Fire Management today

Volume 69 • No. 2

Fire Research

Wind Models
Fuel Models
Forecasting Suppression Costs
Smoke Management

United States Department of Agriculture
Forest Service

This Issue...

This issue provides a glimpse into the role that research and technology play in the management of fires today and into the future. Over the years, the Forest Service and the interagency fire community have considered not only the science behind fire itself, but also the science of predicting fires and what is likely to happen when a fire-start occurs. Many aspects of fire management—fuels, wildland-urban expansion, and environmental factors among them—are different today than they were even a decade ago, making it more critical than ever to use emerging science and state-of-the-art methods of prediction to keep firefighters and the public safe. The articles in this issue reflect just a few of the models, tools, and approaches that are currently shaping and advancing the science and management of fire to achieve that end.

—Tory Henderson, Issue Coordinator

Erratum

In *Fire Management Today* vol. 69, no. 1 [Winter 2009], the caption for the photo of snow geese near a Marsh Master in the "Myth Busting about Wildlife" article gave an incorrect credit. It should have credited Drew Wilson, Virginia Pilot.

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On the Cover:

Flames run through a stand of trees as winds push a fire forward during the Skinner Fire, Tusayan Ranger District, Kaibab National Forest, Arizona. Photograph by Mike Uebel, Forest Service, Kaibab National Forest, 2005.

The USDA Forest Service's Fire and Aviation Management Staff has adopted a logo reflecting three central principles of wildland fire management:

- *Innovation:* We will respect and value thinking minds, voices, and thoughts of those that challenge the status quo while focusing on the greater good.
- *Execution:* We will do what we say we will do. Achieving program objectives, improving diversity, and accomplishing targets are essential to our credibility.
- *Discipline:* What we do, we will do well. Fiscal, managerial, and operational discipline are at the core of our ability to fulfill our mission.

Firefighter and public safety is our first priority.

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Short Feature

Anchor Point

by Tom Harbour
Director, Fire and Aviation Management
Forest Service

Wildland Fire Decision Support System Tools

The Forest Service has always had a symbiotic relationship between the practitioner and the scientist. Throughout the years, this relationship has aided the wildland firefighter in becoming a better, more efficient, safer firefighter on the ground.

Over the past three decades, wildland fires have dramatically increased in size and complexity. Although fires have changed, the tools in our decision support toolbox have remained relatively constant. The major tool available to line officers and incident managers—initially, the Escaped Fire Situation Analysis (EFSA) and now the Wildland Fire Situation Analysis (WFSA)—has not changed for nearly three decades. It is time to adapt!

Fire and Aviation Management is proud to release the Wildland Fire Decision Support System (WFDSS), designed to streamline and improve decisionmaking processes while taking advantage of vast improvements in science and technology. The current evolution through the WFDSS combines the best of the former systems with new improvements to the Wildland Fire Situation Analysis (WFSA), the Wildland Fire Implementation Plan (WFIP), and Long-Term Incident Planning (LTIP) to create one support tool. This system provides agency administrators and incident commanders the ability to use scaleable decision support tools when considering fire behavior modeling, economic principles, and information technology, and will result in decisions that are safer and more effective for the firefighter and the public. The WFDSS provides fire management officials the intelligence to understand where the fire is at a particular time and when it will reach a particular area. It will allow firefighters on the ground to go toe-to-toe with the fire when it is necessary and safe to do so, but help them identify when to engage at another time because the risks outweigh the benefits.

When we look to the future, the role of science will continue to be very important to the firefighter on the ground.

When we look to the future, the role of science will continue to be very important to the firefighter on the ground. It will provide newer, better tools to enhance performance, be more cost-effective, and will provide improved predictability for line officers and fire management officials, allowing them to manage fire—regardless of complexity—in the safest, most efficient, most cost-effective manner. The WFDSS exemplifies our dedication to working toward this future for fire management. ■

Further Information

IinciWeb may be accessed at <http://165.221.39.44/>.

Forest Service employees may access Tom Harbour's Blog by accessing <http://fsweb.wo.fs.fed.us/>, clicking on *FS Blog*, entering e–authentication, clicking on the tab labeled *Directory of Blogs*, and then click on *Tom's Blog*.

The Key Decision Log: Facilitating High Reliability and Organizational Learning

Anne E. Black

If you were involved in the 2008 fire season in the West, you may have heard the term "Key Decision Log" or "KDL." This article describes the KDL concept, it's intent (past and present), how it was applied in 2008, and where the practice is heading.

The KDL's purpose is to facilitate continuous learning in fire management processes and outcomes. It arose out of a dual desire to continually improve organizational performance and to meet societal demands for transparency in decisionmaking. Its development is a story of innovation and feasibility: a mix of 'ivory tower,' grounded practice, learning theory, and hard, cold reality. KDL takes "applied research"—applying and developing research-based knowledge to understand a problem—into the realm of "action research"—an iterative, collaborative effort taken by researchers and managers to understand and improve organizational process and culture.

Concept Development

The content and structure of KDL stem from initial conversations among geographic area and national incident commanders (ICs), Forest Service fire staff, line officers, and researchers during the 2007 fire season in Idaho and Montana. We asked two questions: "How do you define success?" and "How do you know when you're achieving it?" The most common response—meeting the line officer's objectives—was also acknowledged as difficult to impossible to assess because, in the current system, there often isn't a measurable objective to track, some measures are difficult to obtain in the midst of a multiteam incident, and it is difficult to assess or gain insight into the more-effective versus the less-effective choices and actions without also capturing the rationale behind them. Moreover, the key reasons for embarking on such an effort are to improve current incident outcomes, improve next year's actions, and provide a way to describe outcomes, not to grade participants in a given event. This requires a standardized and centralized process that promotes reflection and wide dissemination of lessons learned.

Anne Black is a social scientist/ecologist for the Forest Service's Aldo Leopold Wilderness Research Institute and the Rocky Mountain Research Station, Missoula, MT.

> We asked two questions: "How do you define success?" and "How do you know when you're achieving it?"

We combined our 2007 insights into a collaborative Joint Fire Science Project involving Forest Service researchers, academics, resource agencies' staffs, and board members of the Northern Rockies Coordination Group (NRCG) to develop and test a means for capturing, tracking, and understanding "progress" and "success" in incident management (see A Multidisciplinary Approach to Fire Management Strategy, Suppression Costs, Community Interaction, and Organizational Performance, in this issue). We grounded our thinking on concepts of high reliability, high performance, and organizational learning.

From organizational learning theory (Garvin 2000) comes the understanding that learning has two parts: attention and deliberation. It doesn't simply happen of itself. Organizations that learn successfully do so because they establish explicit protocols to document critical processes and then use these in structured reflection, such as in After Action Reviews, to uncover the root causes of successful and unsuccessful outcomes.

From high-performance theory comes the recognition that, while success depends on effective internal business practices (risk management), achieving and sustaining high performance also requires consistent and effective attention to financial management (operational efficiency and transparency), working relationships (communication and collaboration), and innovation and learning (experimentation, error detection, reflection, etc.) (Norton and Kaplan 2000).

Operating with high reliability (Weick and Sutcliffe 2007) requires noticing and acting quickly and decisively on small deviations. High reliability theory reminds us to periodically question whether we are focusing on the most telling information and how well our interpretation of that information matches the actual situation. Organizational performance theories remind us that *where* we focus attention and how we frame the world are as much determined by organizational policies and culture as by individual experience. Thus, it becomes critical to track and periodically revisit both *operational effectiveness* ("Are we noticing all that we need to, and are we interpreting what we see effectively?") and *organizational effectiveness* ("What do our patterns of focus reveal about perceived organizational priorities and conflict resolution, and are these the most effective?").

Beyond this, we wanted to remain cognizant of "practical drift" in organizational life (Snook 2000): as experts of our local systems, we adapt corporate protocols and procedures to better match local conditions. This works well until local adaptations begin to collide or offset each other. Especially in multilevel and complex situations, periodically checking to ensure that all parts of the system are in alignment and not working at crosspurposes to each other becomes critically important.

Practical drift is particularly difficult to detect when "minor" adaptations cause mismatches across boundaries—geographic areas, functions, time, or organizational scales—because, by definition, a boundary marks the edge of our local expertise or attention. Assessing practical drift requires cultivating a corporate (broader) perspective in which the context and behavior of individual and small group actors, the patterns that emerge from the interaction of these actors across boundaries, and the drivers of these patterns (some of which undoubtedly arise from outside the local context) are identified.

Theory suggests, then, a process that can track alignment among partners, reveal the focus of attention and patterns of focus, and capture the criteria used to interpret what is noticed in terms of risk management, financial management, and partner/stakeholder relations. The process needs to be completed at the team, host, and incident levels but be consistent across incidents and centrally collected to allow for developing insights and lessons at both operational and organizational levels.

> Continuous improvement in decisionmaking considers both the cultural frame of reference that focuses decisionmakers' attention on specific aspects of a situation more than others and the way in which this information is interpreted, weighed, and integrated to arrive at a particular decision.

From Theory to Practice

The fire community is not starting at ground zero; there are a number of practices in place that support organizational learning. For instance, unit or incident logs often capture key decisions, we've begun to build After Action Reviews (AARs) into our business model, and there are a number of ways in which key players communicate and check alignment and progress during an incident (daily check-ins between line officers and ICs, for example).

However, many of these procedures are not consistently practiced, particularly as a means to compare intentions for specific incident outcomes. Recent investigations into who conducts AARs, for instance, indicate that AARs aren't consistently conducted (at least in frequency; "quality" is a separate topic), nor is there a way to build these individual and small group insights into a corporate or collective perspective. So the need is to build on current practice by defining a common practice, consistent method, and central location so that we can better see how (and why) our system operates to produce the outcomes it does at team, incident, and organizational levels. The KDL is intended to do this.

The 2008 Pilot

Working with members of the NRCG, we developed data collection forms for a "balanced scorecard," capturing information on intent (in-brief), actions (daily), and outcomes (closeout) from members of the host agency (agency administrator, fire staff, resource advisor, or public affairs officer) and Incident Management Team (IC, operations staff, or public information personnel).

In May 2008, the Forest Service's Washington Office asked the research team if we could also capture key decisions and decision rationales. After initial testing on the Indians Fire in California, the resulting "significant cost KDL" focused on decisions with significant financial implications using a simple, table-based form to be completed as key decisions were made. The concept was quickly adopted—and locally adapted—and numerous, slightly different versions began circulating. To address this, we created a Web page at the Lessons Learned Centers' Incident Management Team (IMT) site (<http://www.wildfirelessons.net>) in an attempt to establish a consistent format.

The KDL process was presented as part of the Forest Services' Accountable Cost Management rollout, not only to the Northern Rockies, but also to the Forest Service's Regions 2, 4, and 6 and to all four National Incident Management Organization (NIMO) teams. Presentation emphasis was placed on the KDL, but regions were encouraged to help us test the full suite of "balanced scorecard" forms as well. Further discussion with Forest Service Northern Region resulted in a hybrid form, capturing decisionmaking, key elements of the "balanced scorecard," and information needed for large fire cost reviews. All forms were available for download on both an internal Forest Service Web site and the Wildland Fire Lessons Learned Center Web site and for Web-based data entry on the Forest Service Web site.

Despite the numerous variations of the form, all KDLs included six basic questions:

- "Who was the decisionmaker?"
- "What was the decision?"
- "What alternatives/risks were considered?"
- "What was the rationale for the decision?"
- "What were the cost implications?" and
- "With whom was the decision shared or discussed?"

Depending upon the version used, the definitions of a "key decision" included:

- A decision that has a significant impact on cost, sociopolitical conditions, or resource allocation;
- Strategic and tactical incident management decisions that influence the resources allocated to and final cost of the complexes and/or fires; and
- Those strategic and tactical incident management decisions that heavily influence the resources expended on the fire.

The intent of the last of these is to focus on the "20 percent of the decisions that result in 80 percent of the expenditures." Focus was on the "big chunks": the decisions that have implications from hundreds of thousands to multiple millions of dollars. Throughout the process, critical feedback and input have come from all levels of the fire community: the NIMO teams, the Forest Service National Leadership Team, users of the system, and members of the interagency High Reliability Organizing community of practice.

Results and Discussion

KDLs were submitted for 28 incidents, including those managed

Throughout the process, critical feedback and input have come from all levels of the fire community: the NIMO teams, the Forest Service National Leadership Team, users of the system, and members of the interagency High Reliability Organizing community of practice.

as type 1, 2, 3, 4, and 5; prescribed fire events; incidents under single and home unit jurisdiction; and unified command, area command, and theater of operations. Teams completing KDLs included host units; type 1, 2, and 3 incident management teams; NIMO; area command; and the National Multi-Agency Coordinating Group. These incidents occurred on a variety of agency lands, including national forests (Northern, Rocky Mountain, Southwestern, Intermountain, Pacific Southwest, and Pacific Northwest Regions), U.S. Fish and Wildlife Service, and Bureau of Indian Affairs. Most KDLs include information from only one team, so there are relatively few instances of a complete decision log in 2008. In addition to the submitted KDLs, we also actively solicited feedback on the forms, the content, and the process of completion. From this, we learned of a number of additional KDLs that were created but not submitted. These included KDLs for large fires but also for initial attack, extended attack, and type 4 and 5 events.

Analysis of the extensive narrative entries was facilitated by the central database. The Web version populated our central Oracle database directly. KDLs submitted via email were manually copied into the Web database. It was then possible to use qualitative analysis procedures to categorize responses.

Narrative analysis of submissions indicates that the most frequent types of decisions entered can be classed into an intuitive and relatively small set: choice of tactic, choice of resource type, size (team size or number of a given resource, ramp up, or ramp down), and choice of strategy. Decisions made specifically to curb costs were less frequent, and most of these revealed consideration of small—but recurring—issues, such as decisions concerning camp caterers. Entries describe decisions and actions that increase as well as decrease costs. Few entrants were able to quantify short- or long-term cost implications, though most were able to predict whether these would be positive or negative.

Most frequently cited rationales for decisions and actions reveal a focus on (in no particular order):

- *Efficiency*—the decision is most efficient among alternatives;
- *"Right resource at right cost"*—matching the work with its cost (for example, considering "exclusive use" instead of "call-when-needed" or use of Federal crews instead of contract crews);
- *Safety*—limiting exposure, ensuring medical support, and reducing travel time;
- *Probability of success*—selecting options with the greatest probabilities of success and minimizing an insistence on holding a fire line when there is a probability that the line would be breached;
- *Accountability*—tracking or assigning responsibility appropriately; and
- *Task requirements*—identifying and addressing the current situation (for example, demobilizing crews when those resources are no longer needed or ramping up in response to changing fire behavior).

Less frequently cited rationales include (in no particular order):

- *Operations*—actions taken to influence incident duration or size (and thereby, costs) to protect values at risk, to achieve natural resource benefits, or to influence tactical impacts on natural resources;
- *Planning*—anticipating responses to potential fire development or obtaining information in order to make the next decision;
- *Policy*—following mandated procedures as they define (and sometimes limit) strategies;
- *Relationships and communication*—the quality of working relationships (poor or good) or communications as they influence coordination among staffs and personnel;
- *Availability and training*—"making do" with what's available and creating training opportunities; and
- *Complexity*—addressing multiple goals in tactics and number or type of resources selected.

Many teams recorded decisions made by staff members beyond ICs, line officers, and agency administrators, including decisions made by command staff and area command personnel. It was also stated that any decisions that affect cost should be noted, including those made by dispatch personnel and the regional office.

Discussion

An often-heard adage concerning decisionmaking is that decisions are only as good as the perception of reality behind them. We know from organizational theory that perception is profoundly influenced by organizational culture as refined by individual expertise and experience. Continuous improvement in decisionmaking considers both the cultural frame of reference that focuses decisionmakers' attention on specific aspects of a situation more than others and the way in which this information is interpreted, weighed, and integrated to arrive at a particular decision. KDLs capture a slice of this perception, offering the potential for both individual teams and the organization as a whole to reflect upon the conceptual models in use and how these influence what factors are considered and, of those, what factors are incorporated into the decisionmaking process.

When KDLs are uploaded to the central server, they provide the data necessary to cultivate an objective organizational perspective, facilitate organizational learning, and improve corporate effectiveness. They provide a window into the broader organizational culture and structures that create the operational "decisionspace" and attendant constraints within which the individual units and teams must operate. Results from 2008 provide a window into how fire managers see their decisionspace and the range of rationales upon which they based decisions.

In terms of the "balanced scorecard" concept, the KDL entries reveal a significant focus on operational efficiency. The expansion of entrants from the originally target-ed ICs and agency administrators to all command and general staff areas and from an expected suite of line-based decisionmakers to general staff on both team and host units indicates a desire to record and communicate details of incident management.

Safety and probability of success were two of the highest profile aspects of risk management recorded. Much less is revealed about the role of working relationships (particularly external to the host IMT), experimentation, and learning opportunities. Whether these are systemwide patterns or particular to the few teams and units who participated in our pilot project cannot be answered until we get a more extensive dataset.

By creating one form in which key incident participants can note their decisions and subsequent actions, the KDL can help facilitate learning and improve operational effectiveness at the local level. Ideally, each KDL reveals the line of reasoning and choices seen and taken by the key players on an incident to achieve the desired outcomes captured in Delegations of Authority and strategic direction documents (Wildland Fire Situation Analysis [WFSA] or Wildland Fire Decision Support System [WFDSS]). As such, they can be used to link and improve alignment of incident objectives and intent to actual outcomes.

Several teams and at least one host unit report using their KDLs as input for AARs, and the NIMO teams used KDLs to build case studies of large fires for incorporation into 2009 training. Such exercises are particularly useful when the approach recognizes that there are multiple rational responses to any set of circumstances and that all of these serve to improve understanding and promote learning. The NIMO exercises, for example, use the KDLs as a jumping-off point for discussions about effective risk management for future fire seasons.

KDL 2009—Next Steps

The 2008 effort provided significant information for identifying value and critical processes, as well as identifying weaknesses in the pilot effort. Feedback received from field users noted a variety of benefits in the process:

- Transparent documentation of decisions provides value, offering a way to review decisions made in realtime, identify trends, and make planning corrections.
- The process was useful for creating a final fire narrative, tracking large and small decisions, communicating between the agency administrator and IMT, and providing upper echelons with a more explicit record of the commitment to cost management.
- The process was valuable as a tool to capture IMT staff decisions, during the season to provide insight into consequences of alternatives and during postseason reviews.

Feedback also provides advice for further developing the process:

- Decisions made at national, regional, national forest, and IMT levels directly impact resource availability, strategy, tactics, duration, and costs of incidents. To meet the objective of improving organizational "Situational Awareness," KDL must capture the full spectrum of perspectives.
- KDL was useful for recording decisions on smaller fires (types 4 and 5), as well as on larger fires (types 1, 2, and 3).
- Including the KDL in a Letter of Delegation encouraged creation of a complete incident log. Key decisions were most often discussed and identified during evening planning meetings with command and general staffs, with one person given responsibility for data entry. Still, KDL efforts initiated during 2008 were sometimes preempted by higher priorities.
- The current KDL system should be streamlined, avoid duplicating other programs, and allow entrants editing capability. Future development must provide access to the interagency community and include a user's guide, more training, and outreach. KDL should also be linked to WFDSS and document implementation decisions.
- There is followup needed on the 2008 KDL decisions. The agency needs an analysis of project progress, including an assessment of working relationships, innovation and learning, financial management, and other intended outcomes of the KDL process.

Based on this feedback, analysis of entries, and lessons learned from 2008, a steering committee of representatives from research, National Forest System management (fire staff, IMTs, and line officers), and interagency partners has developed a revised version of the KDL. This second version combines the "balanced scorecard" and KDL efforts into a single, streamlined form that can be completed as needed during an incident. This effort is a standalone program built to capture decisions flowing from strategic decisions made and documented in an incident's guiding document (WFSA, Wildfire Implementation

Plan, or WFDSS). The 2009 version provides the opportunity for more rigorous analysis through use of structured responses in addition to narrative. Additionally, the combination of WFSA/WFDSS and KDL will capture the decision flow from land management direction to fire management plan, to incident objectives and strategy, and through implementation. As such, it builds a story:

> I/we have made a decision, taken an action, or raised an issue in order to move towards meeting an objective. We need to do this now because of some pressing or emerging issues or concerns. We expect this to impact key aspects of the incident (safety, ecology, cost). We expect this to affect our incident only, or other incidents as well.

