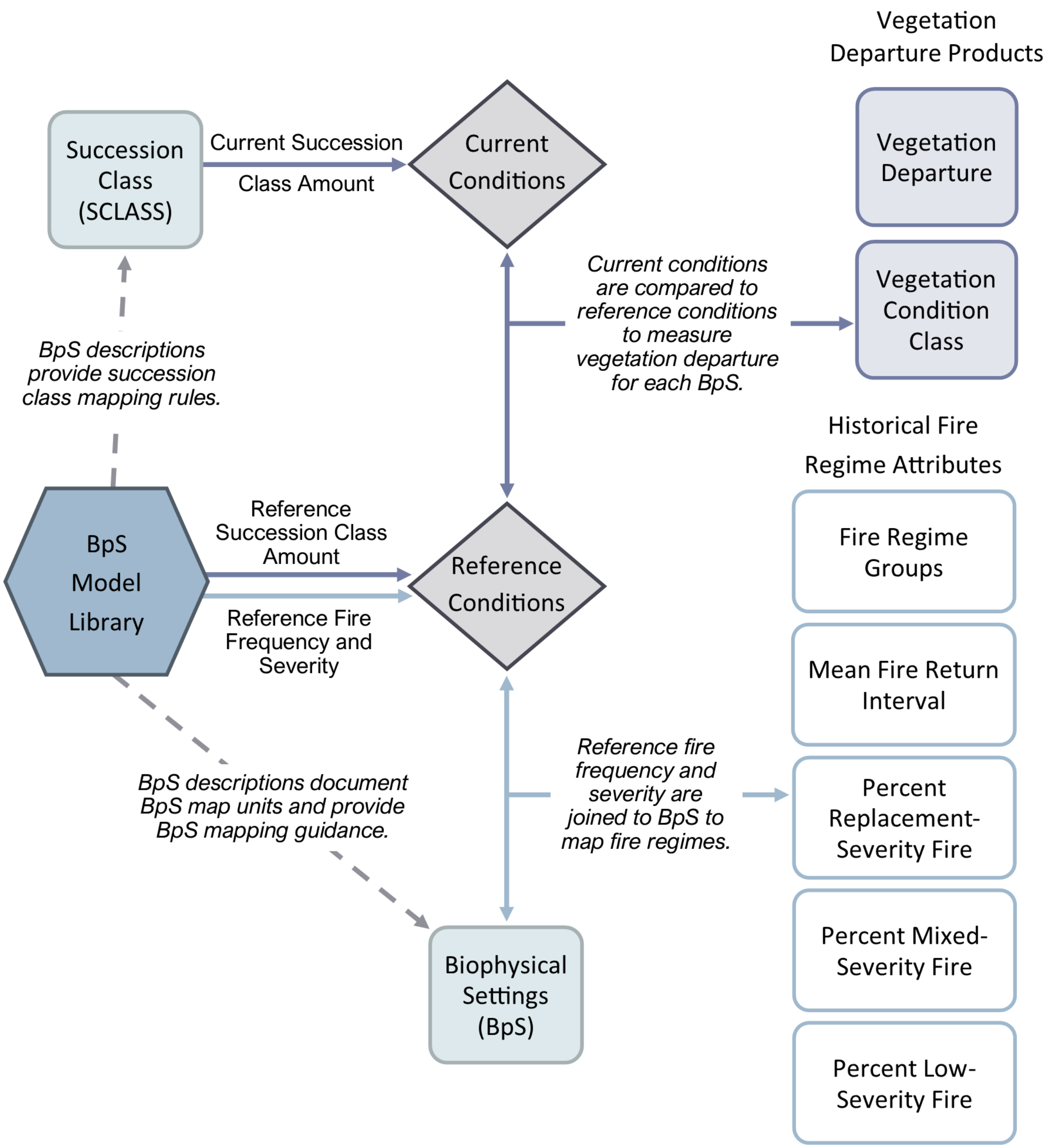

Fig. 6. The BpS model library was an important input into other LANDFIRE products. The BpS descriptions documented the BpS mapping units and were used as a primary information source for creating the BpS geospatial product based on biophysical site factors and disturbance regimes. The BpS descriptions also defined the STSM states and provided a set of rules to map their current location in the succession class geospatial product. LANDFIRE compared the reference succession class amount (estimated from the STSMs) with the current succession class amount (quantified from the succession class geospatial product) to measure and map vegetation departure. Reference fire frequency and severity were mapped through a crosswalk to BpS to produce the historical fire regime attributes.

concepts of succession and disturbance. Cash et al. (2006) describe an effective model of technology transfer as requiring users to "understand the new technology not simply to the point of being able to take it out of the box and turn it on but rather to the point of being able to take it apart, put it back together slightly differently, and fix it when it breaks" (p. 474–475). This aptly describes the instances where we have built relationships with BpS model library users and supported them through reviewing, modifying, and applying STSMs. While outside the Program's original intent (Fig. 6), these applications provide additional pathways by which these collaboratively produced products support other processes (often again incorporating co-production) and often result in feedback that informs LANDFIRE product updates.

