JFSP Final Report Guidance
November, 2005

Each JFSP-funded PI must submit a final report by project termination date. Final report content will naturally differ by project. The following outline of essential information to be included in each final report is adapted from the 2006 AFP's:

- A brief synopsis of what you learned from your research, including how your work met the objectives stated in your proposal.
- A statement of how the deliverables that your collaborators and you specified in your original proposal compare to those that you will provide the JFSP Board.
- Copies of all deliverables in both written and electronic format (on CD).
- A schedule listing yet-to-be completed deliverables and their anticipated availability dates. Please send us these future products as they become available. Please submit hard copies plus electronic files on CD to the Program Office. Please remember to specify web sites/url's for your deliverables. We want to make sure that the public can easily access your science products.

We suggest you consider using the following or similar format to summarize your deliverables (thanks to Roger Ottmar for designing this template):

Proposed	**Delivered**
EXAMPLE: 1 printer-ready manuscript and CD with a maximum of 10 fuelbeds with a maximum of 20 sites each.	One printed photo series volume containing five fuelbed types with 26 sites. One photo series volume in draft form nearly ready for review and printing. Expected availability is late 2005. NWCG advised against development of a CD.
EXAMPLE: Web Page	A website link to the photo series project was established at www.fs.fed.us/pnw/fera/photoseries.html.
Other deliverables not proposed	

Several PI's have asked for examples of final reports. Dr. Carol Miller of the Aldo Leopold Institute and Dr. Bernard Bormann of the Corvallis Forest Sciences Lab have graciously allowed us to use their well-written final reports as examples.

Final report, Joint Fire Science Program AFP3-2003

Project Title: Ecosystem effects and propagation of the Biscuit fire across the large-scale plots of the long-term ecosystem productivity experiment

Project Location: Biscuit Fire, Siskiyou National Forest, southwestern Oregon

Principal Investigators: Bernard T. Bormann (PI), P.S. Homann, K. Cromack Jr., R. Darbyshire, R. Molina, and G. Grant

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This final report details findings to date and proposed and accomplished deliverables. Details on the study background, objectives, methods, and evidence to support these findings are presented on our recently updated web page (http://www.fsl.orst.edu/ltep/Biscuit/Biscuit05_files/frame.htm), which can be considered a contribution to the final report.

SUMMARY OF FINDINGS TO DATE

Simplistic rules sometimes belie inherent ecosystem complexity.

- The Biscuit Fire has important lessons for us, about the effects of wildfire on forest ecosystems. Our study—above all else—demonstrates that interactions of wildfire with ecosystem processes and conditions can create very complex patterns of response. Complex responses from previous fires likely created much of the high small-scale spatial variability described we previously described for these sites (Homann et al. 2001). We also have documented important temporal complexities. For example, many legacies from the last fire, about 110 years ago, persisted until fire returned. Legacies include hardwood mid-canopy trees (tanoak, madrone, and others), over-mature knobcone pines (with serotinous cones), and apparent seed banks in the soil. We expect that Biscuit legacies, by extrapolation, will likely last to the next fire. Spatial and temporal complexities are extended by other uncertainties and surprises about ecosystem processes (such as possible plume-driven soil loss and a damping effect on fire by mid-canopy hardwoods, discussed later).
- These general conclusions are supported by results from our study. We found that the degree that ecosystems were affected by the fire was determined in part by pre-fire management, and that these various outcomes hold different consequences for future ecosystem development, including future fire risks. Some widely held views on the magnitudes and even directions of management effects were not well supported. The most extreme effects of fire on soils that we observed at stand scales should be long-lasting, suggesting that special interest should be paid to pioneering plants that can help rebuild nutrient pools. Soil development itself was substantially affected in many places. New insights into soils, forest productivity, and diversity in forests with frequent fire-return intervals are likely with continued investigation.

Having unburned controls changes interpretations.

- Trends before and after fire in vegetation, woody debris, tree mortality, and even soils can be easily misinterpreted without understanding background changes in unburned stands. In some cases what appears to be distinct fire effects turn out to be lacking or overshadowed by background changes already underway.

Past management changed how the fire burned.

- Past management, created as experimental manipulations in the LTEP study—of 110-yr-old, fire-origin, Douglas-fir-dominated stands—appears to have changed how the fire burned. The thinned and underburned stand had the least mortality (36%); the two burned control stands had intermediate mortality (63 and 77%); thinned, low woody debris stands had moderately high mortality (91 and 94%); while thinned high woody debris and 6-yr-old pioneer and Douglas-fir stands had 100% mortality. The relatively low mortality in the controls was most unexpected, and not predicted by the fire models (Raymond 2004, Raymond and Peterson 2005). The relative similarity among pairs in replicated treatments (controls and thinned, low woody debris) gives us limited confidence in these conclusions. We must also consider, however, that fire behavior is influenced by more than fuels. Even though most stands burned on the same day, how they started, what was adjacent to them, and other factors may have come into play. Potential explanations for observed patterns of mortality—including a possible role for mid-story hardwoods removed in the thinning of these stands—deserve future attention.