The KDL can be accessed by authorized users through the **Fire** and Aviation **Management** Web Applications (FAMWEB) Web site, which provides secure access by interagency partners.

Acknowledgements

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Web Site on Fire

A Hub for Fire Information

The Web site at <http://www.fs.fed.us/fire/> is a gathering place for information on all aspects of fire research, management, logistics, and news. A virtual kiosk, the site serves to inform professionals of the latest developments in equipment and methods, provide fire managers with a gateway to fire management tools, and give newcomers a glimpse of the breadth of fire operations.

Links in the Web site connect the viewer to specialized areas for indepth information. These include familiar topics and some unexpected resources: InciWeb is an interactive list of all recorded fire incidents throughout the United States over the last fire season, and back issues of Fire Management Today can be viewed and printed, from the latest to the first issue of December 1936.

The site serves as a comprehensive source of information on fire incidence and response from historic records up to the present and into the emerging future.

A Multi-Disciplinary Approach to Fire Management Strategy, Suppression Costs, Community Interaction, and Organizational Performance

Anne E. Black, Krista Gebert, Sarah McCaffrey, Toddi Steelman, and Janie Canton-Thompson

Wildland fire management must balance the multiple objectives of protecting life, property, and resources; reducing hazardous fuels; and restoring ecosystems. These Federal policy imperatives, varied yet connected, must be met under an increasingly constrained budget. A key to management success is effectively exercising the full range of management flexibility in responding to wildland fire.

Over the past several fire seasons, there has been increasing emphasis on strategies to achieve fire management objectives using less than full perimeter control, such as more prescribed burning and focused point and area protection. While the strategies and tactics themselves are not new, wider use by Federal agencies, particularly on multi-jurisdiction events and in areas adjacent to private lands, has raised concerns among partners and stakeholders. How effective is the new emphasis? Is it affecting the bottom-line, and if so, for whom? How successful are we regarding land management objectives or safety? How well are we communicating intent with our key partners and the public, and what message is being received?

> Research related to community and public understanding of fire management during a fire event is limited, particularly as that understanding relates to the use of alternatives to full suppression.

Answering these questions in a generalizable way has its challenges. For example, the current financial system can inhibit accurate capture of daily costs. Incident managers have different interpretations of wildland fire response strategies and different meanings for "cost effectiveness." The fire community lacks agreed-upon metrics to measure performance (such as degree of success in meeting objectives: resource benefits, protection, efficiency, and internal and external relations, for example), which inhibits comparison across cases. Furthermore, highly contextual observations, such as perceptions of community relations, quickly deteriorate with time.

In this article, we describe our current work to assess the utility of available data to reflect on the performance of fire management. To date, the available data—which include objectives and strategies captured by decision documents, daily plans, final narratives, and GIS imagery—have not been systematically captured or analyzed.

Using a "Balanced Scorecard"

In summer 2008, we embarked on a Joint Fire Science Program (JFSP) project to develop and field-test a "balanced scorecard" of organizational performance suggestive of outcome, impact, and trend. The "balanced scorecard" framework outlines four critical aspects of management necessary for developing a robust picture of an organizations' performance: customers, financial health, internal business perspective, and innovation and learning (Kaplan and Norton 1992). For use with fire incidents, we translated those aspects to community relations and public sentiment; fiscal efficiency; safety, ecological health, and tactical effectiveness; and organizational learning.

Anne Black is an interdisciplinary ecologist/social scientist at the Forest Service's Aldo Leopold Wilderness Research Institute, Missoula, MT. Krista Gebert is an economist at the Forest Service Rocky Mountain Research Station in Missoula, MT; Sarah McCaffrey is a social scientist at the Forest Service Northern Research Station in Evanston, IL. Toddi Steelman is an associate professor in the Department of Forestry and Environmental Resources at North Carolina State University in Raleigh, NC. Janie Canton-Thompson is a social scientist at the Forest Service Rocky Mountain Research Station in Missoula, MT.

We sought to use this "balanced scorecard" to investigate how tradeoffs are made in the decision-making process, including how community interaction increases or decreases the opportunity to exercise different responses to wildland fire and how management flexibility may or may not contribute to cost and organizational performance. In close partnership with the Northern Rockies Coordination Group (NRCG) and the National Incident Management Organization (NIMO) teams, we are collecting information running the gamut from tangible and measurable (safety, ecology, and costs) to less tangible but still perceptible (suppression effectiveness, community interactions, and efficiency) and fully process-based (organizational learning) through interviews, cost analyses, and the incident key decision log (KDL, see The Key Decision Log: Facilitating High Reliability and Organizational Learning, in this issue).

The benefits derived from this research will include: (1) a clearer description for fire managers of the relationships among costs (to Federal, State, and local entities), community interaction, safety, ecology, organizational performance, responses to wildland fire, and fire management strategies; and (2) a protocol that allows monitoring of and learning from organizational performance trends, both process (agency-team relations) and outcome (the impact of a given fire on human safety, values at risk, community relations, and ecosystems).

Community Relations and Public Sentiment

Fire managers must take into account both public expectations and the degree of public acceptance for different strategies and tactics. Therefore, it is critical to understand how agency/community interactions shape both public acceptance and managers' perceptions of what is acceptable. Much of the recent research related to community response to wildfire has focused on prefire mitigation actions on public and private land. This research indicates that increased understanding of the purpose and effectiveness of mitigation measures is associated with greater acceptance (McCaffrey 2006).

Partnerships and collaboration with communities and agencies are also tied to effective mitigation measures (Steelman and Kunkel 2004; Steelman and others 2004). Additional research indicates that fire mitigation efforts are more effective when wildland managers not only understand and address the factors that may influence stakeholders' acceptance of management practices but also work to engage them in risk management decisions (Winter and others 2002; Zakzek and Arvai 2004). Unfortunately, research related to community and public understanding of fire management during a fire event is limited, particularly as that understanding relates to the use of alternatives to full suppression. Consequently, we do not know much about how agencies reach out to the public, what communities or the public understand about strategies and tactics, or how the public can facilitate or obstruct the use of different options for responding to wildland fire.

One specific objective under the JFSP project is to gain an understanding of the relationships between pre-fire and during-fire community interaction and fire management flexibility. To meet this objective, our research design uses quantitative and qualitative methods to address the following questions:

- Do outreach and interaction with the public prior to the fire, including involvement in land management and fire management planning and hazard mitigation, increase acceptance of alternative strategies (i.e., less than full suppression) during a fire and decrease post-fire conflict?
- How does provision of information during a fire, both in terms of content and presentation, influence acceptance of alternative strategies? Are there particular types of information that are more or less important in shaping acceptance?
- How does public reaction to fire management efforts during an event affect fire management decisions?

In 2008, we collected data on community outreach, interactions, and responses from three fires: the Gap Fire on the Los Padres National Forest in California (full suppression with perimeter control), the Cascade Fire on the Custer National Forest in Montana (modified suppression), and the Gunbarrel Fire on the Shoshone National Forest in Wyoming (prescribed burning). We interviewed participants from incident management teams, host agencies, and key community members. We plan to test the importance of some of the dynamics identified in these discussions on a wider audience as the research continues.

Fiscal Efficiency

Many policy and decisionmakers hoped that the use of less-aggressive suppression strategies, where appropriate, in 2007 would result in lower costs (OIG 2006; USDA and USDI 2007; NRCG 2007). However, the interplay of wildland fire management decisions and cost containment is not well understood, and research designed to assess the factors affecting suppression expenditures has been limited due to a lack of data. Early research by Gonzalez-Caban (1984) estimated suppression expenditures based on the number and type of the different resources used on the fire. More recently, Donovan and others (2004) used regression analysis to identify variables affecting suppression expenditures for 58 fires that occurred in Oregon and Washington in 2002. The Forestry Sciences Lab in Missoula has conducted research on large fire suppression costs since fiscal year 1998 (Gebert and others 2007; Canton-Thompson and others 2006; Canton-Thompson and others 2008). Still, much remains to be learned about fiscal efficiency related to fire management.

We hope to extend this work by focusing quantitative and qualitative assessments on how wildland fire management strategies and tactics influence wildland fire costs and vice versa. Quantitative techniques include economic assessments of previous fires. Qualitative assessments include interviews with agency officials, cooperators, and stakeholders about their experiences with the interplay of response strategies and costs. Our two major questions are:

- Does point protection/monitoring, rather than full perimeter control, affect suppression costs for Federal agencies?
- Do strategies and tactics aimed at less than full perimeter control reduce the costs of fire management or simply shift the cost burden to non-Federal entities?

Preliminary economic work suggests that the data and regression models used to derive the "stratified cost index" (a current performance measure for both the Forest Service and U.S. Department of the Interior Bureau of Land Management, Gebert and others 2007) may also be useful for assessing the effect of responses to wildland fire on suppression expenditures per acre. Early analysis of interviews shows that State and local cooperators, in most cases, are quite concerned about their costs increasing as Federal policy shifts toward more prescribed burning, monitoring, and point protection strategies. The general assumption is that less-aggressive strategies will result in cost savings for the agency. However, some interviewees argue that less-aggressive strategies cause fires to last longer and increase chance of escape to private land, culminating in higher private costs and prolonging costs to local stakeholders, particularly with respect to personal health and tourism losses. We are hoping that our analyses (both qualitative and quantitative) will shed light on this issue or at least that we will start to collect the type of information necessary to answer this question over the next few years.

> An assumption is that less-aggressive strategies will result in cost savings. However, some argue that less-aggressive strategies cause fires to last longer, so the savings may be minimal at best.

Risk Management and Organizational Learning

To fully understand the mechanics of the current decisionmaking process, we need to know how decisionmakers frame their decision space and how they weigh potentially conflicting objectives within that space. Indepth field interviews in the fall of 2008 helped us to better understand the full context and impact of other factors on the relationship between response and cost, due to the fact that contextual information is not captured in financial records. These interviews focused on understanding:

- How does an increasing emphasis on cost containment influence the strategies and tactics used on wildland fires?
- How does the use of the new Wildland Fire Decision Support System (WFDSS) influence the strategies/tactics or costs of suppressing fires?
- How do decisionmakers weigh potentially competing fire management objectives and risks (long- versus short-term risks, safety, cost, probability of success, and public opinion), and are there patterns to these weights across strategies?

We are also building and testing a Web-based system in which fire managers (both line officers and team members) can document their key decisions and decision rationales. This effort recognizes that while Federal fire management policy (1995) outlines four major objectives—safety, property and resource protection, hazard reduction, and ecological restoration—as yet, there are no consistent assessment criteria or data collection protocols through which to measure progress. Not only is a system important for program reporting; it is critical for organizational learning (Garvin 2000). Thus, we also want to evaluate:

- How consolidated and comprehensive a story of fire management can we tell by capturing currently available incident data in a central location and through a log of key decisions during an incident?
- How effective is maintaining the log at facilitating organizational learning?

In consultation with NRCG and NIMO, we developed and launched a Web-based database for use by incident and management units. Originally envisioned for use only in the Northern Rockies, the effort generated substantial interest and was utilized on all types of fires (type 5 to type 1 and wildland fire use events) in six Forest Service regions and by both National Forest Systems units as well as the U.S. Department of the Interior Fish and Wildlife Service and the State of North Carolina. We are currently assessing progress and outcomes of this effort and anticipate additional work in 2009: particularly, extending capabilities to include inter-agency partners. A key question we are addressing is the extent to which such a system can and should function as a tool for both documentation and rigorous organizational learning.

Conclusion

Changes in the wildland fire environment—climate change, hazardous fuels buildup, and rising human populations in the wildland-urban interface—are resulting in longer fire seasons and wildfires that are increasingly resistant to control and expensive to suppress. Under these conditions, the tactics relied upon in the past now often pose unacceptable risks to firefighter safety. This has led to the call for changes in the way we manage wildfires. Flexible management means less emphasis on putting fires out, no matter what the cost, and more emphasis on using our scarce firefighting resources to effectively meet multiple objectives. To help land managers and policy makers succeed in this new arena, information is needed on the interplay of fire management strategy, suppression costs, Forest Service/community interaction, and organizational performance. We hope this project will provide some of this missing information and lay the groundwork for information collection systems to consistently capture the information fire managers need to adapt to our changing environment.

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Efforts To Update Firefighter Safety Zone Guidelines

Bret Butler

One of the most critical decisions made on wildland fires is the identification of suitable safety zones for firefighters during daily fire management operations. To be effective (timely, repeatable, and accurate), these decisions rely on good training and judgment, but also on clear, concise guidelines. This article is a summary of safety zone guidelines and the current research efforts focused on improving firefighter safety zones, and a request for input from firefighters and fire managers.

How Far Should We Be From the Flames?

Guidelines for the minimum distance a firefighter should be from a flame are discussed in training curricula and published in the Incident Response Pocket Guide (IRPG) and Fireline Handbook (fig. 1). The current safety zone guidelines are based on the distance at which exposed human skin will develop a second-degree burn in less than 90 seconds (the distance corresponding to a radiant incident energy flux level of 7.0 kW-m^{-2}). An approximation of this model used in the field indicates that a firefighter should keep a minimum distance of four times the flame height. For a circular safety zone, this would be the safety zone radius.

Current safety zone guidelines were developed based on fires located on flat terrain. When fires burn on flat terrain, convective energy transfer is primarily upward in the plume and radiant energy transfer is directed in all directions, including out ahead of the fire front. Therefore, firefighter safety guidelines are based on the assumption that radiant energy transfer is the dominant energy transfer mode. Experimental measurements verify the accuracy of this assumption, but also indicate that when fires are burning on slopes, convective energy transfer can be significant.

> When fires are located on slopes or ridges, convective energy transfer may reach distances equal to several flame lengths ahead of the fire front. This implies that the current safety zone guidelines may be inadequate in situations where the safety zone and/or fire are on slopes.

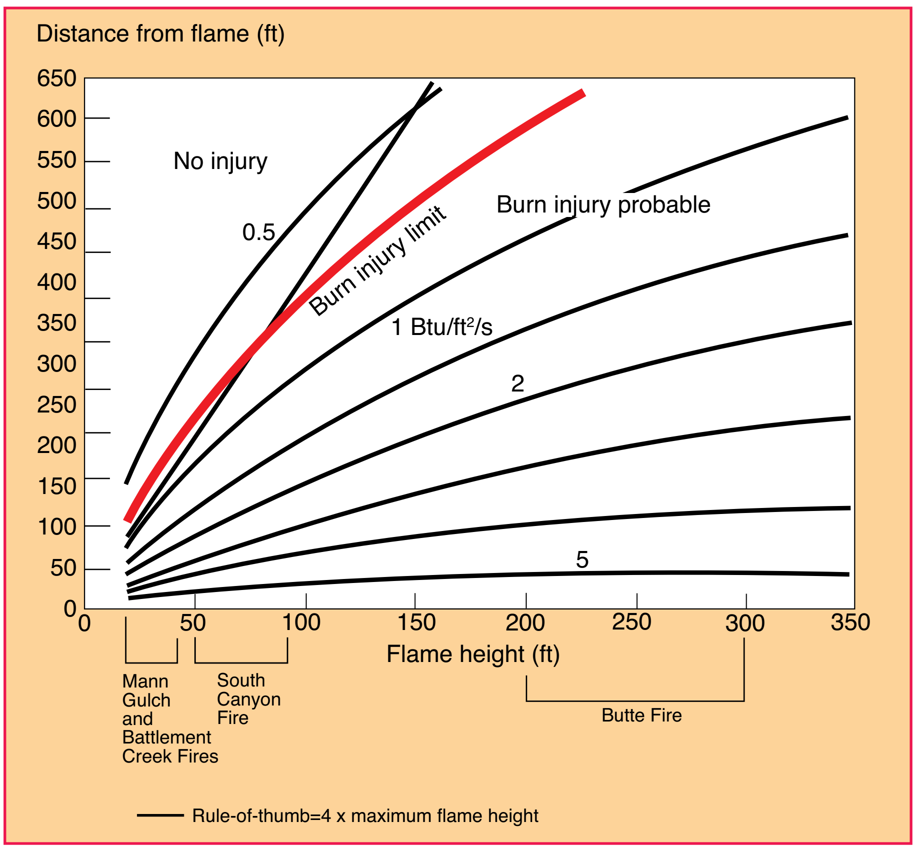

Figure 1—*Results from original safety zone analysis. Model results were verified by comparison against past fires.*

Bret Butler is a research mechanical engineer for the fire, fuel, and smoke science program at the Forest Service Missoula Fire Sciences Laboratory in Missoula, MT.

Intuition, professional observations, and the few experimental measurements that have been reported indicate that, when fires are located on slopes or ridges, convective energy transfer may reach distances equal to several flame lengths ahead of the fire front. This implies that the current safety zone guidelines may be inadequate in situations where the safety zone and/or fire are on slopes. It is also clear from visits to designated safety zones on numerous wildland fire incidents that considerable ambiguity exists regarding identification or creation of true "safety zones," versus "deployment zones."

Fire researchers installing a video acquisition box. Photo by Bret Butler, Forest Service.

A new research project supported by the Joint Fire Science Program is underway to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes.

New Research for Variable Terrain

The Joint Fire Science Program is supporting a new research project to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes. We expect the guidelines will depend on multiple variables, including fire characteristics (flame length or height), site characteristics (e.g., slope), and relative location (i.e., chimney, ridge, midslope, ridgetop). We place special emphasis on the effect of "chimneys" and other terrain features that produce dangerous levels of convective heating ahead of the fire front. The approach for this study has several phases:

1. Measure convective and radiant energy transport in fires across a range of slopes and fuel types. An experienced team has started gathering measurements at various sites over a range of slopes and fire intensities using two types of instrument packages: the Fire Behavior Package and the Video Acquisition Box.

   The Fire Behavior Package (FBP) measures 11 inches (27 cm) by 5.9 inches (15 cm) by 7.1 inches (18 cm) and provides an insulated protective enclosure for a datalogger, sensors, and other electronics. The standard instruments consist of radiometers that measure total and radiant energy fluxes; small-gauge thermocouples—36 gauge (0.13 mm diameter) wires—that sense flame and air temperature; and pitot-static type velocity probes that sense the magnitude and direction of airflow before, during, and after the fire passes.