Project teams across multiple regions and ecosystems have used the BpS model library as the foundation for stakeholder-driven planning processes (Low et al. 2010, Price et al. 2012, Nixon et al. 2014). The STSM's structured framework can help facilitate the engagement and buy-in of both subject matter experts and nontechnical stakeholders by providing a shared and modifiable model of how ecosystems function. Using this framework, groups can test assumptions, visualize possible outcomes of management actions, and compare trade-offs between proposed activities (Low et al. 2010, Price et al. 2012). For example, a diverse stakeholder group calibrated LANDFIRE STSMs for the North Zone of the Cherokee National Forest and used them to explore possible outcomes of forest management activities. The modeling process created a common understanding of the impacts of potential management decisions on the landscape and resulted in a forest-wide set of recommendations acceptable across the stakeholder spectrum (Cherokee National Forest Landscape Restoration Initiative Steering Committee 2012).

Assessing current conditions and informing desired conditions

Building from a deep history of using information on historical conditions to inform management and conservation activities (e.g., review by Beller et al. 2020), many users have deployed the BpS model library to evaluate current vegetation and departure from reference conditions. In the Pacific Northwest, Haugo et al. (2019) used the BpS model library to gain insight into potential impacts of changing fire regimes. Similarly, Noss et al. (2015) used LANDFIRE reference conditions to identify the South Atlantic Coastal Plain as a biodiversity hot spot. On the Nantahala and Pisgah National Forests, Forest Planners coupled locally calibrated LANDFIRE STSMs with social, economic, cultural, and ecological considerations to develop a set of desired conditions for the proposed land management plan (Nantahala and Pisgah National Forests 2020).

Simulating effects of management actions

LANDFIRE STSMs can be modified to examine the potential impacts of landscape changes resulting from management activities, which can help inform and support effective decisions. DeMeo et al. (2018) and Haugo et al. (2015) used LANDFIRE STSMs in regional-scale restoration need assessments to identify the types, location, and amount of treatments needed to restore Pacific Northwest forests. Various projects modified the LANDFIRE STSMs to include novel states (e.g., cheatgrass) and pathways (e.g., prescribed fire) to simulate management scenarios (Low et al. 2010, 2017, Tuhy et al. 2010, Cherokee National Forest Landscape Restoration Initiative Steering Committee 2012). Using a collaborative scenario development process, Swearingen et al. (2015) retooled LANDFIRE STSMs to compare different management scenarios in northeast Wisconsin under current and future climate representations to understand possible future landscape conditions and inform conservation planning. Similarly, Costanza et al. (2015*b*) used modified LANDFIRE and other STSMs to represent current conditions for 49 ecosystems in North Carolina and used these tools to examine projected impacts of three forest biomass production scenarios.

Understanding Model Limitations and Appropriate Use

We anticipate that the BpS model library will continue to offer land managers a flexible tool for understanding dynamic ecosystems. We identify three types of limitations for users to consider when applying the BpS model library: the knowledge base, resolution and scale, and the framing of ecological variability.

Each STSM represents an aspatial estimate of pre-settlement vegetation structure and function based on literature and expert judgment. While we instructed model developers to cite and use literature and data appropriate for the geographic range of the BpS and the reference time period, ultimately it was developers' decisions that shaped the definitions of states and transitions used to describe each BpS. The use of expert judgment by LANDFIRE and other programs, such as Ecological Site Descriptions, has been criticized (Knapp et al. 2011, Twidwell et al. 2013), but often local knowledge and expert opinion are the only information sources available for creating STSMs (Knapp et al. 2010, Czembor et al. 2011). Even when available, published literature did not always promote agreement among model developers. The wide range of fire frequencies reported in the literature for sagebrush ecosystems (Innes and Zouhar 2018, Innes 2019) is reflected in the eight STSMs in the BpS model library representing Inter-Mountain Basins Montane Sagebrush Steppe. Fire return interval estimates for these STSMs range from approximately 30 to more than 200 years. We suggest that users calibrate LANDFIRE STSMs with locally relevant information when it is available. When data are lacking, users can conduct sensitivity analyses to test assumptions and explore the implications of key uncertainties such as fire return intervals. To support these types of efforts, Blankenship et al. (2015) developed a method for incorporating uncertainty in LANDFIRE STSMs to estimate state class reference condition ranges rather than single point estimates.