Tree mortality and fire temperatures are significantly related.

- Although not surprising, tree mortality averaged across individual treatments explains about 50% of the variation in average temperature as measured by the degree that aluminum tags melted along our grid system. Future work will examine relationships between caloric consumption, temperature, fuel distribution, hardwood distributions, slope, woody debris, and other variables

The effects of the fire on some soils were extreme.

- Our quantitative-pit soil sampling across 2-ha area grids, before and after the fire allows us to determine fire effects quantitatively at the stand scale. Some soils were greatly affected by the fire, and soil effects appear related to stand conditions before the fire as well as temperatures during the fire. Stands with less mortality appear to have less soil effects (for example, surficial rocks are positively related to mortality on an averaged stand basis).
- The most affected soils appear to have lost their entire organic horizon, all of the top mineral horizon (A), as well as over 10% of the upper B horizon. More than 5 kg/m^2 of soil (organic and fine mineral components) are now missing, changing particle size distributions (for example, many rocks at the surface), soil bulk densities, charcoal content, and many other factors.
- Nitrogen associated with these losses and changes in remaining soil add up to about 400 kg/ha. Combined with vegetative losses (not yet quantified) we expect that up to 18 years of typical N uptake in vegetation was lost. Losses of other elements know to volatilize at lower temperature (S, P, K) have yet to be quantified.
- Taken together, changes in soil organic matter, bulk density, particle size, and nutrient content are likely to impact forest productivity for some time to come. Tracking new growth against that observed before the fire, and that in unburned treatments will reveal direct measures of wildfire on productivity. Of particular interest will be to follow the nitrogen-fixing plants that may or may not come to dominate burned stands. The LTEP program is considering growth plots of uniform seedlings to evaluate fires of different intensities. Unlike background changes in vegetation, soils appear relatively unchanged in unburned stands. Thus, observed changes are easily attributable to the Biscuit Fire.

Rain-driven erosion was large but local.

- Erosion was large on burned soil relative to unburned soil, at least at small scales. Evidence indicating large short-distance transport included controlled erosion boxes and pins. Boxes showed a relation between slope and transport for burned soil as expected. Pins demonstrated fluctuating soil surface heights (relative to the top of rebar grid-point posts). We failed to see significant movement at the base of hotly burned units. Little soil accumulated in ditches along the road. Microtopography from old windthrow mounds, stumps, and decaying logs appeared to sharply limit long-distance transport.
- Needles that fell from fire-damaged conifers formed numerous needle dams in the first and second year after the fire, trapping large amounts of ash in stands that had large conifers left standing. Needles appeared to decompose by the 3rd year and ash may be moving again, so any nutrient or soil trapping effects may not differ from initially treeless areas over time.

Wind-driven erosion appears large.

- The mineral components of missing soil can be considered as eroded, unlike most of the organic components combusted in the fire. Mechanisms for this erosion include water transport (there's little evidence of long-distance transport), soil infilling, and aolian or wind transport during or after the fire. Many decaying stumps, roots, and logs combusted leaving deep holes in the ground. Short-distance transport would likely fill these holes. Our sampling did not indicate this process was important across the entire stands (but our sampling was not designed to test for this). The most probable mechanism we have surmised is fire-driven winds. Smoke is mostly made of particles including larger, but light burned organic matter as well as small mineral particles. As the upper soil burns, some soil particles disaggregate into smaller fractions. Winds at the soil surface in hot fires can reach over 100 mph, easily picking up such particles. The satellite photos of the plume extending more than 50 miles across and, on some days, nearly to Hawaii are suggestive of significant particle movement.

Added large woody debris did not significantly affect fire temperature.

- Observed temperatures were hotter on the high-wood treatment in only 1 of 3 pairs—and no significant differences were found. Woody debris, added in 1996 in some LTEP stands, contributed little additional combusted material in the fire. About 3 times more fine wood was consumed than larger-diameter wood. Older larger-diameter woody debris was more important than recently added woody debris. Decayed wood was more consumed (85%), compared to less-decayed wood (41%).

Past management changed how fire affected species composition

- Vegetative succession, already influenced by the LTEP treatments, changed again after the fire. Tree mortality ranged from 5 to 100% and tree species composition will change as knobcone pine and shrubby hardwoods initially dominate young stands.
- At first glance, the numbers of understory species found appear to radically increase after the fire (compared to pre-fire frequencies on burned plots), but because we have similar treatments that were not burned, we can evaluate elements of change caused by the fire. When background changes are taken into account, the fire had positive, negative, or little effect depending on the LTEP treatment. Small increases were seen in the burned compared to unburned control plots; large decreases were seen in the burned compared to unburned Douglas-fir plots; and no or minor changes were seen in the Late-successional, Pioneer, and Underburned plots.