   The Video Acquisition Box provides digital video imagery, an integral component of our field campaigns. Collecting video imagery not only allows us to observe actual footage of the fire behavior but also provides insight into our data analysis. Camera(s) are housed within 3.9-inch (10 cm) by 7.1-inch (18 cm) by 7.5-inch (19 cm) fireproof enclosures. The boxes have a double-lens configuration: one lens of high temperature Pyrex glass and a second lens of hot mirror coated glass that reflects infrared radiation (heat) while allowing visible light to pass through. The cameras can be turned on manually or set to trigger and record through a wireless link to the FBP sensor packs.
2. Use measurements to "tune" and validate theoretical heat transfer models. Tools include software that simulates heating rates due to conduction; radiation; convection (steady-

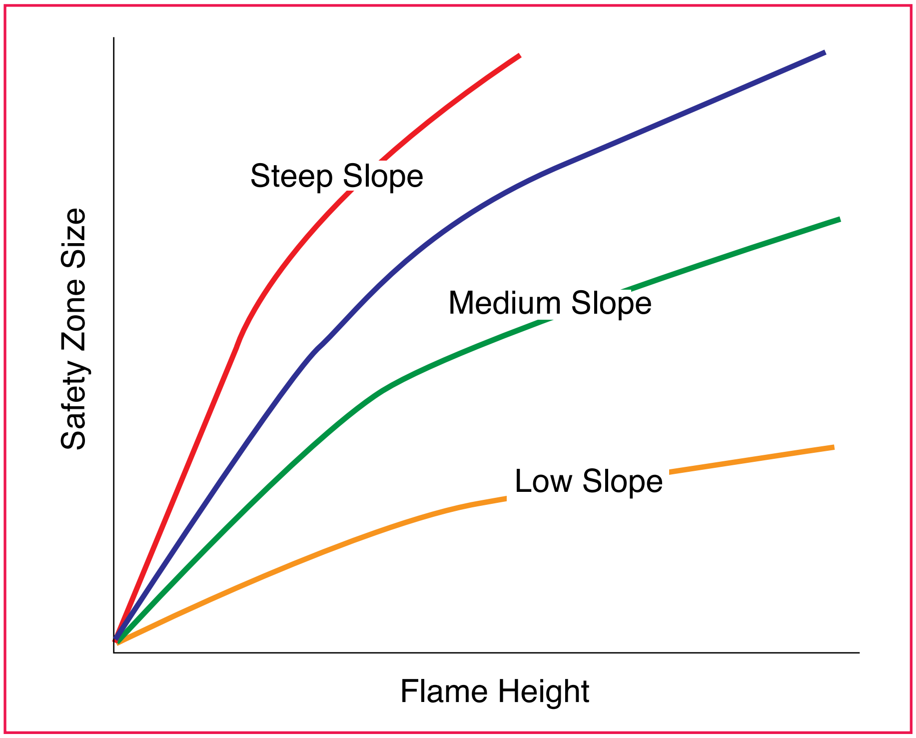

Figure 2—*A possible format for Safety Zone guidelines on slopes.*

state or transient); and the flow field that develops ahead of a fire over the expected range of flame sizes, fire front location relative to slope, slope steepness, and slope shape (i.e., concavity). Fire growth is being explored using existing spatial fire models like FARSITE and the new Wildland Fire Dynamics Simulator developed at the National Institute for Standards and Technology. The measurements collected in the field efforts are being used to "tune" and validate theoretical heat transfer models. Measured and modeled convective and radiant energy distributions around the fires are being compared to human burn injury limits to determine appropriate separation distances and associated safety zone sizes.

3. Consult with incident management teams (IMT), fire crews, and others from the wildland fire community to determine the best methods for delivering new slope/safety zone guidelines. We expect that the results will indicate that slope steepness and concavity may be nearly as critical to safety zone characteristics as fire intensity. Consequently, the attributes of an effective safety zone may depend on more than one variable. Some potential tools for presenting and using multidimensional information are pocket cards, nomograms (graphic representations), and computer models. Figure 2 presents one possible method for presenting the results—here, slope steepness and fire intensity dictate the minimum safe separation distance from the flames. Interviews and consultations with IMTs and fire crews during the field deployment phase of the study will guide the selection and development of one or more products for delivering the new safety zone guidelines.

How Firefighters Can Help

This effort depends heavily on participation from the wildland firefighting community. The research team requires assistance during all phases, and particularly in identifying potential measurement sites and developing the best format for presenting new guidelines. If you have suggestions for potential opportunities to measure convective flow, either on prescribed burns or ongoing wildland fires, or how best to convey the new guidelines (pocket card, nomograms, and/or computer models, etc.), please contact the author. Your input will be greatly appreciated. ■

Modeling Fuel Succession

Brett Davis, Jan van Wagtendonk,
Jen Beck, and Kent van Wagtendonk

Surface fuels data are of critical importance for supporting fire incident management, risk assessment, and fuel management planning, but the development of surface fuels data can be expensive and time consuming. The data development process is extensive, generally beginning with acquisition of remotely sensed spatial data such as aerial photography or satellite imagery (Keane and others 2001). The spatial vegetation data are then crosswalked to a set of fire behavior fuel models that describe the available fuels (the burnable portions of the vegetation) (Anderson 1982, Scott and Burgan 2005). Finally, spatial fuels data are used as input to tools such as FARSITE and FlamMap to model current and potential fire spread and behavior (Finney 1998, Finney 2006).

The capture date of the remotely sensed data defines the period for which the vegetation, and, therefore, fuels, data are most accurate. The more time that passes after the capture date, the less accurate the data become due to vegetation growth and processes such as fire. Subsequently, the results of any fire simulation based on these data become less accurate as the data age. Because of the amount of labor and expense required to develop these data, keeping them updated may prove to be a challenge.

Brett Davis is a geographic information specialist and fire modeler for the Forest Service Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, in Missoula, MT. Jan van Wagendonk is a research forester emeritus for the U.S. Geological Survey, Western Ecological Research Center, Yosemite Field Station, El Portal, CA. Jen Beck is a fire ecologist for the National Park Service at Redwood National Park, Orick, CA. Kent van Wagtendonk is a geographer for the National Park Service at Yosemite National Park, El Portal, CA.

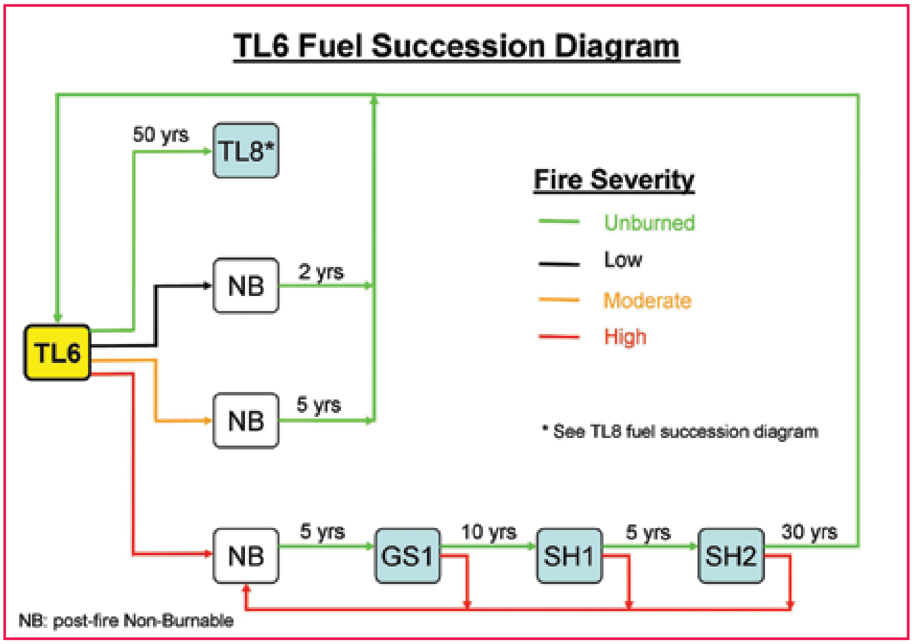

Figure 1—*Successional pathway diagram for the Timber Litter 6 (TL6) fire behavior fuel model.*

In this article, we describe the Sierra Nevada Fuel Succession Model, a modeling tool that can quickly and easily update surface fuel models with a minimum of additional input data. Although it was developed for use by Yosemite, Sequoia, and Kings Canyon National Parks, it is applicable to much of the central and southern Sierra Nevada. Furthermore, the methods used to develop the model have national applicability.

Fuel Model Development

To characterize fuels and fuel succession, we started with the fire behavior fuel models described in "Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model" (Scott and Burgan 2005). These models provide a more detailed representation of fuels than the standard 13 Northern Forest Fire Laboratory (NFFL) fuel models (Anderson 1982) and, therefore, gave us the flexibility to depict different successional stages. We then developed crosswalks between current vegetation data and fire behavior fuel models in a series of collaborative meetings with fuels experts from the parks and the U.S. Geological Survey (USGS). Among

Table 1—*Fuel models represented in Yosemite, Sequoia, and Kings Canyon National Parks.*

Fuel Model	Description
Grass 1 (GR1)	Short, sparse, dry climate grass
Grass 2 (GR2)	Low load, dry climate grass
Grass 4 (GR4)	Moderate load, dry climate grass
Grass-Shrub 1 (GS1)	Low load, dry climate grass-shrub
Grass-Shrub 2 (GS2)	Moderate load, dry climate grass-shrub
Shrub 1 (SH1)	Low load, dry climate shrub
Shrub 2 (SH2)	Moderate load, dry climate shrub
Shrub 5 (SH5)	High load, dry climate shrub
Shrub 7 (SH7)	Very high load, dry climate shrub
Timber Litter 1 (TL1)	Low load, compact conifer litter
Timber Litter 2 (TL2)	Low load, broadleaf litter
Timber Litter 3 (TL3)	Moderate load, conifer litter
Timber Litter 4 (TL4)	Small downed logs
Timber Litter 6 (TL6)	Moderate load, broadleaf litter
Timber Litter 7 (TL7)	Large downed logs
Timber Litter 8 (TL8)	Long needle litter
Timber Understory 1 (TU1)	Low load, dry climate timber-grass-shrub
Timber Understory 5 (TU5)	Very high load, dry climate timber-shrub

the three parks, we classified vegetation into 18 unique surface fuel models (table 1) and then we developed successional pathways for each (fig. 1).

Our end result is a deterministic model of fuel succession, based on expert local knowledge, that accounts for both fuel accumulation and consumption. The model predicts how fuels—represented by the fire behavior fuel models—can be expected to change over time. Rules governing transitions from one fuel model to another reflect our best judgment about how quickly fuels accumulate and how different vegetation types respond to fires of various severities.

Fire Severity: The Major Model Input

Fire severity and time since last fire are the key inputs that dictate which successional pathway the model will follow. We defined fire severity as the degree of post-fire change that would be seen from a remotely sensed (aerial) perspective, a definition compatible with Normalized Burn Ratio techniques for assessing fire severity (Key and Benson 2005, Thode 2005, Miller and Thode 2007). Sequoia and Kings Canyon National Parks have used delta Normalized Burn Ratio (dNBR) (Thode 2005) and Yosemite National Park has used Relative delta Normalized Burn Ratio (RdNBR) (Miller and Thode 2007) data to obtain estimates of fire severity on most of their larger fires for fires that have burned in the past 30 years. We used these estimates of fire severity, usually classified into low, moderate, high, and unburned categories, to model post-fire transitions among fuel models.

Fuel Model Transitions

For each of the 18 unique surface fuel models developed for park vegetation types, we created a state-and-transition model, represented by a successional pathway diagram (fig. 1). A "state" is a standard fire behavior fuel model, and "transitions" are the changes to the fuel model that occur as a result of either fuel accumulation or low, moderate, or high severity fire. Transition times associated with each state represent the waiting period before the current state changes to the subsequent state (fuel model) in the absence of fire. We based the state, transition, and transition time selections on the distribution of the underlying vegetation for each fuel model assigned in the crosswalk.

There are two general categories of fuel model transitions: (1) transitions resulting from low, moderate, or high severity fire, and (2) transitions resulting from fuel accumulation. Transitions resulting from fire are to a temporarily unburnable state—several years may be required before enough fuel accumulates to support another fire and thereby transition back to a burnable fuel model. Transitions based on fuel accumulation reflect the rate of post-fire recovery or fuel accumulation that occurs in the absence of fire; these rates vary with the severity of the fire and the accumulation potential of the post-fire vegetation. For example, if the Timber Litter 6 (TL6) fuel model burns in a moderately severe wildfire, it becomes unburnable for 5 years. After 5 years, enough fuel will have accumulated for it to transition back to the original TL6 fuel model (fig. 1).

We developed 22 diagrams, one for each of the 18 original fuel models plus four "special cases" (see below). Most diagrams are self-contained, reflecting successional pathways that are either circular or dead-end in a "final" fuel model (fig. 2). But in a few cases, a fuel model transition reflects an underlying vegetation type change that necessitates a transition to a new succession diagram. For example, if fuel model TL6 burns in a high severity fire, it will eventually become a Grass-Shrub 1 (GS1) fuel model and continue to follow the successional path illustrated in the TL6 diagram (fig. 1). On the other hand, if it remains unburned for 50 years, it will transition to fuel model Timber Litter 8 (TL8) as a result of an underlying vegetation type change, and the succession model will then follow the successional pathways in the TL8 diagram.

The four "special cases" represent situations where multiple vegetation types were similar enough in their expected fire behavior to be crosswalked to a single fuel model but were markedly different in their accumulation rates or response to fire. In these special cases, we developed multiple distinct successional diagrams for the fuel model. For example, fuel model Timber Litter 2 (TL2) was crosswalked from evergreen oaks (Quercus spp.) as well as a variety of deciduous tree species. These two vegetation types have very different fuel accumulation rates and responses to fire, and, therefore, separate succession diagrams were developed for each type (fig. 3, fig. 4).

Updating Fuels Data

The Sierra Nevada Fuel Succession Model provides a simple, practical, and easy way to keep surface fuels data current. It extends the useful life of these expensive and labor-intensive data and should improve the predictive accuracy of fire modeling tools such as FARSITE and FlamMap. To keep fuels data current, the model should be run each year at the end of the fire season, starting the first year after the creation of the fuels data (generally the vegetation data's capture date). Model outputs include a fuel model grid representing the next year's fuels (prior to next year's fire season) and inputs for the following year's succession run.

Conclusions

One must keep in mind that, like all models, the Sierra Nevada Fuel Succession Model is subject to the quality of the underlying data and the accuracy of the predictions of the fire and fuel modeling experts. It is also subject to all assumptions of the models and classification systems used to generate its inputs, specifically the vegetation and severity classifications based on remotely sensed imagery. In addition, fire is the only landscape-scale process modeled—the roles of other processes such as insects, diseases, blow-downs, or avalanches are not accounted for in this version of the model.

As the Sierra Nevada Fuel Succession Model is put into use at Yosemite, Sequoia, and Kings Canyon National Parks, the transitions and transition times in the successional pathways will be vali-

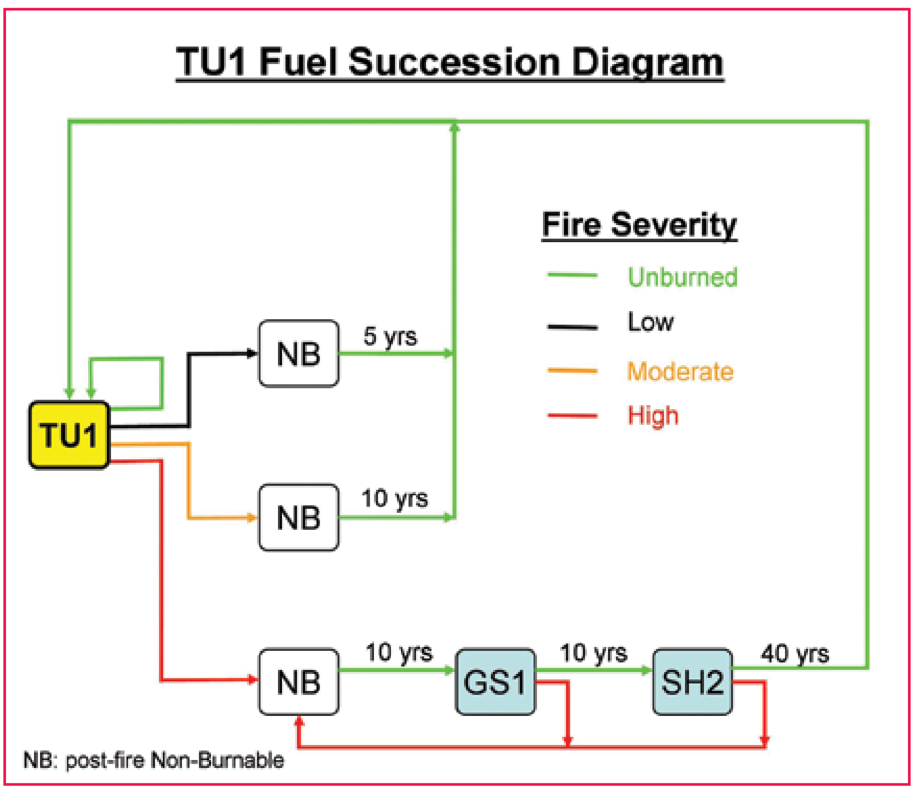

Figure 2—*Fully self-contained successional pathway diagram for the Timber Understory 1 (TU1) fire behavior fuel model.*

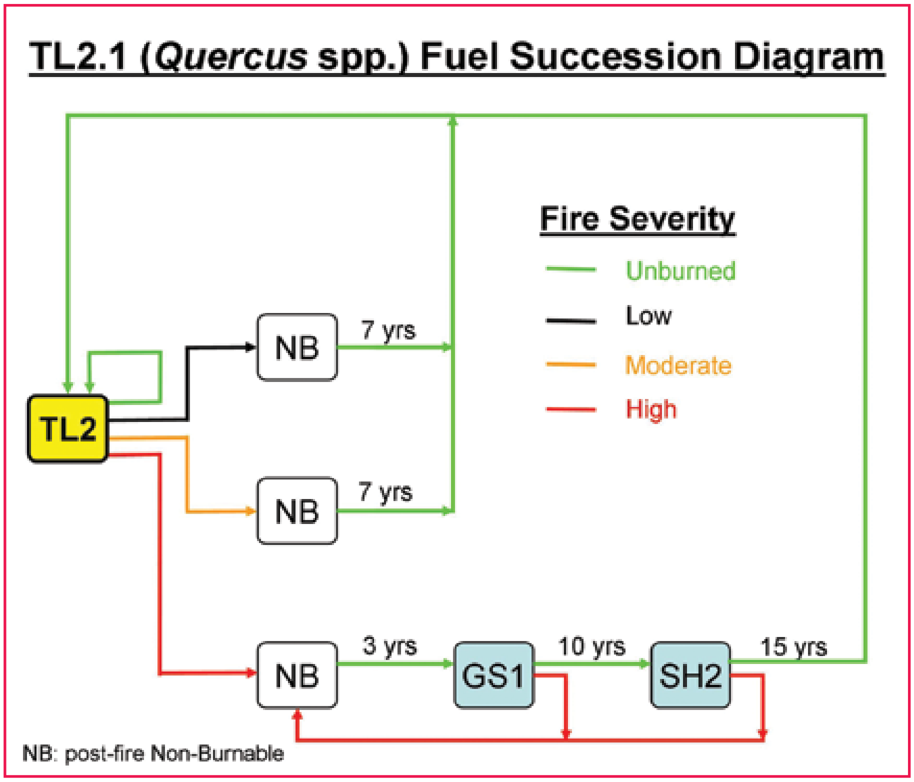

Figure 3—*Successional pathway diagram for the Timber Litter 2.1 (TL2.1 - evergreen oaks) fire behavior fuel model.*

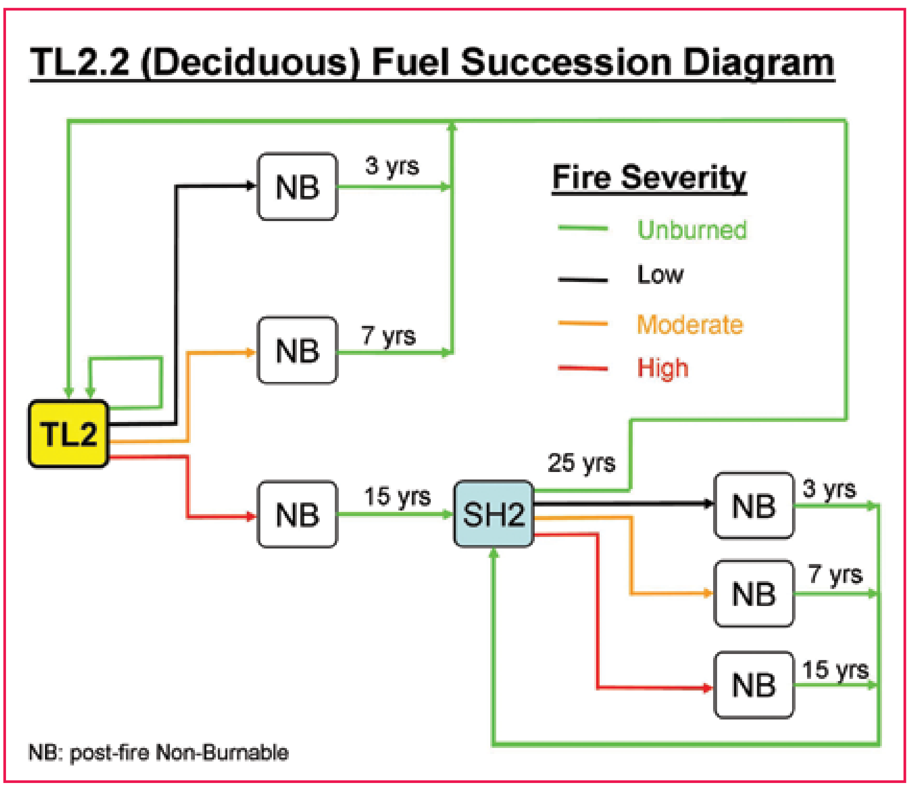

Figure 4—*Successional pathway diagram for the Timber Litter 2.2 (TL2.2 - deciduous) fire behavior fuel model.*

dated and adjusted in response to field observations. Currently, the model is only applicable to the central and southern Sierra Nevada, but the techniques should be generally applicable to any fire-prone landscape.