LANDFIRE STSMs have an inherent spatial and thematic resolution that determines their recommended application scale. For consistency and compatibility, the Program chose to use map zones as a geographic framework for its products during the National Implementation phase. As a result, model developers could not always utilize finer scale local data in STSM development, and vegetation dynamics for a BpS were held constant throughout a map zone. LANDFIRE also constrained its STSMs thematically by limiting model developers to defining five or fewer states per BpS. Given these constraints, the BpS model library and the reference conditions derived from it are intended for use at the map zone scale (Appendix S2). However, many users have found the STSMs useful at finer scales, especially after review and with local adjustment.

LANDFIRE chose not to include spatial or temporal variability in its STSMs due to lack of data and the need to maintain a consistent level of detail across over 900 STSMs. We discuss two primary effects of this choice. First, LANDFIRE STSMs do not incorporate spatial processes such as fire spread or insect outbreaks that contribute to landscape heterogeneity. Second, all BpS were simulated based on average annual probabilities at the scale of a simulation cell. Therefore, for BpS with very infrequent but large episodic disturbances (e.g., wet temperate forests in the Pacific Northwest), simulated disturbance events were more frequent and affected smaller extents (i.e., fewer simulation cells) than actual historical events (Donato et al. 2020). For these reasons, LANDFIRE's STSMs exhibit less variability than real landscapes, especially those with infrequent, large disturbances.

Given the Program's use of STSMs to generate reference conditions as long-term averages for large areas (i.e., map zones), the under-estimation of variability is less important than for application at finer scales, where variability is expected to have more significant impacts (Wimberly et al. 2000). When working at scales finer than the map zone, we advise users to consider adding temporal variability and spatial processes as needed to create more realistic ranges of reference landscape conditions. Such an approach has been developed using STSMs to estimate the natural range of variability for the Western Cascade Range of Washington (Donato et al. 2020). In addition, ST-Sim can be run spatially or linked with other models to incorporate spatial dynamics such as fire spread (Jarnevich et al. 2019).

Future Improvements

Future improvements to the BpS model library can be thought of as programmatic; that is, changes are made to STSM parameters and incorporated by LANDFIRE, or changes can be local, made by users and possibly not shared beyond a specific landscape or project. We plan to make programmatic improvements and to help tie local improvements back to the official BpS model library. For example:

1. *Living models*. Ongoing review and improvement of the BpS model library is needed to incorporate new science. For example, during the Remap and BpS Model Library Review phase, the reviewers of the Central Appalachian Dry Oak-Pine Forest STSM and BpS description changed the fire frequency estimate from 99 to 13 years based on multiple fire history studies published since the STSM was created during the National Implementation phase (Lafon et al. 2017). In the future, we intend to develop a continuous improvement process to capture new information and keep the BpS model library consistent with the latest research.
2. *Identifying research needs*. LANDFIRE and the STSM user community more broadly recognize the need to systematically track the data that support STSMs (Wilson et al. 2015). LANDFIRE used the BpS descriptions to report the sources and assumptions behind its STSMs. We are exploring several additional ways to make this information more transparent including linking source citations to STSM parameters within the software (a function that does not currently exist in ST-Sim), adding a Research Needs section to each BpS description, and assigning a rating to each STSM indicating its level of scientific support. Conducting sensitivity analyses of uncertain STSM parameters could help identify key uncertainties and guide future research.
3. *Supporting collaboration*. We encourage local refinement of the BpS model library and support these efforts when possible. We are collaborating with the ST-Sim developer on the creation of an online STSM library where model developers could publish STSMs and allow others to use and further refine them in a collaborative environment.

Conclusion

Since 2002, LANDFIRE has worked with approximately 800 model developers around the nation to collaboratively produce a library of more than 900 STSMs and BpS descriptions covering all major terrestrial ecosystems in the USA. This product establishes the first comprehensive national baseline for measuring vegetation change in the USA, providing land managers and policymakers with a tool to support vegetation restoration and fuel management activities at regional to national scales. To our knowledge, this effort represents the largest participatory modeling effort of its kind completed in the USA, and we expect it is one of only a few efforts that incorporate revision of collaborative models. The BpS model library synthesizes information about the growth and development of vegetation over time, documents the frequency and effects of disturbances, and offers users an all-lands resource for understanding ecosystem ecology. In the current environment characterized by unprecedented ecological change, the BpS model library is an adaptable tool for evaluating land management options and forecasting future conditions.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3484/full