DELIVERABLES

Proposed	*Accomplished/Status*
Annual progress reports	Annual progress reports completed
Series of 3 or more journal papers describing changes in our plots relating to initial conditions, pre-fire experimental manipulations, fire intensity and severity, and our interpretation of the implications of combined effects on long-term productivity and biodiversity (focus on changes in plants, soils, nutrients, and erosion).	Publications examining fire-effects have been produced in several formats: o Bormann, B.T., R. Darbyshire. 2005. Ecosystem effects of the Biscuit Fire. Conference proceedings, Mixed severity fire regimes: ecology and management symposium, Spokane, WA. ONLINE [http://www.emmps.wsu.edu/fire/secondary/ PROCEEDINGS.html] o Raymond, C.L. 2004. The effects of fuel treatments on fire severity in a mixed-evergreen forest of Southwestern Oregon. Master of Science thesis, University of Washington, Seattle, WA. o Raymond, C.L., D.L. Peterson. 2005. How did prefire treatments affect the biscuit fire? Fire Management Today 65: 18-22. Additional publications that provide context for post-fire evaluation and plant-soil productivity relations o Homann, P.S., S.M. Remillard, M.E. Harmon, and B.T. Bormann. 2004. Carbon storage in course and fine fractions of Pacific Northwest old-growth forests. Soil Science Society of America Journal 68: 2023-2030. o Homann, P.S., M.E. Harmon, S.M. Remillard, E.A.H. Smithwick. 2005. What the soil reveals: Maximum ecosystem C stores of the Pacific Northwest region, USA. Forest Ecology and Management. *In press*. Planned future journal articles comparing post- and pre-fire conditions: o Wildfire effects on soils and long-term productivity o Wildfire effects as influenced by pre-fire stand structures, downed woody debris, and species composition (including role of sclerophyllous-tree mid stories) o Utility of Lidar to characterize stand structures and species composition of burned and unburned forests o Evaluation of stand-scale soil sampling approach, looking at magnitude and causes of spatial and temporal variability.

Proposed	***Accomplished/Status***
Publish on the post-LTEP and post-fire changes in mycorrhizal morphotypes and fruiting fungi.	Work was completed under cooperative agreement with Dan Luoma at Oregon State University. We have been given some preliminary findings but are awaiting a final report.
Publish on changes in bird populations. This element was dropped when the budget was reduced.	Although funding was removed for this part, other funds were found to support work by C.J. Ralph. The work was completed and we are awaiting a report.
Pursue opportunities to link this study to other ongoing wildfire-effects research—mainly that funded by the Joint Fire Science Program and the PNW Station—and especially where we share similar data, such as in the fire-surrogate study, work by Dave W. Peterson, and Marilyn Walker (Institute of Northern Forestry, Fairbanks, AK). We will also seek to link with other work being considered in this competition that we are aware of, including re-measurement of inventory plots. We will also explore linkages with major assessment efforts the OSU College of Forestry is currently exploring. We can help to extend interpretations from broader, but shallower inventory or remote-sensing datasets because the fire effects in our study area cover a range of fire intensities and severities.	o Link to Seattle Fire Lab—we developed a close and mutually beneficial arrangement with the Seattle Fire Lab (D. Peterson and others). They provided a field crew to make many above-ground measure and have taken the lead on several publications. We expect this collaboration to continue. o Link to Rogue-Siskiyou National Forest—we continued and expanded our collaboration with the Forest, including volunteering to be the research liaison and team member for the Biscuit Fire EIS (Darbyshire) and to develop a 36,000-acre landscape management experiment (see below; Bormann and Darbyshire). o Link to NCSSF biodiversity program and OSU—we wrote and were awarded a small grant from the National Commission on Science and Sustainable Forestry to develop methods to evaluate lidar methods of predicting biodiversity indicators by using our LTEP ground data from the Biscuit Fire. This study is underway. o Link to the PNW Research Station Director's Office and the Silviculture and Forest Models team in Seattle, WA, who contributed funds to fly $80,000 of lidar over the LTEP plots and the landscape experimental area on the Biscuit Fire. We are collaborating with Steve Reutebuch and his UW collaborators in this ongoing project. o Link to JFSP project on Biscuit retrospective study (Spies et al.). We are actively collaborating with this group, and have been advising them, providing them with aerial photos, and helping to interpret their data. Several other proposed links did not materialize. For example, Marilyn Walker moved from the Fairbanks lab, and Dave W. Peterson did not have the time to work with us. These deficiencies were countered with other links described above.