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Fuel Age and Fire Spread: Natural Conditions Versus Opportunities for Fire Suppression

Richard W. Halsey, Jon E. Keeley, and Kit Wilson

Wildfires are driven and restrained by an interplay of variables that can lead to many potential outcomes. As every wildland firefighter learns in basic training, the ability of a fire to spread is determined by three basic variables: fuel type and condition, weather, and topography. Fire suppression obviously plays a significant role in determining fire spread as well, so firefighter activity becomes an additional variable.

In southern California, where wildfires occur predominately in shrubland ecosystems, such as chaparral, there is continual debate over the relative roles of weather and fuels in fire spread. During Santa Ana wind conditions, often characterized by single digit humidity, temperatures over 90 °F (23 °C), and 80 mile-per-hour (130 km/h) sustained wind speeds, weather typically overwhelms the influence of fuel type. During milder conditions, fuel type becomes much more important.

Questions about the chaparral's natural fire regime and what role younger aged vegetation can play in assisting fire suppression efforts are frequently intertwined when they are actually addressing two different issues: the role that younger aged vegetation may play in stopping fire spread naturally versus its role in assisting firefighting efforts. The fact that fires in younger, lighter fuels are typically easier for firefighters to extinguish than those in heavier, older fuels does not necessarily correlate with what would occur under natural conditions without active fire suppression.

Richard Halsey is director of the California Chaparral Institute, Escondido, CA. Jon E. Keeley is a research scientist for the U.S. Geological Survey, Western Ecological Research Center, in Sequoia National Park, Three Rivers, CA. Kit Wilson is a geographic information specialist consultant with Open Spaces GIS, Escondido, CA. *The authors would like to thank Bill Howell, Nicholas Halsey, and Jake Halsey for assistance in data collection.*

The Study

To examine these issues and better understand the interplay of variables that determine fire spread, we examined four sites in San Diego County, California, that burned in the January 2001 Viejas Fire and were adjacent to (but unburned by) the October 2003 Cedar Fire.

The four study sites are particularly interesting for two reasons. First, they provide a test case for how young fuels respond during a wildland fire. After the Cedar Fire jumped Interstate Highway 8, spot fires ignited the Viejas Fire scar's 3-year-old fuels and continued burning for a considerable amount of time. Secondly, the sites are in close proximity to the location of an important fire suppression action taken by Forest Service firefighters that likely prevented the Cedar Fire from dramatically increasing in size. This has allowed us a unique opportunity to combine quantitative analysis of fuels with observations of actual wildfire behavior and the results of actions taken by firefighters.

Although firefighters can provide extremely valuable information about wildland fire, this information is generally underutilized by the scientific community. To take advantage of their observations, we conducted extensive interviews with those who were on scene when the Cedar Fire burned into the study area. These firefighters provided us with the tactical details of their suppression efforts, as well as the weather conditions they encountered. While Remote Automated Weather Stations (RAWS) can provide a general view of prevailing weather conditions, they are frequently too far away from the site of interest to offer the data needed; this was especially true during the Santa Ana wind condition that existed during the Cedar Fire, as wind speeds varied dramatically within relatively short distances.

The Location

The sites are located in a portion of the Cleveland National Forest, California, in what could be classified as a *fire corridor*, a site where wildfires frequently start or burn through due to local topographical and weather conditions. Four of San Diego's largest fires have either

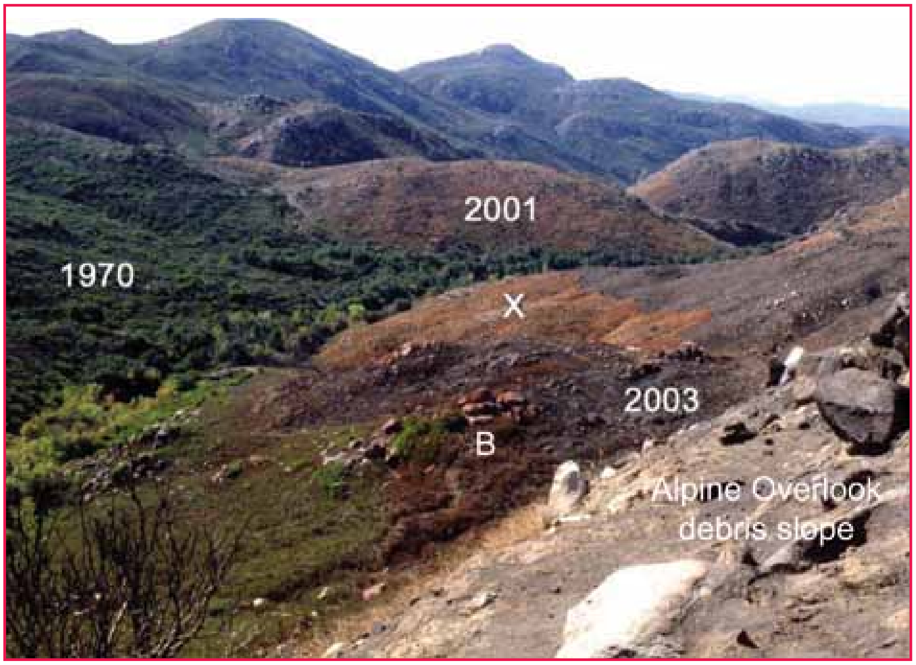


Figure 1—*Looking down (southwest) from the Alpine Overlook into the Sweetwater River canyon. Many of the largest fires in San Diego County have burned through this area. The 2003 Cedar fire scar ("2003") is the blackened ground in the middle and right of the photo. Two of the study sites where vegetation in the 2001 Viejas fire scar ("2001") was sampled are located near the "X" mark. The Hotshot handline cut to the large boulder outcropping (B) and down into the canyon starts at the lower middle of the photo. The stain from red fire retardant can also be seen near the boulders. Note how close the Cedar fire came to the dense chaparral stand that last burned in 1970. Photo by Richard W. Halsey.*

burned through or bordered this location. The focal point of the area is the Alpine Overlook, a highway overlook off Interstate 8, about 25 miles (40 km) east of San Diego. About a quarter mile (.4 km) below the overlook lies the canyon bottom of the Sweetwater River, only a trickling stream most of the year. At 3,000 feet (914 m), with an average annual rainfall of 17 inches (43 cm), the area supports an interesting mix of vegetation, featuring several differently aged patches of chaparral. The south-facing slope, immediately below the overlook, is covered by a sparse stand of chamise (*Adenostoma fasciculatum*) chaparral partially burned in a 42-acre (17 ha) blaze in 1982. Across the river, on the north-facing slope, is a dense stand of old-growth mixed chaparral last burned in the 1970 Laguna Fire, a 175,425-acre (70,992 ha), wind-driven blaze that raced 30 miles (48 km) within 24 hours to the outskirts of El Cajon, CA. The nearby Viejas and Cedar Fire scars complete the patchwork (fig. 1).

When the Cedar Fire made contact with the area on October 27, 2003, the overall weather conditions were conducive to fire spread. The nearest RAWS station recorded relative humidity range of 9–12 percent for October 27, between 0800 and 1630 hours. Temperature ranged from 69 to 78 °F (67–83 °C) with 16–24 mph (26–39 km/h) northeast wind speeds. Topography reduced the winds in the canyon below the overlook, although they were still blowing an estimated 10–15 mph (16–24 km/h) from the northeast during the suppression action.

The Fuel

Estimates of the young fuels in the 2001 Viejas Fire scar that were available but unburned during the October 2003 Cedar Fire were obtained during the summer of 2004. Although these samples were taken 9 months after the Cedar fire, they would have been representative of the fuels burned in 2003 because there was a severe drought in 2004 and observations revealed relatively little growth by most species.

All plant material was collected from ten 1-meter squares equally spaced along the periphery of a 66- by 164-foot (20-by-50 m) plot. This sampling protocol was repeated at four sites. The sites were on flat or south-facing slopes within the 2001 Viejas Fire scar between Interstate Highway 8 and the Sweetwater River.

Prior to the 2001 fire, the plots were covered by relatively sparse chamise chaparral. The average 3-year-old fuel component consisted of approximately .75 kg/m^2 coarse fuel (largely shrub skeletons resulting from the 2001 Viejas Fire) and a similar level of fine dead fuels (<0.25 in [0.6 cm] in diameter) arising from annuals, herbaceous perennials, and short-lived perennials with annual dieback (fig. 2). Several of the meter squares had more than a total of 2 kg/m^2 of fuel due to the presence of large, resprouting chamise and sugar bush (*Rhus ovata*) and substantial skeletons of coarse fuels (fig. 3a). Much of the cover at the site was contributed by short-lived plants that died back each summer, resulting in a marked relationship between fine fuels and plant cover (fig. 3b).

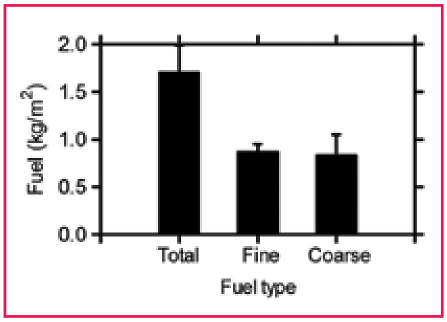


Figure 2—*Fuel types. The study area's 3-year-old fuel component was an equal mixture of burned sticks (coarse) and fine fuels, such as short-lived perennials.*

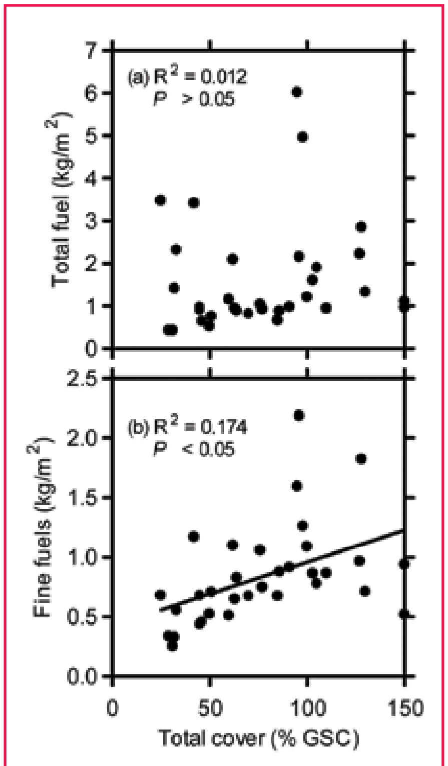


Figure 3—*Fuels analysis. Some of the samples (a) had significant amounts of course fuels due to resprouting shrubs. However, much of the cover was contributed by short-lived plants, (b) resulting in a marked relationship between fine fuels and plant cover.*

Although small amounts of non-native grasses, primarily red brome or foxtail chess (*Bromus madritensis*), were present in some of the meter-squares, they did not make a significant contribution to the fine-fuel mix. This was expected because relatively undisturbed chaparral

Table 1—*Comparison of fuel loads in various plant communities common in southern California.*

Plant Community	Metric tons/hectare (acre)
Chamise chaparral (study site)	10/24 (59)
Mature chaparral[1]	
Light	22/34 (84)
Medium	34/67 (166)
Heavy	65/90 (222)
Mature coastal sage scrub[2]	7/25 (62)
Annual grassland[2]	1/5 (12)

[1]Dodge 1975

[2]Green 1981

stands away from roads and fuel breaks with fire return intervals greater than 20 years are generally free of non-native weeds (Keeley 2006). Therefore, the fine-fuel component was dominated by native ground cover, especially deerweed (*Lotus scoparius*), rush-rose (*Helianthemum scoparium*), and resprouting chamise. Deerweed is a prolific, post-fire species composed of a multitude of thin stems that die back during seasonal drought. The amount of plant material available as fuel in the study area is comparable to similar, unburned plant communities in southern California (table 1).

The Fire

After returning from fighting the Old Fire in the San Bernardino National Forest and a quick briefing on the Cedar Fire, the crew of Engine 47 arrived at the Alpine Overlook on Monday, October 27, 2003, at about 1400 hours. "The fire had already jumped the highway when we got there and was burning directly below the overlook parking lot," Engineer Jerry Amador recalled (J. Amador, pers. comm. 2005).

Before Engine 47 arrived, the Vista Grande Hotshots had been on scene for less than an hour but were unable to attempt any fire suppression efforts. Ten- to twenty-foot (3–6 m) flame lengths blasting up from below the overlook, unburned fuel on both sides of the fire, and steep, rocky terrain made an approach too dangerous. In addition, estimated 30 mph (48 km/h) northeastern wind gusts were whipping the fire into unpredictable directions.

This was a critical juncture in the Cedar Fire's southeastern expansion. The flames had jumped Interstate 8 and ignited the 3-year-old fuels west of the overlook at approximately 0800 hours. By the time the Hotshots arrived, the fire had moved southeast through the young fuels, across slope, and against the wind into the older chamise chaparral stand directly below the overlook. The flames had also spread to the southwest, having consumed a significant amount of the 3-year-old vegetation. The winds in the canyon below the overlook were weaker than those near the top, moving an estimated 10–15 mph (16–24 km/h) when the crews began working the fire.

The potential danger was obvious to everyone on scene. The 33-year-old fuels across the Sweetwater River would have created extremely dan-

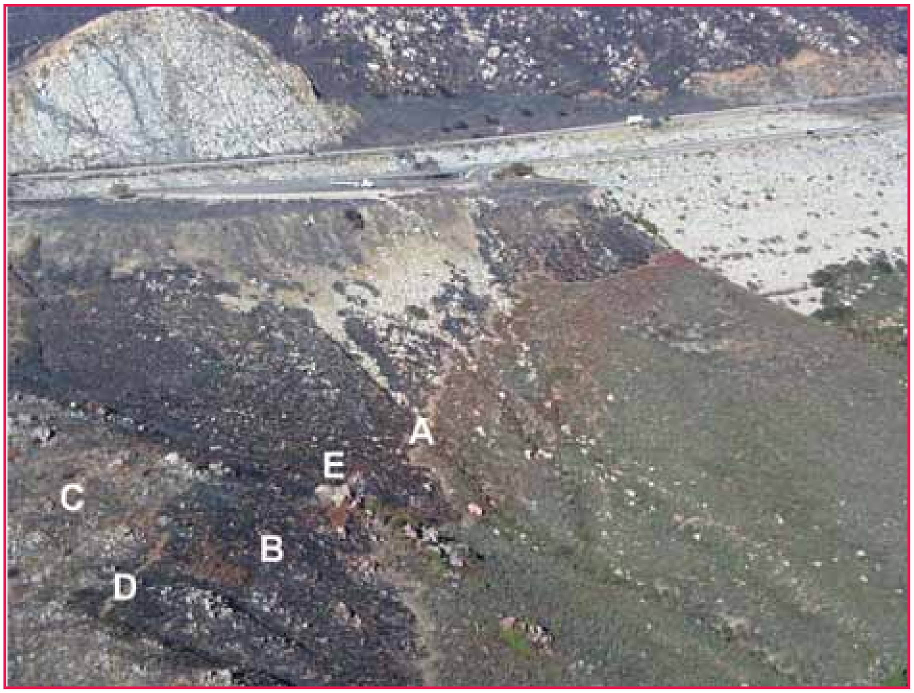


Figure 4—*The Alpine Overlook looking toward the northeast. The 2003 Cedar Fire was stopped at the visible Hotshot handline (A) running downslope through the center of the image. The fuel within the blackened ground immediately above the handline (B) was sparse chamise. The lighter burned area to the far left (C) was composed of lighter vegetation that had recovered after the 2001 Viejas fire. Note the previous Viejas fire handline (D) between the darker and lighter burned areas. The boulder outcropping (E) shown in Figure 1 is also visible. Photo by Randy Lyle.*

gerous conditions if ignited, preventing firefighters from continuing their fire suppression efforts. "If we had any hope of controlling the fire at this location," Battalion Chief John Truett said, "it had to happen before it jumped into those heavy fuels across the canyon. There's no way we'd send firefighters into that stuff" (J. Truett, pers. comm. 2005).

After a load of fire retardant was dropped by a helicopter, the crew of Engine 47 began laying hose below the overlook and along a barbed-wire fence, extinguishing the flames as they went. Following close behind, the Hotshot crew cut a cold trail through the chamise chaparral on the southeast flank. More aerial support was provided by two twin-engine S-2 tankers, which dropped one load of red fire retardant, each, near the lower flank of the fire burning into the chamise (fig. 4).

The Black Mountain Hotshots took over beyond a large rock outcropping and continued cutting the handline all the way to the Sweetwater River, arresting the fire's southeastward expansion. As the crew of Engine 47 had run out of hose at this point, the Hotshots worked without water support. The southwest flank, burning through the 3-year-old fuels, was extinguished by helicopter water drops. The fire was cold by approximately 1630 hours. After jumping Interstate 8, the fire burned approximately 75 acres (30 ha), moving 0.5 miles (0.8 km)over a period of 8 hours (fig. 5).

Analysis

Modeling of expected fire behavior using field measures of fuels from these young seral stands was done with Behave Plus, a PC-based Windows software application used

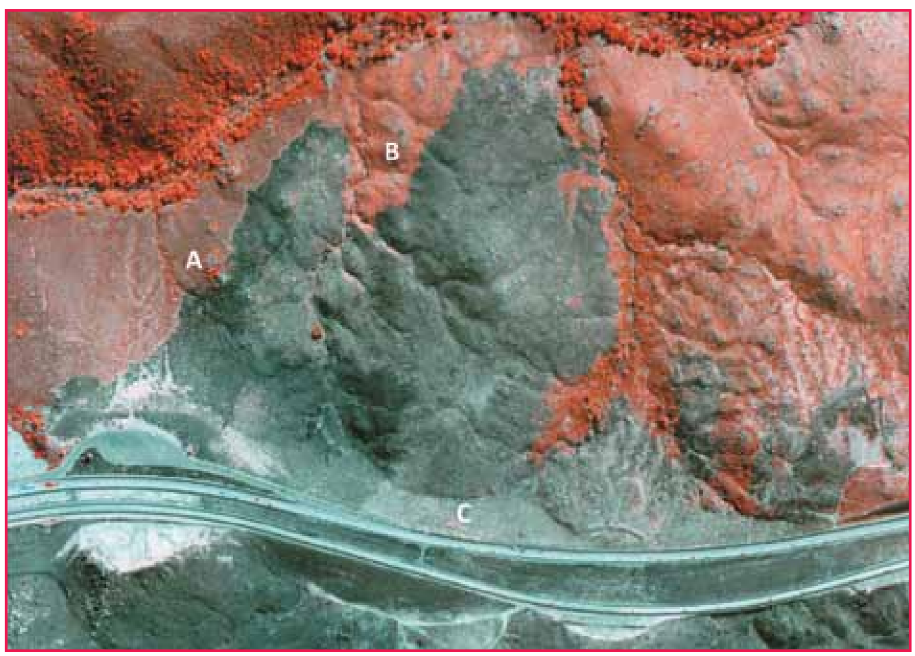


Figure 5—*Infrared aerial overview of the Alpine Overlook area. The Cedar fire scar is shown in black, with unburned areas in red. Interstate 8 is shown at the bottom of the photo with the overlook at the far lower left. The boulder outcropping shown in Figures 1 and 4 is to the right of "A." Two sample sites are at "B." The approximate location where the Cedar fire jumped Interstate 8 is marked "C." The Sweetwater River canyon is at the top of the photo. North is at the bottom. Image acquired and processed by Furgo EarthData, Inc.*

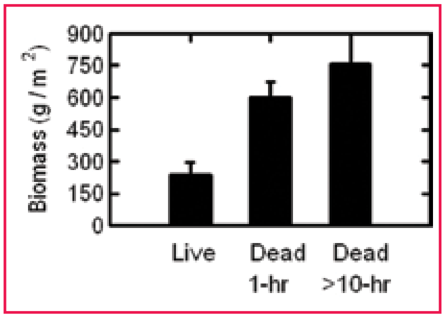


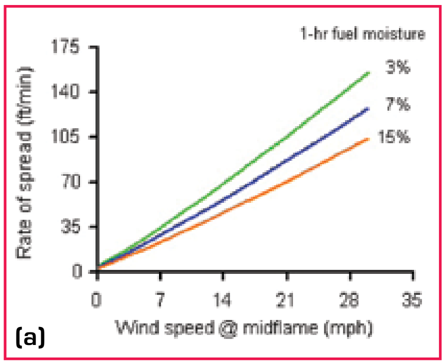
Figure 6—*Fuels status. Dead fuels dominated the samples within the 2001 Viejas Fire scar.*

to predict wildland fire behavior (see <http://www.firemodels.org/ content /view/12/26/>). Rothermel equations that are used in Behave have shortcomings when applied to chaparral (Zhou and others 2005), but we believe it is appropriate to our application in young seral chaparral. Here, dead fuels dominated and the bulk was within 30 inches (76 cm) of the soil surface (fig. 6).

Based on the fine-fuel component of the sites sampled and expected fuel moisture conditions in late summer and fall, we based the Behave runs with a 1-hour dead-fuel moisture parameter. According to firefighter observations of a 10 mph (16 km/h) wind and our measurements, Behave models predicted a maximum flame length of 10 feet (3 m) with a rate of spread of 0.5 mph (0.8 km/h) for a fire on flat ground. As the actual fire was backing downhill, the predicted maximum flame length was approximately 3 feet (1 m) with a rate of spread of about 0.3 miles (0.5 km) over 8 hours. These predictions are relatively close to what was observed on the ground. By contrast, Behave predicted maximum flame lengths of 28 feet (8.5 m) and a rate of spread of about 1.75 mph (2.8 km/h) under a worst-case scenario (figs. 7a and b).

Conclusions

We have found that 3-year-old, post-fire native vegetation in a recovering chamise chaparral stand is capable of carrying a fire under moderate weather conditions. Under more severe conditions, such fuels are capable of generating substantial flame lengths and spread rates. Consequently, these younger fuels would not likely provide the necessary barrier to stop wildland fires in chaparral systems under natural conditions. This was demonstrated on a much larger scale during San Diego County's 2007 firestorm. Approximately 60,000 acres (24,280 ha) of shrubland that had burned in 2003 burned again when the wind-driven fronts of the 2007 Poomacha, Witch, and Harris Fires pushed into existing fire scars (fig. 8 and table 2).



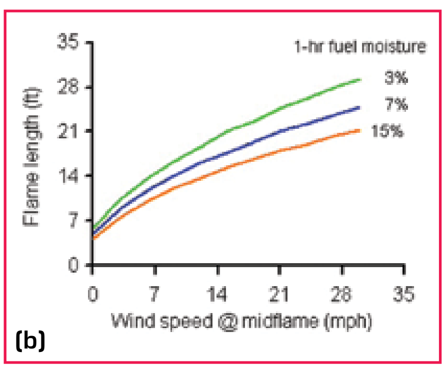


Figure 7—*BEHAVE predicted (a) the rate of spread and (b) the flame length of the 3-year-old fuels sampled in the 2001 Viejas Fire scar.*

The 3-year-old fuels within the Viejas Fire scar did, however, make it possible for firefighters to approach the area with acceptable risk in order to conduct fire suppression activities. By 1800 hours on Monday afternoon, the northeast winds had begun shifting to the northwest. The flames were already backing southeast downslope toward the heavy fuels across the river prior to the wind shift. If the fire had not been extinguished within the short, 4-hour time window, it is likely the fire would have made the jump into the heavier fuels on the other side of the canyon that afternoon. Had the jump occurred, this portion of the Cedar Fire would have likely been picked up by the stronger northwest winds on Tuesday, October 28, spreading the flames into two wilderness areas and potentially burning an additional 70,000 acres (28,328 ha). This event would have coincided with the wind-driven blowup east of State Highway 79 in Cuyamaca State Park on Tuesday evening. Further movement of the fire into the 3-year-old Viejas Fire scar to the southwest, however, may have been unlikely due to increasing humidity levels and the change in wind direction from a northeast Santa Ana flow to a northwest onshore flow.

Implications

There is considerable speculation concerning the natural fire regime in southern California chaparral ecosystems prior to the arrival of humans. Minnich (1983, 1989) has hypothesized that fires were generally frequent, creating small "patches" (250 to 2,500 acres [101 to 1012 ha]) of mixed-aged vegetation. According to this hypothesis, fuel age is the primary determinant of fire size because fires will stop

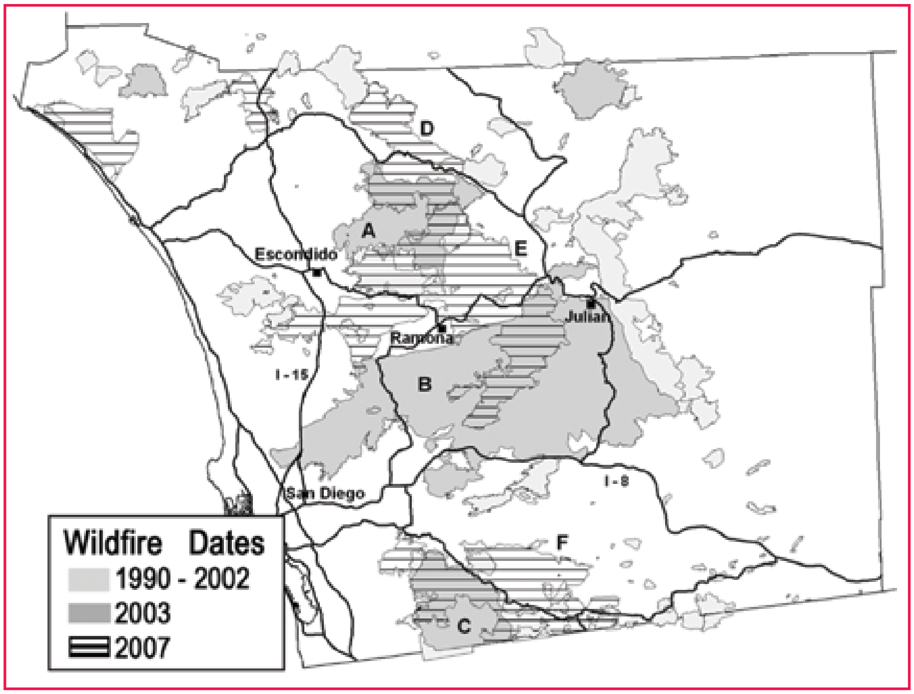


Figure 8—*2003 and 2007 San Diego County fire overlap map. The map shows the perimeters of the 2003 Paradise Fire (A), Cedar Fire (B), and Otay Fire (C). 2007 fires are labeled to the right of their perimeters: Poomacha Fire (D), Witch Creek Fire (E), and Harris Fire (F). Major roads are represented by dark lines. Note the significant areas of overlap between the 2007 and 2003 fires. From Halsey (2008).*

spreading once they reach younger aged patches. Consequently, large shrubland wildfires over 10,000 acres (4,047 ha) are viewed as "unnatural," byproducts of past fire suppression efforts that have allowed large, older stands of chaparral to develop.

Our research does not lend support to this hypothesis as we found that younger aged fuels of the type found in recovering chaparral stands can carry fire, even under moderate weather conditions. Although fuel type and condition play a critical role in determining fire spread, other factors (such as weather and topography) can dominate the outcome. For example, the western expansion of the 2003 Cedar Fire burned through numerous younger aged patches of vegetation before hitting the community of Scripps Ranch in San Diego (Halsey 2006). Interestingly, this edge of the fire finally stopped in extremely dense chaparral without the aide of fire suppression efforts. This abrupt perimeter edge was likely caused by a combination of higher fuel moisture content, slowing of Santa Ana winds, and the influx of a marine moisture layer.

Other research has also suggested there is not a strong relationship between hazard of burning and fuel age (Moritz and others 2004) and that large fires are not dependent on old age classes of fuels but rather extreme weather conditions (Keeley and others 1999). In addition, the relatively low lightning frequency that occurs in southern California, especially at lower elevations, would not likely ignite the number of fires required to create small, mixed-aged patches of veg-

Table 2—*Wildlands burned in 2003 and 2007 firestorms. The baseline data for this table was drawn from San Diego County vegetation data, 2003 fire scar perimeter, and 2007 fire perimeter. All results are expressed in thousands and rounded off to reflect estimated values and are intended only as general indicators of habitat loss, as some areas within mapped perimeters may not have burned. Compiled by Kit Wilson.*

	Total Habitat Area (acres/ha)	Area Burned 2007 (acres/ha)	Percent burned 2007	Area Burned 2003 (acres/ha)	Percent Burned 2003	Area Burned Twice (acres/ha)	Percent Burned Twice	Percent Burned in 4 Yrs
Chaparral	856 (346)	117 (47)	14%	173 (70)	20%	27 (11)	3%	31%
Coastal + Scrub	290 (117)	94 (38)	32%	79 (32)	27%	34 (14)	12%	48%
Grasslands	161 (65)	21 (8.5)	13%	17 (7)	11%	2 (1)	2%	22%
Riparian + Marsh	64 (26)	9 (4)	14%	6 (2)	9%	2 (1)	3%	20%
Woodland	112 (45)	33 (13)	30%	27 (11)	24%	10 (4)	9%	44%
Forest	86 (35)	13 (5)	16%	20 (8)	23%	1 (0.4)	1%	37%

etation (Keeley 1982, Christensen 1985).

While we seriously doubt that southern California shrubland fires can be naturally constrained by younger aged vegetation, strategically placed fuel treatments can play a supporting role in fire suppression efforts. Our data support the observation that younger fuels in post-fire chaparral ecosystems can provide greater opportunities for firefighters to establish fire suppression anchor points, especially under moderate weather conditions and along the flanks of wind-driven fires. This explains the desire of some land managers to establish an artificial "mosaic" of age classes on a landscape scale to prevent the development of large, contiguous old-age fuel beds (P. Scully pers. comm. 2008). However, beyond the strategic application of fuel manipulations at the wildland/urban interface, we have only limited understanding of the efficacy of such treatments on the broad landscape.

Another important factor to consider regarding the artificial creation of mixed-aged mosaics is the resource damage that additional fires may cause to native plant communities. In conjunction with this research, we have been investigating the health of the study site's chaparral ecosystem after it was subjected to the fires of 2001 and 2003. Preliminary data have shown that there is significant mortality of chamise burls, reduction of several native plant species, and spread of invasive, non-native grasses such as foxtail chess (*Bromus madritensis*). By adding more fire to the landscape through rotational burning in order to create mosaics, type-conversion of native shrubland systems to non-native grasslands will likely increase.

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Fuel Treatment Guidebook: Illustrating Treatment Effects on Fire Hazard

Morris Johnson, David L. Peterson, and Crystal Raymond

The Guide to Fuel Treatments (Johnson and others 2007) analyzes potential fuel treatments and the potential effects of those treatments for dry forest lands in the Western United States. The guide examines low- to mid-elevation dry forest stands with high stem densities and heavy ladder fuels, which are currently common due to fire exclusion and various land management practices, such as timber harvesting. These stands are the focus of potential management activities intended to modify forest structure and fuels to reduce crown fire hazard on public lands. The guide is intended for use by fire managers, silviculturists, and other resource specialists who are interested in evaluating the effects of fuel treatments on dry forest ecosystems.

Development of the Guide

In April 2003, the Forest Service initiated the Fuels Planning: Science Synthesis and Integration project (known as the Fuels Synthesis Project) to accelerate the delivery of research information to fuels specialists and others involved in project planning. The geographic focus of the project was on the dry forests of the Western United States. Project goals included developing accessible analyses, protocols, and tools; writing peer-reviewed documents that synthesize and integrate the ecological and social science relevant to fuels treatments; and delivering these products in a user-friendly format to community leaders and educators, fuels management specialists and resource specialists, National Environmental Policy Act (NEPA) planning team leaders, and line officers in the Forest Service and the Department of the Interior. Information derived from this effort is applicable to categorical exclusion documents, environmental impact statements, environmental assessments, and other NEPA documents.

Morris Johnson is an ecologist and David Peterson is a research biologist with the Forest Service's Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, in Seattle, WA. Crystal Raymond is a researcher and Ph.D student at the Fire and Mountain Ecology Lab, Department of Forest Resources, University of Washington, Seattle, WA.

> The goal was to link information from silviculture and fire science to provide quantitative guidelines for fuel treatment that consider desired future conditions for multiple resources.

Scientists at the Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station, developed the guide in cooperation with other scientists and resource managers throughout the Western United States. The goal was to link information and data from silviculture and fire science in order to (1) assist decisionmaking about fuel treatments in dry forest stands and (2) provide quantitative guidelines for fuel treatments that consider desired future conditions for multiple resources (e.g., wildlife, water, and timber production). Developers determined the final structure of the guide after reviews by scientists and resource managers and two test efforts involving national forests.

The scientific basis for fuel treatments is documented in recent syntheses (Graham and others 2004, Peterson and others 2005) and numerous publications (Agee 1996, 2002; Brown and others 2004; Carey and Schuman 2003; Fitzgerald 2002; Kalabokidis and Omi 1998; Keyes and O'Hara 2002; Pollet and Omi 2002; Sandberg and others 2001; Scott and Reinhardt 2001; Weatherspoon 1996). The guide provides quantitative guidelines for treatments based on the scientific principles in these documents and is intended to cover a broad range of possible treatments and stand conditions. However, the representative cases in the guide are not comprehensive, and interpretation and application of quantitative output will typically need to be adjusted based on local conditions and objectives.

Analytical Tools

The Fire and Fuels Extension of Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) was used to prepare the guide. This tool links forest growth modeling with fire behavior modeling to produce information relevant to management of forest stands, fuels, and fire. FVS has been widely used by resource managers and scientists for over two decades, has been programmed to cover many of the major forest types in the United States, and is regarded as a credible tool for applications in forest management (Dixon 2002). Integration of fire concepts is a recent and valuable extension of the FVS approach to forest stand simulation, but it has not been available long enough to be thoroughly tested. However, it is the only analytical tool currently available that quantitatively links stand dynamics and fire science. At a minimum, FFE-FVS requires input of forest stand attribute data (species, diameter at breast height [d.b.h.], and height), but fuels data are extremely helpful.

In the guide, the effects of fuel treatments are quantified for forest structure, surface fuels, and potential fire behavior. FFE-FVS was used to calculate a variety of fuel treatment combinations (including the no-action alternative, four levels of thinning, three types of surface fuel modification, and prescribed fire alone) for each of 25 representative forest stands (fig. 1). FFE-FVS runs are summarized for each stand with visualizations and extensive tabular data (not included in this article). In addition, forest structure and fuels are calculated for 50 years posttreatment at 10-year increments, so that long-term stand conditions can be assessed and users can determine when additional fuel treatments might be needed. Users familiar with FFE-FVS have the option of running their own simulations to calculate site-specific effects of treatments.

The guide provides quantitative guidelines for treatments based on the scientific principles in these documents and is intended to cover a broad range of possible treatments and stand conditions.

Scenarios displayed in the guide are intended to represent a range of dry forest types in the Western United States, specifically those forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), mixed conifers—often including Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) as a codominant—and pinyon-juniper (*Pinus* spp. and *Juniperus* spp.). Specific stand data were obtained from resource managers on national forest units throughout the Western United States. Stands selected for analysis had high stem densities and had not experienced recent fire or thinning. In the guide, only stands at relatively low elevations and slopes of less than 40 percent were considered as potential candidates for fuel treatment. Fuel treatment scenarios are organized according to Forest Service regions in the Western United States.

Fuel Treatments

Fuel treatment scenarios analyzed in the guide to Fuel Treatments were determined with extensive feedback from Federal resource managers. These scenarios cover a range of potential thinning and surface fuel treatments that would be reasonable and appropriate alternatives for NEPA analysis and similar documentation. The scenarios illustrate representative situations that might be encountered in operational management and planning and do not illustrate all possible treatments.

Thinning from below (or low thinning) refers to removal of stems starting from smallest to increasingly larger stems until the target density is reached. In practice, thinning from below often has a d.b.h. limit below which no stems are harvested, with that lower limit set to reduce costs and maximize value of harvested material.

In guide scenarios, stem harvesting begins with trees smaller than 1 in (2.5 cm) d.b.h. and then proceeds to larger stems. For all thinnings, no trees larger than 18 in (44 cm) d.b.h. are harvested. This limit is intended to retain larger, more fire-resistant individuals. In practice, this upper d.b.h. limit could

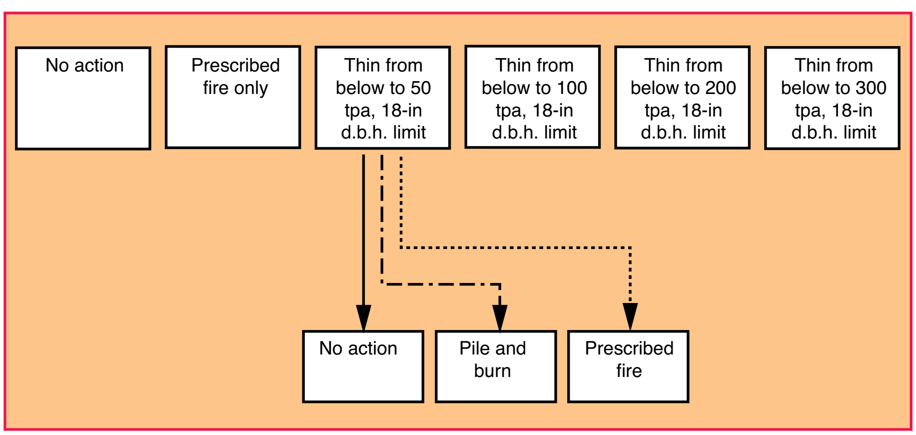

Figure 1—*Matrix of thinning and surface fuel treatments implemented for each stand in the guide to Fuel Treatments. Each stand was projected through a series of 14 potential treatments.*

Table 1—*Summary of values and assumptions used in FFE-FVS for surface fuel treatments.*

Surface fuel treatment FFE	FVS values and assumptions	FVS keywords
No action	All boles greater than 6 in diameter at breast height (d.b.h.) are removed from stand. The entire tree (branch and bole) and branch material from trees greater than 6 in d.b.h. are left in stand.	Yardloss
Pile and burn	All boles greater than 6 in d.b.h. are removed from stand. The entire tree (branch and bole) and branch material from trees greater than 6 in d.b.h. are left in stand. 80 percent of the remaining fuel from the entire stand is concentrated into piles that cover 10 percent of the stand area. No tree mortality will result.	Yardloss PileBurn
Prescribed fire	All boles greater than 6 in d.b.h. are removed from stand. The entire tree (branch and bole) and branch material from trees greater than 6 in d.b.h. are left in stand. Windspeed at 20 ft above vegetation = 10 mph. FVS predefined moisture group (3) selected to represent fuel moisture percentages for prescribed fires. Temperature equals 70 °F. Note: predefined moisture values are specific to FVS variants.	Yardloss SimFire

be higher or lower depending on local harvest specifications and resource objectives. Thinning from below is the most commonly used approach to modify stand structure, density, and fuels, although many other silvicultural approaches are available (Graham and others 1999). Thinning as used within FVS is applied equally across a given stand. In practice, variable-density thinning—a spatial pattern of tree clumps and openings—can be used to achieve the same final tree density but attain greater heterogeneity in stand structure. Variable-density thinning cannot be represented in FVS and is, therefore, not considered here. For target densities different than those in the guide, users can interpolate or extrapolate the results found in tables and visualizations. Exploratory runs of FFE-FVS indicate that thinning to densities greater than 300 trees per acre (TPA) (741 trees per hectare [TPH]) rarely changes fuel conditions enough to modify fire hazard significantly from initial stand conditions.

Some managers prefer to use basal area (BA) as a target for thinning. This measurement may be more appropriate for even-aged stands with relatively low variability in tree size. BA is calculated for each thinning treatment, so both BA and stem density are available for all scenarios.

In practice, techniques used for modification of activity fuels and residual surface fuels vary considerably, as does the effectiveness of those techniques. Options included in the guide are intended to capture the more common approaches currently used in the field and to represent moderately high effectiveness. Assumptions regarding slash disposal, material left on site, area affected, and effectiveness of treatments are summarized in table 1. Prescribed fire is considered to be a broadcast burn that covers the entire treatment area.

The following is an example of scenarios derived from the guide.

Figure 2—*Computer simulation of forest structure prior to the four thinning treatments in the Forest Vegetation Simulator. Stand visualization taken from stand data for the Bitterroot National Forest.*

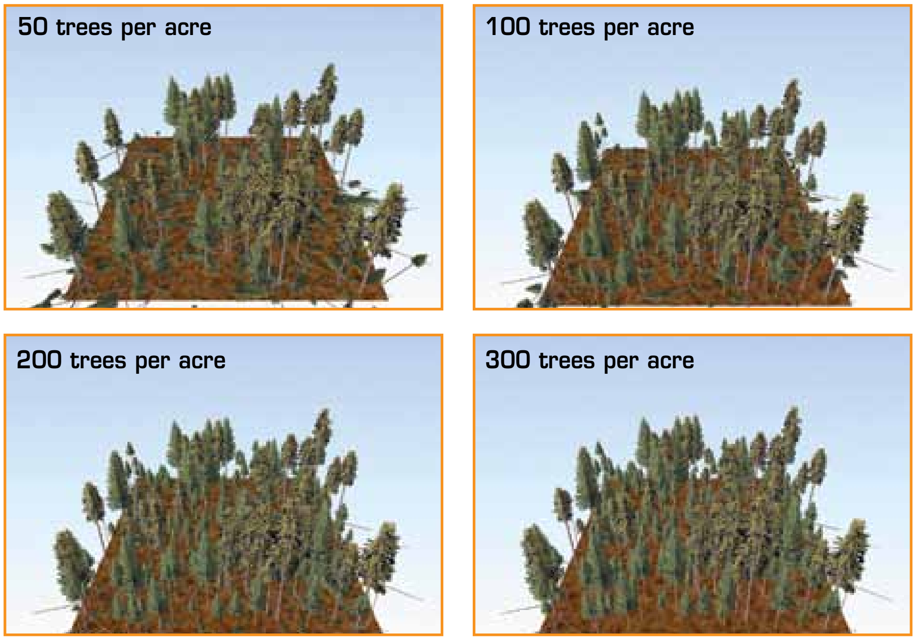

Figure 3—*Computer simulation of forest structure following the four thinning treatments in the Forest Vegetation Simulator: thinning to 50, 100, 200, and 300 trees per acre. Stand visualization taken from stand data for the Bitterroot National Forest.*

Initial Conditions/No-Action Trajectory

This stand (fig. 2) has a high tree density of 2,345 TPA (5,795 TPH) primarily composed of grand fir and Douglas-fir with a ponderosa pine overstory. Woody fuel loading is 9 tons/ac (20,175 kg/h), and litter and duff loading is 7 tons/ac (15,692 kg/h). Canopy bulk density is 0.0087 lb/ft^3 (0.14 kg/m^3), and canopy base height is 3 ft (0.91 m), so ladder fuels are sufficient to enable passive crown fire, but canopy fuels are not sufficient to enable active crown fire spread. Crowning index is 19 and severe weather wind speed is 17 mph (27 km/h), so although this stand is not classified as active crown fire, crown fire hazard is high. Potential BA mortality is 97 percent for severe fire weather. With no action, flame lengths, surface fuels, and canopy base height increase slightly over time, with crown fire potential decreasing in 20 years and then increasing again in 40 years. Crown fire potential and flame lengths remain low for moderate fire weather for the entire 50-year projection.

Silvicultural and Surface Fuel Treatments: Immediate Effects

According to results from FFE-FVS, the prescribed fire-only treatment decreases canopy bulk density and slightly increases canopy base height, but not enough to prevent passive crown fire for severe fire weather. This treatment reduces surface fuels in all size classes, but flame lengths increase after treatment owing to grass fuels associated with the use of fuel model 2. Grass fuels are not tracked in FFE and may or may not be the primary fuel following prescribed fire.

All thinning treatments reduce canopy bulk density and increase canopy base height; the greater the thinning, the greater is the change in forest structure (fig. 3). The predicted fire type after treatment is surface fire for all thinning options, but the more open stands are characterized predominantly by fuel model 2, so flame lengths increase and potential BA mortality remains above 20 percent regardless of surface fuel treatment. The 200 and 300 TPA (494 and 741 TPH, respectively) treatments have a more closed canopy and fire behavior is influenced less by grass fuels, so flame lengths and potential BA mortality are lower than the more open stands. Activity fuels are reduced by the pile-and-burn treatment and, to a greater extent, by the prescribed fire treatment, which also reduces litter and duff, but flame lengths and BA mortality remain high owing to grass fuels.

Silvicultural and Surface Fuel Treatments: Long-Term Effects

Although the prescribed fire-only treatment does not reduce crown fire potential in the short term, the predicted fire type is surface fire after 10 years. Crown fire potential continues to decline as canopy base height increases and flame lengths decrease. In all thinning treatments, flame lengths decrease over time as canopy cover increases and fuel model assignment shifts from predominantly fuel model 2 to predominantly fuel model 9. The 200 TPA treatment has the greatest long-term effect on crown fire potential, with a predicted surface fire type for 50 years with pile-and-burn or no surface fuel treatment and 40 years with prescribed fire treatment. The 50 TPA (124 TPH) treatment had the most short-lived effect on crown fire potential, with regeneration causing a drop in canopy base height in 30 years regardless of surface fuel treatment.

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A Suite of Fire, Fuels, and Smoke Management Tools

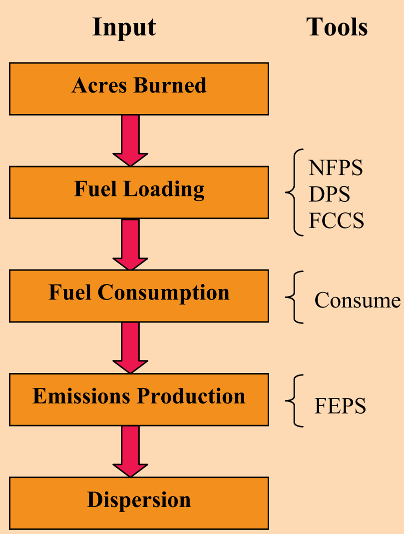
Roger D. Ottmar, Clint S. Wright, and Susan J. Prichard

The Fire and Environmental Research Applications Team (FERA) of the Forest Service, Pacific Northwest Research Station, is an interdisciplinary team of scientists that conduct primary research on wildland fire and provide decision support for fire hazard and smoke management. The team is committed to providing easy-to-use tools that help managers in their fire and fuels planning. Several tools developed by FERA include:

- *Natural Fuels Photo Series (NFPS).* These published photo series volumes (available through <http://www.fs.fed.us/pnw/fera/research/fuels/photo_series/>) provide a quick and easy way to quantify and describe fuel and vegetation characteristics.
- *Digital Photo Series (DPS).* This Web-based application (<http://depts.washington.edu/nwfire/dps>) makes it easy for users to search for existing fuels data and high-quality photographs of the NFPS.
- *Fuel Characteristic Classification System (FCCS).* FCCS allows users to build fuelbeds and assess them for their relative fire hazard, surface fire behavior, and potential carbon stores. See <http://www.fs.fed.us/pnw/fera/fccs/>.
- *Consume 3.0.* Consume provides users the ability to estimate fuel consumption and emissions from fuelbeds burned during prescribed and wildland fires. See <http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml> for more details.
- *Fire Emission Production Simulator (FEPS).* FEPS enables users to estimate the rate of fuel consumption, heat release, and emissions production from fuelbeds burned during prescribed and wildland fires. The application can be downloaded from <http://www.fs.fed.us/pnw/fera/feps/>.

Roger D. Ottmar and Clint S. Wright are research foresters with the Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, in Seattle, WA. Susan J. Prichard is a research scientist with the College of Forest Resources, University of Washington, in Seattle, WA.

FERA tools are used to estimate wildland fire emissions



The tools can be used individually or in combination to support a variety of management situations. For example, for a fuel reduction project, managers may need to first assess fuel characteristics, including the loading and configuration of wildland fuels. The NFPS and DPS contain a wealth of fuels information and can be used to quickly and inexpensively assess fuel characteristics. FCCS can be used to build custom fuelbeds based on actual fuel assessment data. Managers then can evaluate potential fire behavior and fire hazard in FCCS and explore different fuel reduction scenarios. If prescribed fire is planned as a fuel reduction strategy, Consume and FEPS can be used to estimate potential fuel consumption and pollutant emissions for each custom fuelbed.

Natural Fuels Photo Series

NFPS provides a quick and easy way to quantify and describe current fuel and vegetation properties, such as loading of dead and down woody material, tree density, or height of understory vegetation. This information is critical for making fuel management decisions and predicting fire behavior and fire effects. NFPS currently comprises 14 volumes representing various regions and fuel types of the United States and two volumes representing Mexico and Brazil. A significant national effort over the last decade resulted in publication of NFPS for previously unrepresented vegetation types. Future photo series will include a hurricane damage series for the Southern United States and a volume focusing on relevant fuelbed types in the San Francisco Bay area.

Each volume contains up to four photo series for 1 to 17 sites. Series for each site include standard, wide-angle, and stereo-pair photographs and inventory data summarizing:

- vegetation composition, structure, and loading; woody material loading;
- density by size class, forest floor depth, and loading; and
- various site characteristics.

The photo series are important land management tools that can be used to assess ecological landscapes through appraisal of living and dead woody material, vegetation biomass, and stand characteristics. Once an ecological assessment has been completed, stand treatment options, such as prescribed fire or harvesting, can be planned and implemented to better achieve desired effects while minimizing negative impacts on other resources.

Digital Photo Series

NFPS was developed primarily for field-based assessments. Technological advances, coupled with development of new fire- and natural resource-based software applications, highlighted the need for an electronic version of the photo series. DPS was the result (see Wright and others, in this volume, for a more detailed description). DPS provides easy access to data and images from all of the volumes, series, and sites in the NFPS. Information presented in this new format can be used for planning fuels treatments or other management actions and as inputs to fire behavior and fire effects models and applications. DPS has the ability to grow as new photo series are developed and as the priorities and needs of fire and fuels managers change and evolve.

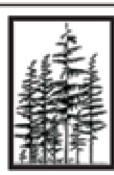
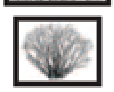
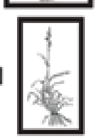
Published volumes of the Natural Fuels Photo Series.

Region	Fuelbed Type(s)	Volume
Pacific Northwest	Mixed-conifer with mortality, western juniper, sagebrush, grassland	I[1]
Alaska	Black spruce, white spruce	II[1]
Alaska	Hardwoods with spruce	IIa[1]
Rocky Mountains	Lodgepole pine, quaking aspen, gambel oak	III[1]
Southwest	Pinyon-juniper, chaparral, sagebrush	IV[1]
Midwest	Red and white pine, northern tallgrass prairie, mixed oak	V[1]
Lake States	Jack pine	Va[1]
Southeast	Longleaf pine, pocosin, marshgrass	VI[1]
Southeast	Sand hill, sand pine scrub, hardwoods with white pine	VIa[1]
West Coast	Oregon white oak, California deciduous oak, mixed-conifer with shrub	VII[1]
Northeast	Hardwood, pitch pine, red spruce/balsam fir	VIII[1]
Southwest	Oak/juniper	IX[2]
Montana	Sagebrush with grass, ponderosa pine-juniper,	X[2]
Hawaii	Grassland, shrubland, woodland, forest	N/A[2]
Brazil	Cerrado	N/A[2]
Mexico	Montane subtropical forests, temperate forests, montane shrublands	N/A[2]
Southeast	Hurricane damaged pine	N/A[3]

[1] Photo series can be purchased from the National Interagency Fire Center in Boise, ID, for a nominal charge.
[2] Photo series can be requested free of charge from the Fire and Environmental Research Applications Team.
[3] This photo series is in preparation; expected publication is spring 2009.

Photo series photograph from the new hurricane damage photo series that is in preparation.

Fuelbed strata and categories in the FCCS

Stratum		Category
CANOPY		Trees, snags, ladder fuels
SHRUBS		Primary and secondary layers
NONWOODY VEGETATION		Primary and secondary layers
WOODY FUELS		All wood, sound wood, rotten wood, stumps, and woody fuel accumulations
LITTER-LICHEN-MOSS		Litter, lichen, and moss layers
GROUND FUELS		Duff, basal accumulations, and squirrel middens

Application of NFPS and DPS

NFPS and DPS are useful tools in several branches of natural resource science and management. Inventory data provided by these tools can be used as inputs for evaluating animal and insect habitat, nutrient cycling, and microclimates. Fire managers will find these data useful for predicting fuel consumption, smoke production, fire behavior, and fire effects during wildfires and prescribed fires. In addition, the photo series can be used to appraise carbon sequestration, an important factor in predictions of future climate, and to link remotely sensed signatures to live and dead fuels on the ground.

FCCS

FCCS enables land managers to create and catalog fuelbeds for fuels and fire planning. It contains searchable fuelbed data sets that represent much of North America and were compiled from scientific literature, natural fuels photo series, fuels data sets, and expert opinion. The system allows customization of these fuelbeds or creation of new fuelbeds to represent a particular situation or scale of interest. FCCS reports assigned and calculated fuel characteristic for each of six fuelbed strata, including the canopy, shrubs, nonwoody, woody, litter-lichen-moss, and duff.

FCCS calculates the relative fire hazard of each fuelbed, including surface fire behavior, crown fire, and available fuel potentials, scaled on an index from 0 to 9. The FCCS also uses a modified version of the Rothermel surface fire behavior equations (Rothermel 1972, Sandberg and others 2007) to predict actual surface fire behavior, including reaction intensity (Btu ft^{-2} min^{-1}), flame length (ft), and rate of spread (ft min^{-1}), and based on both benchmark and user-specified environmental conditions. By comparing predicted flame length and rate of spread, FCCS provides a crosswalk to any of the original 13 Fire Behavior Prediction System fuel models (Albini 1976) and to any of the 40 standard fire behavior fuel models (Scott and Burgan 2005). FCCS also reports carbon storage by fuelbed stratum, category, and subcategory and predicts the amount of combustible carbon based on selected fuel moisture scenarios. Finally, the system reports in English and metric units, provides the capability to upload photos to represent fuelbeds, and can be run in a batch mode to provide outputs for multiple fuelbeds simultaneously.

Application of the FCCS

FCCS facilitates the mapping of fuelbed characteristics and fire hazard assessment by storing realistic fuelbed data, summarizing and calculating fuel characteristics, and predicting surface fire behavior, crown fire behavior, and available fuel for consumption. FCCS also provides the necessary inputs to run fuel consumption and emission production models, such as Consume and FEPS.

FCCS fuelbeds are being mapped on the Okanogan-Wenatchee and Deschutes National Forests to allow managers to evaluate fire hazard and maximize fuel treatment effectiveness. The U.S. Environmental Protection Agency is developing a national air pollutant and carbon emission inventory based on FCCS fuelbeds (fig. 1). LANDFIRE (a project producing consistent and comprehensive maps and data describing vegetation, wildland fuel, and fire regimes across the United States) (Rollins and others 2006) is also developing a 30-meter resolution map layer of FCCS fuelbeds for the United States.

FCCS was introduced to managers and scientists during 15 national workshops and through 8 pub-

Acronyms

DPS	Digital Photo Series
FCCS	Fuel Characteristic Classification System
FEPS	Fire Emision Production Simulator
FERA	Fire and Environmental Research Applications Team
FIREMON	Fire Effects Monitoring and Inventory Protocol
FOFEM	First Order Fire Effects Model
FVS	Forest Vegetation Simulator
NFPS	Natural Fuels Photo Series

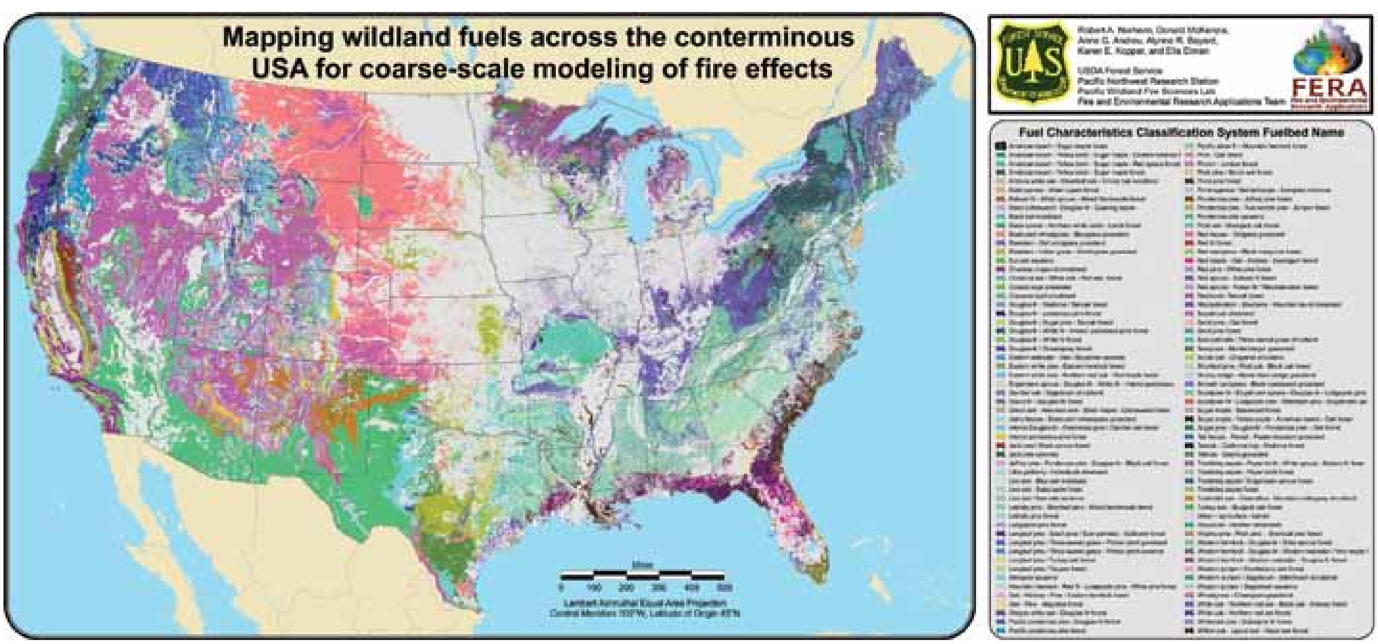


Figure 1—*One-km resolution FCCS fuelbed data are available for the continental United States (map available through <http://www.fs.fed.us/pnw/fera/fccs/maps.shtml>).*

The photo series are important land management tools that can be used to assess ecological landscapes through appraisal of living and dead woody material and vegetation biomass and stand characteristics.

lished papers in a special section of the Canadian Journal of Forest Research (Berg 2007; Ottmar and others 2007; Riccardi and others 2007a; Riccardi and others 2007b; Sandberg and others 2007a; Sandberg and others 2007b; Schaaf and others 2007; McKenzie and others 2007). Source data references for each fuelbed, as well as supplementary fuelbeds useful to specific locations and purposes, can be found on the FCCS Web site (<http://www.fs.fed.us/pnw/fera/fccs>). In future versions, linkages with other FERA tools, Fire Effects Monitoring and Inventory Protocol (FIREMON), the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997), and the Forest Vegetation Simulator (FVS) (Dixon 2003) are envisioned.

Consume 3.0

Fuel consumption is a key variable in fire effects modeling and in understanding when and how fire should be applied to meet site and landscape objectives while at the same time mitigating air quality impacts. Until recently, much of the considerable research on fuel consumption focused on prescribed burning following logging in forested ecosystems. FERA's new fuel consumption studies in natural environments (developed with support from the Joint Fire Science Program and the National Fire Plan) have improved our understanding of fuel consumption in shrublands (including chaparral, sagebrush, and palmetto-galberry types), hardwood forests (including southern and eastern regions of the United States), and boreal forests (including white spruce, black spruce, and hardwood forests of Alaska). Consume also resolves differences in fuel consumption between the relatively short flaming phase of combustion and the longer smoldering phase of combustion that generally contributes to the majority of wildland fire emissions.

Consume is a decisionmaking tool designed to assist resource managers in planning for prescribed fire and wildfire, and reflects our improved understanding of fuel consumption and emissions in wildland fire throughout major fuel types in the United States.

For Further Information, visit:

Fuel Characteristic Classification System:
<http://www.fs.fed.us/pnw/fera/fccs>.

Natural Fuels Photo Series:
<http://www.fs.fed.us/pnw/fera/research/fuels/photoseries>.

Consume 3.0:
<http://www.fs.fed.us/pnw/fera/research/smoke/consume>.

Fire Emission Production Simulator:
<http://www.fs.fed.us/pnw/fera/feps>.

Consume predicts fuel consumption, pollutant emissions, and heat release based on a number of variables, including fuel loadings, fuel moisture, and other environmental factors. Using these predictions, resource managers can determine when and where to conduct a prescribed burn or to plan for a wildland fire to achieve desired objectives while reducing the impact on other resources.

Consume allows land managers and researchers to input fuel characteristics, lighting patterns, fuel conditions, and meteorology to more accurately predict fuel consumption and emissions. Consume can import data from the FCCS, and its reports are formatted to feed other models (e.g., FEPS), as well as for inclusion in burn and smoke management plans.

Application of Consume 3.0

Consume can be used to estimate fuel consumption and emissions from wildland fire in most forests, woodlands, shrublands, and grasslands of North America. The outputs provide managers with fuel consumption and emissions information for fire planning and for meeting smoke management reporting requirements. Fuelbed data are the basis for all Consume calculations. Because fuelbeds can represent any scale of interest, Consume can be applied to small-scale fuel reduction projects and to large-scale landscape assessments of consumption and emissions. For example, on smaller scales, Consume can be used to develop burn prescriptions for prescribed fire planning. On a much larger scale, the BlueSky smoke modeling framework (O'Neil 2003) (<http://www.airfire.org/bluesky>), uses

Consume algorithms to estimate emissions to predict smoke impacts across landscapes.

Fire Emissions Production Simulator

Modeling the impact of emissions from wildland fire on visibility and public health requires the rates as well as the total amount of fuel consumption, heat release, and emissions production. These rates are required inputs for smoke dispersion models for assessing potential visibility and health impacts of smoke at a distance from the fire. FEPS, an update of the Emissions Production Model (EPM) (Sandberg and Peterson 1984), models the characteristics of prescribed burns and wildland fires. FEPS significantly improved the usability, applicability, and accuracy of EPM. FEPS 1.1 includes the fuels data from the most popular fuelbeds in the FCCS and produces hourly emission and heat release data for prescribed and wildland fires. It can also accept fuel consumption data generated by the FOFEM (Reinhardt and others 1997), Consume 2.1, and Consume 3.0.

FEPS distributes total fuel consumption amounts over the life of the burn to generate hourly emission and release information. FEPS allows users to produce reasonable results with very little information by providing default values and calculations while maintaining the ability of advanced users to customize data inputs to produce very refined results.

Application of FEPS

Hourly emission and heat release data for wildland fires in fuel types in the United States produced by FEPS 1.1 can be fed into dispersion models, such as the BlueSky smoke modeling framework (O'Neil and others 2003) and V-Smoke (Lavdas 1996) for assessing smoke impacts from wildland fire.

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Using Wind Models To More Effectively Manage Wildfire

Brian Potter and Bret Butler

Fire and Wind

Surface wind is often the dominant environmental variable affecting wildland fire intensity and spread. Traditionally, fire analysts and managers have depended on local measurements and site-specific forecasts to determine winds influencing their fire. However, advances in computer hardware, increased availability of electronic topographical data, and advances in numerical methods for computing winds have led to the development of new tools capable of simulating surface wind flow. Several options for estimating winds across the landscape now exist, and they have the potential to dramatically improve fire growth estimates. Their benefits include improved firefighter and public safety and more efficient use of fire management resources.

Wind modeling for fire management presents unique challenges. Fire managers must develop new tactics within a matter of a few hours while considering changing weather conditions and the potential for fire to move into new areas. Often, to be relevant to short-term fire management tactics, wind speed and direction must be calculated within an hour or two of a weather forecast and must be provided at fine scales (tens of yards or meters). Fire behavior analysts (FBANs), long-term fire analysts (LTANs), and incident meteorologists (IMETs) on fire management teams use all the technology available to them to prepare their forecasts. To do this accurately and efficiently, they need to know the strengths and weaknesses of the available wind models—knowing where and how to obtain wind information for a specific site at a fine scale can be a challenge.

> This resolution of wind information can be useful to fire models simulating fire growth in very specific locations, such as individual drainages or ridges.

Some wind models are more appropriate for research, some for daily forecasts, and some for field applications. The goal of this article is to provide an overview of models that can be used to support operational fire management. We briefly describe how the different models work and what they provide in terms of output.

Wind Models

All physics-based wind models use some derivation of Newton's laws of motion and thermodynamics and need some starting data, such as the wind's direction and speed in or near the area being modeled. These data are commonly called boundary conditions or initial conditions. Further information needed to yield useful projections include:

- Broad-scale pressure variations
- Topography
- Atmospheric stability
- Surface heating
- Surface friction

Broad-scale pressure variations (such as pressure ridges, troughs, and fronts) influence surface wind flow primarily as the pressure engine that drives the flow. Topography can modify the pressure-driven flow of winds, changing both direction and speed, especially near the ground. Stability, defined as the tendency for air to move up or down, is caused by vertical changes in temperature and moisture and is a key factor in determining gustiness. Surface heating differences arise from variations in soil types, vegetation, and water/land boundaries, and are responsible for phenomena such as onshore and offshore breezes. Surface friction caused by the size and orientation of vegetation and other surface features (e.g., forest, brush, grass, and open water) create more or less drag on the wind. This drag, or friction, can force the air to rise, fall, or flow around an area. The fire also has a significant influence on local wind flow, but no existing wind model includes the effect of the fire on the winds around it

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Brian Potter is a research meteorologist on the AirFire Team at the Forest Service Pacific Wildland Fire Sciences Laboratory in Seattle, WA. Bret Butler is a research mechanical engineer for the fire, fuel, and smoke science program at the Forest Service Missoula Fire Sciences Laboratory in Missoula, MT.

(except for a few currently appropriate only as research tools).

The art of wind modeling lies in determining how the various wind models treat these processes and their interactions. Proper use of wind models requires that the user recognize what features are influencing the situation at hand. As a general rule, the more physical processes the model includes, the more accurately it estimates their influence, but also the slower and/or more computer-intensive the model will be. Similarly, the more extensive the geographic area being modeled, the more computer memory and time the model needs to complete a simulation.

All wind models fall into one of two categories: diagnostic or prognostic. Diagnostic wind models give an estimate of winds at one specific time and do not provide any information on potential change. Such models essentially assume that the forces producing the winds are not changing quickly over time, which make the calculations much simpler. Prognostic wind models, taking into account changing conditions, estimate how the winds will behave over time. Prognostic models are the more accurate of the two types, but they require much more computer time, more data to start the calculations, and generally more expertise to run. The farther out in time the prognostic model forecasts, the higher the likelihood the simulations will deviate from reality.

Diagnostic models vary in complexity: for example, WindNinja, a recently released wind simulation tool, considers a minimum number of physical factors (Forthofer 2007). This tool generally gives good estimates of winds on the upwind sides and tops of hills. However, the wind estimates degrade on the lee-sides of hills because turbulence is not included in the model and it is necessary to accurately simulate the effects of hilltops or terrain curvature on the surface winds. WindWizard, another tool developed over the last 8 years, includes the processes found in WindNinja but also includes the effects of nonbuoyant (mechanically) generated turbulence (Forthofer 2007). Because of this added complexity, outputs from WindWizard show better accuracy, including moderate success in predicting lee side winds. Both of these models have been shown to simulate wind in stable and neutral atmospheric conditions well, in a qualitative sense, with WindWizard providing the better accuracy of the two. Lastly, the CALMET model (Scire and others 2000) was originally developed for air pollution studies and includes effects of turbulence, slope flows, and flow over land and water surfaces. It is the most computationally intensive of the three models named here, and requires substantially more expertise to operate. In comparison to prognostic models, these diagnostic models typically have relatively cheap computational requirements (from seconds to a couple of hours per run on a single processor computer). The price for cheap computing is incorporation of fewer parameters and a wind field prediction capability of only one point in time.

Wind variations on a similar scale can cause sudden and dramatic changes in fire behavior; in other words, fine-scale variations in winds can significantly influence fire growth at larger scales.

The most widely known prognostic models are those used by the National Weather Service (NWS) for daily weather forecasting. The NWS uses several models, the most widely known perhaps being the North American Meso (NAM) and the Global Forecast System (GFS) models. NAM output is available at 7.5-mile (12-km) resolution, while the highest resolution GFS output is 50 miles (81 km). Another prognostic model, the NCAR/Penn State Mesoscale Model 5 (MM5), is primarily a research model, designed to be run on large computers for scientific research. Spatial resolution of MM5 data depends on the source, but grid resolution is rarely finer than 2.5 miles (4 km). The newest prognostic model is the Weather Research and Forecasting (WRF) model. WRF is a faster, updated version of MM5 capable of running with a grid as fine as 330 feet (100 m), although the computational requirements are huge. All of these prognostic models simulate the atmosphere in all three dimensions as it changes over time. To do this requires powerful computers and large amounts of time—they cannot be used on a laptop in the field and require users with extensive specialized skills. However, the advent of remote computing has provided access to the output from these models for meteorological specialists working in fire camps.

Generally, diagnostic models can provide predicted winds at the 330-foot (100-m) scale and, in some cases, at even finer scales. This resolution of wind information can be useful to fire models simulating fire growth in very specific locations, such as individual drainages or ridges. The relatively coarse scale of most prognostic models can limit their use on wildland fires: a large fire might be represented by only a few grid points (predicted values) and many fires by possibly just one. The coarse resolution also means that the models approximate the effects of larger features, such as mountain ranges, but smooth over small-scale terrain features. As a result of such smoothing, the models cannot resolve the winds modified by individual ridges, valleys, or mountains. In many cases, these small-scale features have a great influence on the local winds influencing a fire and should be considered (Butler and others 1998).

Matching the Model to the Application

There are two critical issues that influence the selection of a wind model to support management of a specific fire: the management objectives and the scale of input (and therefore output) data available to address those concerns. In general, the model must provide output data on the same or finer scale than the issue of greatest concern. When the concerns relate, for instance, to the rate of fire spread up a valley or over a ridge, the model must show winds at numerous locations in the valley or along the ridge—typically at a resolution of about 330 feet (100 m) or less between points. This suggests selecting a diagnostic model if model results are needed quickly. If, in contrast, the issue relates to smoke dispersion across a region of one or several States, then only a prognostic model can provide the necessary wind data. If the issue of concern is average rate of spread on a fire complex, then wind data on a scale of a few miles or kilometers may be adequate—though this might be too wide an area for typical diagnostic modeling, yet too limited for most prognostic models. In such a situation, computer access and time constraints are more likely to dictate the modeling option selected.

> In general, the model must provide output data on the same or finer scale than the issue of greatest concern.

The ideal model for a given application must include the physical processes acting on the air at the same time scales as the issue of concern. If one needs to estimate winds for a period during which there is considerable change in the regional pressure pattern or when the surface heating is changing rapidly (as when the sun crosses a ridge near the fire front) or when there are strong differences in surface heating and weak regional pressure variations (such as near a lake or ocean shore in the absence of a cold front), then a prognostic model may be necessary. Most of the rest of the time, one need not include all of the physical processes to get a good estimate of winds. If high resolution is also important, then the best solution might be to use the relatively coarse-scale wind information generated by prognostic models as input to a diagnostic model. The diagnostic model can be run multiple times from the prognostic simulation to capture alternative scenarios or sequential weather patterns and to provide fine spatial resolution that better accounts for fine scale topographical effects. Think of this as the equivalent of taking individual image frames from a video and enlarging or enhancing them for greater detail.

In addition to wanting winds data for existing fires, fire managers often are interested in "what if" scenarios that explore the effects of various wind scenarios on planned fire events (prescribed fires) or for the analysis of long-term fire growth potential or to understand what caused a fire to burn as it did (e.g., accident investigations). For example, it is useful to know what might happen to a prescribed fire under various potential weather scenarios or to project potential fire behavior at specific locations if an unplanned ignition should occur.

It is not feasible for the average fire modeler to obtain multiple, custom prognostic weather simulations. Even if it was feasible, it would be difficult to specify the initial and boundary conditions for the simulations, as these are typically obtained from coarser-scale global models and weather station measurements not generally available and require the expertise of an experienced meteorologist to interpret. In cases where time, computational resources, and technical expertise are abundant, prognostic models could be appropriate; but in general, given typical wildland fire management time and resource constraints, diagnostic models are the only practical option available for such pre-planning needs.

Model Application

Recent research and anecdotal observations suggest that variations

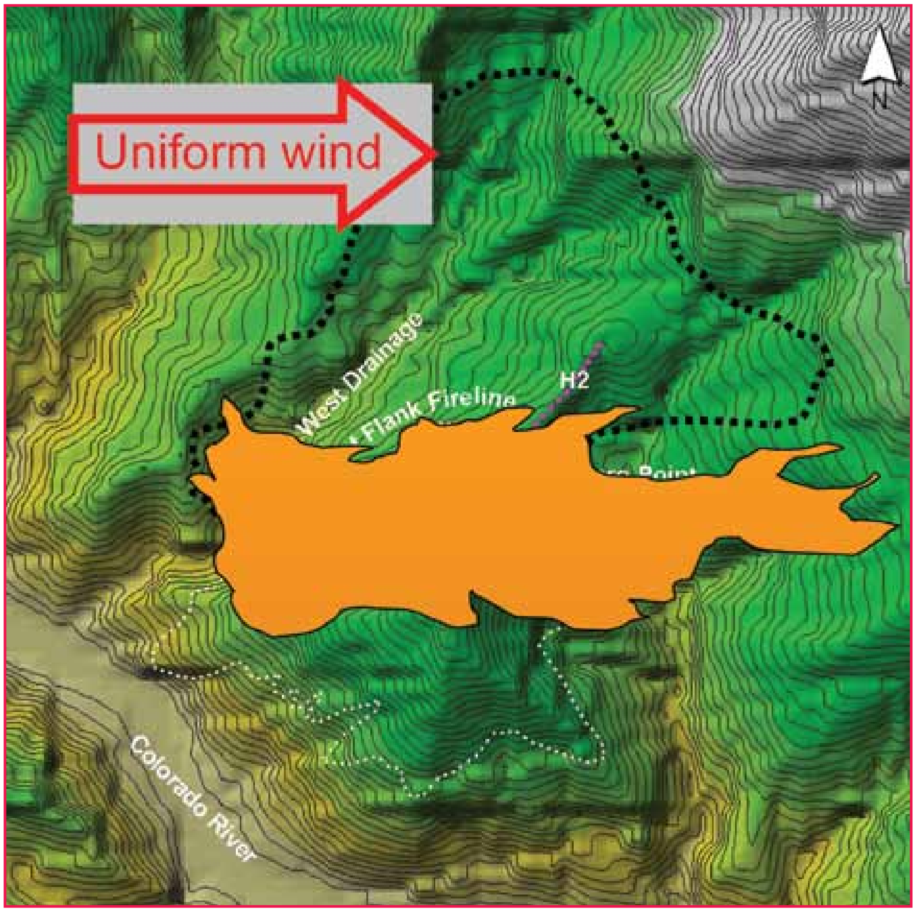

Figure 1—*Fire growth simulation based on uniform wind speed and direction. White and black dashed lines represent actual fire perimeters prior to and after the large fire spread event that occurred July 6, 1996. Pink dashed lines are firelines constructed by crew. The wind used for this simulation was steady from the west at 32 mph. The fire growth was simulated using FARSITE.*

in slope and vegetation on scales of 3 to 30 feet (1-10 m) can trigger the transition of a surface fire to a crown fire. Wind variations on a similar scale can cause sudden and dramatic changes in fire behavior; in other words, fine-scale variations in winds can significantly influence fire growth at larger scales. While regional pressure drives air flow, surface topography (i.e., individual terrain features) and the relative position, shape, and size of vegetation direct and channel that flow at the fine scale. While prognostic models use most or all of the elements mentioned above, they require detailed data at larger scales and across large spans of time to compute even short forecasts of winds at high resolution; thus, they cannot resolve the fine-scale wind variations near the ground surface.

Forthofer (2007) has shown that the use of winds generated by the WindNinja and WindWizard diagnostic models increased the accuracy of fire spread simulations for the South Canyon Fire (Butler and others 1998) over those based on uniform wind fields (figs. 1 and 2). The winds from the diagnostic models significantly improved the accuracy of growth projections for fires burning in complex terrain. Also, the fire spread simulations for both Mann Gulch and South Canyon were more sensitive to initial wind direction when run with uniform winds than when they were run with a diagnostic wind model. Forthofer interprets this to mean that local terrain features, such as the individual turns and twists of drainages, spur ridges, or rock outcroppings, tend to affect and control near-surface wind speed and direction, sometimes regardless of the upper-air wind direction.

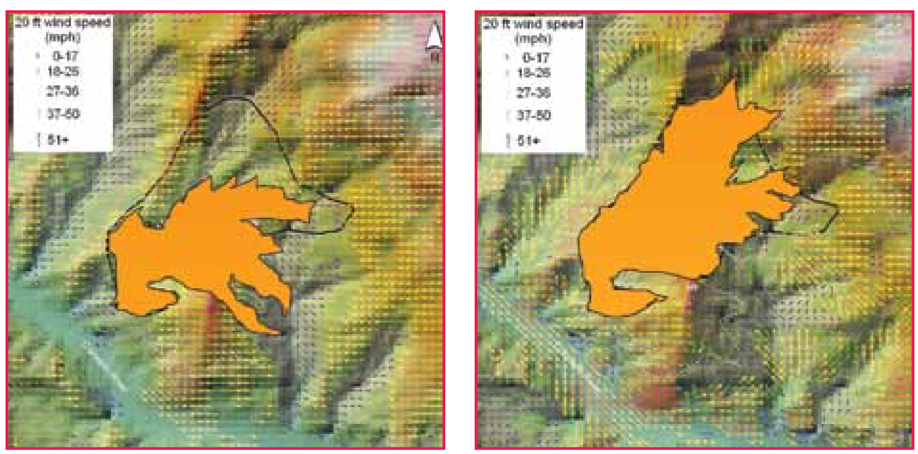

Figure 2—*Wind field and associated fire growth prediction for the South Canyon Fire on July 6, 1996, based on FARSITE simulations using winds produced by the WindNinja model (a) and by the WindWizard model (b). Winds used for the boundary condition were west at 49 mph (79 km/h) measured at the Rifle, CO, remote automatic weather station at the time of the fire and according to witness statements. The dashed white line represents the fire perimeter prior to the cold front passage, and the solid black line is the fire perimeter that existed after the cold front passage. Pink dashed lines are firelines constructed by crew. This perimeter was reconstructed from witness statements and other evidence. The orange solid area is the projected fire growth during the cold front event.*

Table 1—*Various wind modeling alternatives.*

Model name	Type[1]	Pressure variations	Surface heating	Atmospheric Stability	Surface Friction	Topo-graphy	Typical time to compute solution[2]	Minimum cell dimension	Comments/Web site
MM5	P	X	X	X	X	X	3-4 hours	4 km	Comprehensive atmospherics physics, Technical expertise required. <http://www.mmm.ucar.edu/mm5/>
WRF	P	X	X	X	X	X	3-4 hours	100 m	Comprehensive atmospherics physics, Technical expertise required. <http://www.wrf-model.org/index.php>
CALMET	D		X	X	X	X	2-4 hours	100 m	Technical expertise required. <http://www.src.com/index.htm>
CANYON	D				X	X	1 hour	<50m	Shows promise as CFD type model, but not readily available or documented. Output file type unclear. <http://www.adai.dem.uc.pt>
WindWizard	D				X	X	1.5 hr	<50 m	Documented physics based solution, cost associated with license. Outputs files in multiple formats compatible with typical North American fire modeling systems. <http://www.firemodels.org>
WindNinja	D				X	X	5 min	<50 m	Simple to use, free, well documented. Simulations not as accurate as other models due to simplified physics. Outputs files in multiple formats compatible with typical North American fire modeling systems. <http://www.firemodels.org>

[1] *P designates prognostic model, D designates diagnostic model.*
[2] *Solution times for MM5, WRF, and CALMET are given for situations running a multiprocessor computer, typically 48 or more processors. Solution times for CANYON, WindWizard, and WindNinja are for a single-processor laptop or desktop computer.*

Accuracy in fire growth simulation improves when more detailed local wind fields are included. The utility of these winds to fire planning and management has been documented. For example, Butler and others (2006) and Stratton (2006) present several cases in which WindNinja and WindWizard can be used in prescribed fire planning, wildland fire accident investigations, fire management, firefighter and public safety, and emissions monitoring. But even the simplest of wind models requires experience: Weise and others (2007) have shown that the use of diagnostic models does not guarantee accurate fire growth simulations—an indication of the "art" required in wind modeling.

There is active debate in the scientific community about whether diagnostic model winds (such as from WindWizard or WindNinja) are accurate or even the best information available to fire behavior analysts. This discussion is entirely appropriate, as it is the key to motivating scientific research and likely will lead to improved tools and methods for determining wind information. However, for operational purposes, there is one fundamental question: do any of these models provide fire behavior analysts with better winds data than they currently get in a timeframe that helps them do their jobs? Compared to using single-point wind data to predict fire growth over the entire area of a fire, the cases described above show quite clearly that fine-scale predictions from diagnostic models yield improvements in fire growth modeling. WindWizard and WindNinja are currently the only models readily available in North America capable of providing high-resolution wind data in a timely fashion for operational purposes to fire analysts working on a laptop. Their utility is increased when supported by good prognostic models.

Future Research Directions

There are many areas of active research related to winds and fire, and a number deal directly with wind models. Work is underway to develop easier methods whereby the output from prognostic models can be used to initialize the flow calculations in diagnostic models. This approach could provide users with the benefits of the numerous variables handled by prognostic models along with the computational speed and fine-scale resolution of diagnostic models.

Ongoing work seeks an understanding of how wind moves through forest canopies and how variations in vegetative cover cause microscale changes in wind flow. Other research seeks to better understand how winds high above the ground might influence fire spread. Updrafts and downdrafts caused by fire, topography, or solar heating can carry winds from hundreds of feet above ground down to the surface; these winds could be very different in speed or direction from those at the surface and so produce otherwise unexpected fire behavior. Research is still needed to understand conditions under which upper atmospheric winds are most likely to drop near the surface, how far they might drop, and on what horizontal scale these processes occur.

New research prognostic models are in development and testing that include the capability to account for some surface drag due to vegetation and can simulate flows at scales of 30-300 feet (10-100 m). But these are currently only research models not generally available for real-time application. In the meantime, current research efforts both within land management agencies and the National Weather Service promise continued improvement in existing wind-modeling tools.

There is ample evidence that newly developed wind simulation tools can provide fire managers with valuable information. Both diagnostic and prognostic models have their particular strengths, weaknesses, and roles in supporting wildland fire management. Using them effectively requires identification of the processes affecting winds on a fire and the model(s) most appropriate for the situation so that the data and models available complement each other. Table 1 summarizes the various wind modeling alternatives.

The human component is never far from the technical component. Once necessary data are identified, accurate input is required from lookouts, spotters, and observers. After model execution, it is critical that winds from any computer model should be reviewed by an experienced, knowledgeable IMET. The output can then be passed to analysts and fire managers, who can use it to lay out effective strategies. This coordination of software and decisionmakers is ultimately what makes wind and fire modeling software valuable.

Acknowledgements

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Assessing Changes in Canopy Fuels and Potential Fire Behavior Following Ponderosa Pine Restoration

John Paul Roccaforte, Peter Z. Fulé, and W. Wallace Covington

In 1995, the Ecological Restoration Institute (ERI) at Northern Arizona University, the U.S. Department of the Interior Bureau of Land Management (BLM), and the Arizona Game & Fish Department (AZGFD) began a collaborative effort to implement landscape-scale restoration treatments in a ponderosa pine ecosystem at Mt. Trumbull, located in northwestern Arizona. The primary goal of the project was to restore forest structure and ecosystem processes within the historical ranges of variability (Moore and others 1999) with an adaptive management approach. Other project objectives included reducing fuel loads, disrupting fuel continuity, and reducing the likelihood of stand-replacing crown fires by implementing mechanical thinning followed by prescribed fire (Moore and others 2003, Roccaforte and others 2008). The project also aimed at providing research opportunities in a southwestern ponderosa pine ecosystem.

We initiated a study to examine canopy fuels and potential fire behavior during three time periods: 1870 (prefire-exclusion), 1996/97 (pre-treatment), and 2003 (post-treatment). Our goals were to:

- Compare three common canopy fuel estimation approaches;
- Compare the output from two fire behavior models; and
- Use the comparisons to assess the effectiveness of landscape-scale restoration treatments on reducing crown fire hazard.

John Paul Roccaforte is a research specialist, Peter Z. Fulé is the director of operations, and W. Wallace Covington is the director for the Ecological Restoration Institute at Northern Arizona University in Flagstaff, AZ.

> The reduction in canopy fuels is visually evident in the treated area, where surface fuels, once dominated by forest floor and coarse woody debris, now consist of an abundant herbaceous understory.

Using tree-ring analysis, we reconstructed a prefire-exclusion stand structure for the year 1870. In 1996 and 1997, we installed permanent monitoring plots and collected pre-treatment forest structure data for estimating canopy fuel load (CFL) and canopy bulk density (CBD) across the ~3,000 acre study area (fig. 1). Approximately half of the study area, a contiguous, densely-treed area, was left untreated and used as a control. By 2003, most of the other half had received restoration treatments—thinned and/or burned with prescribed surface fire (Roccaforte and others [in press]). We collected post-treatment data for each plot in the summer of 2003. Stand structure data were used to derive CFL and CBD in the study area for all three time periods. Those estimates were then fed into two fire models to compare historic fire behavior with potential fire behavior on the control site and the site that received restoration treatments.

Estimating Canopy Fuels

Canopy fuels are critical inputs for models that predict crown fire (Scott and Reinhardt 2002) but they are rarely measured directly. There are various methods for estimating CFL and CBD, and the resulting estimates can vary widely. Many methods rely on allometric equations that estimate the mass of foliage and fine twigs based on tree diameter. We examined three common techniques that are based on the following equations:

- Fulé and others' (2001) allometric equations for foliage and fine twigs of ponderosa pine developed in Arizona,
- Brown's (1978) allometric equations for foliage and fine twigs of ponderosa pine developed in the northern Rocky Mountains, and
- Cruz and others' (2003) stand-scale equations based on tree density and basal area.

Changes in Canopy Fuels

For all of the time-treatment combinations, Brown's (1978) equations always produced the highest value for average CFL, the Fulé and oth-

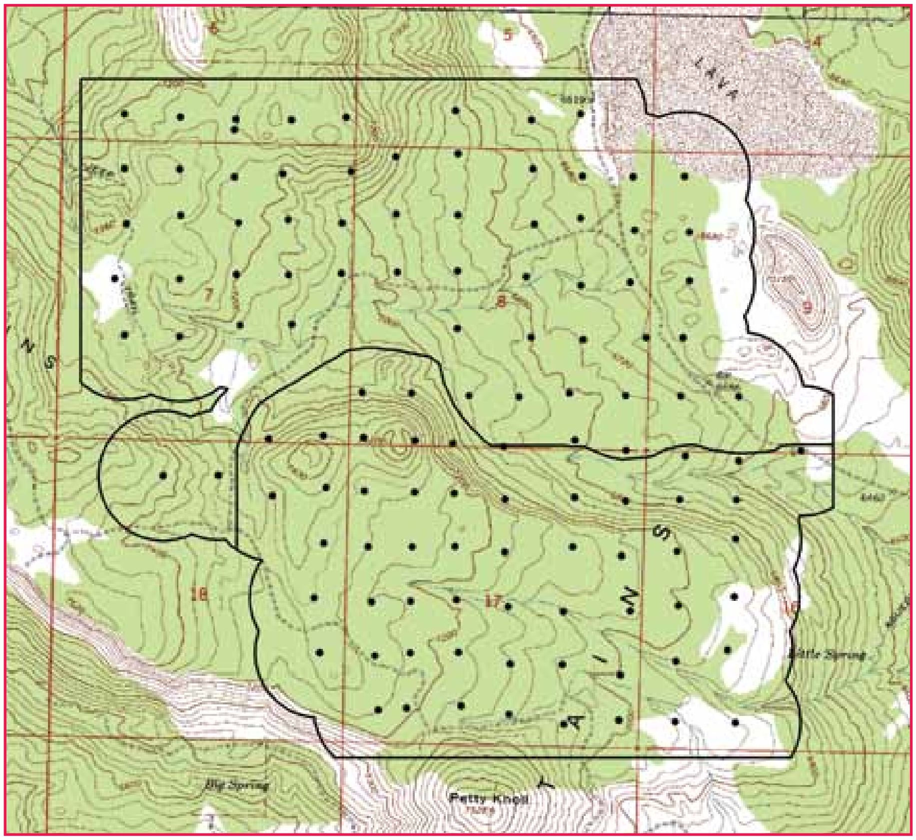

Figure 1—*A map of the study site (~3,000 acres) showing permanent plot locations (black dots). The treated area is in the northern part of the study area; the control is in the southern part.*

ers (2001) estimate was always lowest, and the Cruz and others (2003) estimate always produced intermediate values (fig. 2a). For CBD, Fulé's equation again produced the lowest estimate, but Cruz's estimate was highest and Brown's estimate was intermediate in all but the treated area in 1870 (fig. 2b).

Regardless of which equation was used, CFL and CBD values were relatively low over the entire study area in 1870, with dramatic increases across the entire landscape by 1996/97. By 2003, treatment lowered CFL and CBD by about 40-60 percent compared with slight increases in the control (fig. 2). The reduction in canopy fuels is visually evident in the treated area, where surface fuels, once dominated by forest floor and coarse woody debris, now consist of an abundant herbaceous understory (fig. 3).

Modeling Potential Fire Behavior

We used two common fire behavior models to predict potential fire behavior and evaluate treatment effectiveness:

- FlamMap, a spatially explicit model that assesses fuel hazards by simultaneously predicting fire behavior for each individual pixel on the raster landscape (Stratton 2004), and
- NEXUS, another hazard model, which uses plot- or stand-scale data to predict potential fire behavior (Scott 1999; Scott and Reinhardt 2001).

These fire behavior models are designed for assessing fuel hazards rather than fire growth; we selected them because both are ideal for evaluating treatment effects on fire behavior. We ran both models under scenarios of extremely dry conditions and a range of windspeeds to simulate the severe weather under which uncontrollable crown fires most commonly spread.

Changes in Potential Fire Behavior

Initial modeling results for the three CBD levels showed that crown fire activity was correlated with CBD for both FlamMap and NEXUS. However, the FlamMap simulations were sensitive to CBD, showing little active crown fire for any of the time-treatment combinations when the low and intermediate CBD values were used. Therefore, we restricted our analysis to results from the two fire behavior models using the highest CBD values (i.e., from Cruz and others 2003).

FlamMap predicted that active crown fire would not occur within the study area in 1870 even with 43 mph (70 km/h) windspeeds. By 1996/97, nearly 90 percent of the landscape was classified as either passive or active with 43 mph (70 km/h) windspeeds. After treatment, the percent of the landscape in the treated area susceptible to active crown fire was reduced from 46 percent to less than 5 percent compared to the control, which showed little change.

NEXUS predicted that some active crown fire would occur within the study area in 1870 with windspeeds greater than 31 mph (50 km/h), with up to 17 percent of the landscape supporting active crown fire when modeled with 43 mph (70 km/h) windspeeds. NEXUS predicted that 80 percent of the pretreatment landscape would support active crown fire with 43 mph (70

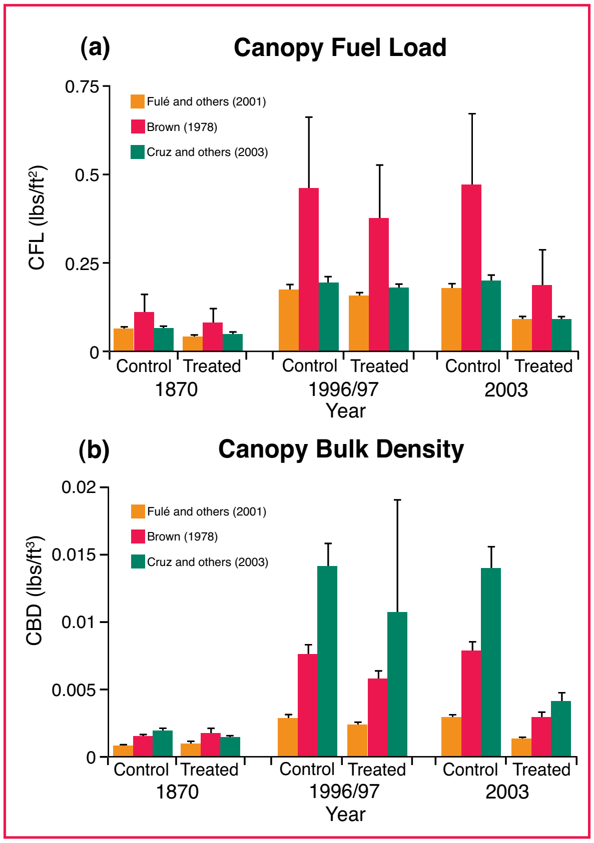

Figure 2—*Although canopy fuel load (a) and canopy bulk density (b) estimates were variable, all methods showed low values in 1870, marked increases by 1996/97, and substantial reduction in the treated area by 2003.*

km/h) windspeeds. By 2003, NEXUS predicted that active crown fire was reduced from 82 percent to 48 percent in the treated area with 43 mph (70 km/h) windspeeds with no change in the control over the same time period. NEXUS also predicted a substantial increase in crowning index (the windspeed required to sustain active crown fire) in the treated area (fig. 4).

Model Comparisons

The purpose of modeling fire behavior at Mt. Trumbull was to use the output as a way of comparing potential fire behavior between three time periods and between the control and treated areas following restoration treatments.

One should always interpret model output with caution, and these model runs were not expected to accurately predict the behavior of an actual fire. Using the output from two different fire models is a way of validating each of their treatment comparisons.

There are two key differences between FlamMap and NEXUS. First, in FlamMap, the model inputs are interpolated or calculated across the plot grid to produce output across the landscape, whereas in NEXUS, inputs are calculated for each plot and outputs are interpolated across the landscape. Thus, even though the fundamental fire behavior predictions are nearly the same in the two models, the different approaches to modeling fire across the landscape lead to somewhat different results. Second, only NEXUS accounts for the occurrence of conditional crown fire, the situation where passive crown fire is not predicted to occur due to a high canopy base height even though active crown fire could occur due to high CBD (Scott and Reinhardt 2001).

Although FlamMap and NEXUS differ, predicted outcomes were consistent: under extreme drought and wind conditions, the proportion of the landscape susceptible to active crown fire decreased in the treated area. In contrast, the models show little change in crown fire hazard in the control over the same time period.

Figure 3—*This before and after photo series illustrates the reduction in canopy fuels and consequent increase in herbaceous surface fuels. The upper photo was taken in 1996 prior to treatment; the lower photo was taken in 2003 after the area was thinned and burned. Arrows indicate the same trees for reference. Photos: John Paul Roccaforte, Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 1996, 2003.*

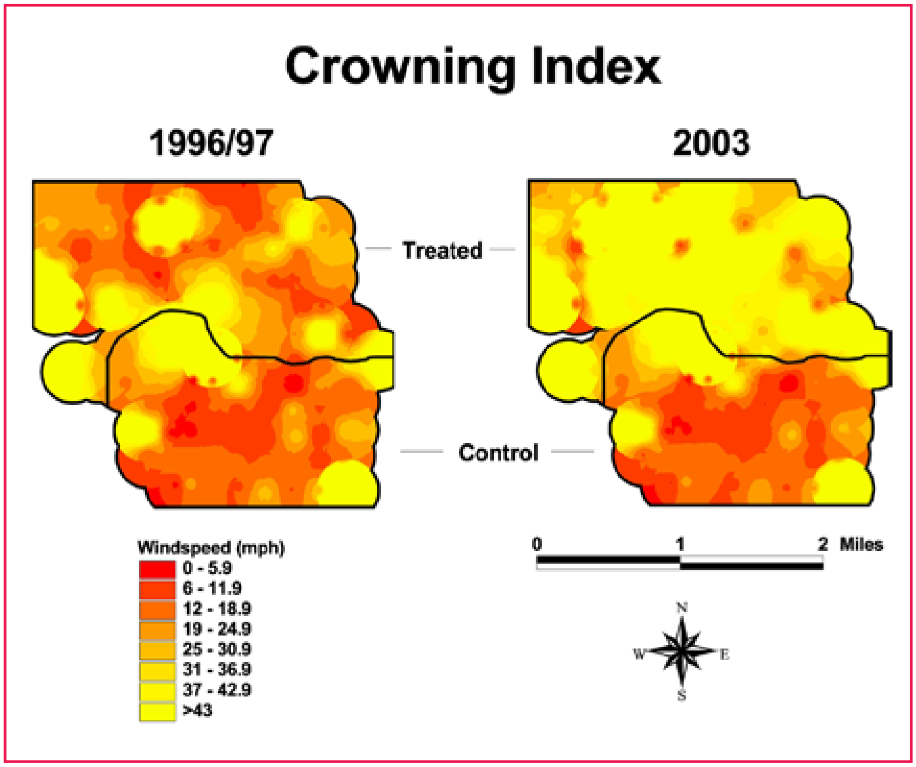

Figure 4—*Fire behavior modeling output from NEXUS shows that higher windspeeds are necessary to sustain active crown fire in the treated area in 2003; hence, active crown fire hazard was reduced following treatment. Alternatively, little change in potential fire behavior occurred in the control over the same time period. [Figure 4 in this electronic version varies from the printed publication to correctly portray the windspeeds required.]*

Management Implications

This study provided a quantitative evaluation of the effectiveness of landscape-scale restoration treatments on canopy fuels and crown fire hazard for the Mt. Trumbull landscape. Although canopy fuel estimates and fire behavior predictions varied depending on which models were used, all modeling scenarios resulted in substantially lowered canopy fuels and crown fire hazard in the treated area. This suggests that restoration treatments were an effective management strategy.

It should be noted that treatments have also resulted in the loss of some old trees from prescribed fire activities (Fulé and others 2002) and the spread of cheatgrass (Bromus tectorum), an invasive species (McGlone and others 2009). The ERI, BLM, and AZGFD will continue to address these and other challenges in the future.

The Mt. Trumbull ecosystem will never be "fireproofed." Maintenance of the surface fire regime will be vital to retaining open forest conditions and relatively low crown fire hazard into the future. Although the Mt. Trumbull ponderosa pine ecosystem is not yet "restored," restoration treatments have been successful at substantially reducing crown fire hazard and creating more sustainable forest conditions.

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