Proposed	***Accomplished/Status***
Additional technology transfer: advising on an administrative study testing effectiveness of mulching that was implemented by the Forest; revising the LTEP program web page, participating in the Joint Fire Science workshops, writing a popular publication we envision, "Do fires really sterilize the soil?", perhaps submitted to Natural History or a similar outlet; and presenting initial findings at the planned Umpqua-Siskiyou-Rogue Forests workshop on disturbance ecology as an alternative to the Northwest Plan.	o Advised on a Siskiyou NF mulching study—finished advising and have preserved records after employee retired. o Revised the LTEP Biscuit web page—a revision was just completed to complement this final report [http://www.cfsl.orst.edu/ltep/biscuit05] o Attended Joint Fire Science workshop (March 18-19, 2003 in Corvallis, OR) o Wrote a popular article—for Fire Management Today, another is planned on fire effects on soil. o Presented at the disturbance ecology workshop—completed by presenting an invited paper at the Mixed Severity Fire Regime workshop in Spokane, WA [http://www.emmps.wsu.edu/fire/secondary/PROCEEDINGS.html] as well as a popular talk at the Marys Peak Natural Resources Interpretive Center [http://www.orww.org/MPIC/] Several additional products (not specifically proposed): o Designed a 36,000-acre landscape experiment comparing 3 different approaches to managing late-successional reserves after fire. This experiment was adopted in the Biscuit EIS and is being implemented. o Participated in an Oregon Public Broadcasting broadcast. The popular Oregon Field Guide invited us to be the focus of a show on the Biscuit Fire. The show highlighted aspects of our JFSP work. The producer remarked that it was one of their most highly rated shows, and they rebroadcast it a second time. We have various forms of the broadcast and can disseminate it for educational purposes. o Presented to a Congressional field tour (2003). "Biscuit Fire**:** how can managers and researchers work better together to learn at the landscape scale?" Invited presentation to congressional staffers sponsored by the Northwest Forestry Association. Siskiyou National Forest, Cave Junction, OR. o Presented to the R6 Regional office (2004) "Landscape experiments at Five Rivers and on the Biscuit Fire as a model for a new cooperative relationship between regional managers and the PNW Station." Invited presentation to the Regional Forester, Station Director, and staff. o Assisted entrants in the State Science Fair. Robyn Darbyshire worked with several area high school students on a project on effects of the fire on seedling survival and growth. They won the State Fair, and were funded to compete in the national science fair.

Proposed	*Accomplished/Status*
New items (not initially proposed) being pursued, partly attributable to JFSP funding	o Expanding work into cation losses and rock fragmentation using X-ray fluorescence (total elemental content) and X-ray diffraction (mineral composition) measures, with additional funding from the PNW Research Station (long-term studies program). o Expanding work into the role of mid-story hardwoods, and how they affected mortality of 110-yr-old Douglas-fir. We will perform a spatial analysis to assess the role of hardwoods. o Updating out LTEP sample archive (including samples collected under the grant) to maintain options for long-term tracking of soil recovery. o Replanting parts of the burned LTEP stands to evaluate effects on forest tree productivity. o Continuing more detailed work on micro-topographic erosion effects using the 1-m DEM from lidar, other field methods, and sequential photos. o Continuing the digital photo points (1400) across the LTEP treatments that date back to 1992. o Developing methods to better assess biomass before the fire on young stands, using unburned stands, and evaluate potential nutrient losses from burned vegetation. o Exploring burn severity and seedling establishment in whitebark pine communities

Can Wildland Fire Use Restore Natural Fire Regimes in Wilderness and Other Unroaded Lands?

Final Report to the Joint Fire Science Program

Project #01-1-1-05

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December 31, 2004

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Executive Summary

Can Wildland Fire Use Restore Natural Fire Regimes in Wilderness and Other Unroaded Lands?

Overview

The goal of this project was to help evaluate the feasibility and effectiveness of wildland fire use (WFU) as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. Five wilderness areas and national parks were used as study areas to develop our analysis approach, which we then used to evaluate the existing fire management plans at each of these study areas. The information produced resulted in "improved understanding of the options for restoring and managing fire in unroaded, wilderness, and similar areas" and provided a "tool for evaluating and understanding management and restoration goals in unroaded, wilderness, and other areas with restricted access" (Task 1 of RFP 2001-1).

Two rounds of site visits to each study area allowed fire management staff to provide input and feedback on the approach and analysis results in the form of expert knowledge. At the request of fire and resource management staff, additional analyses were conducted to improve their assessments of the risks and opportunities from WFU.

Estimates of the probability of burning were used to evaluate the impact of suppressing ignitions that occur outside designated WFU zones and otherwise would have immigrated into these zones for each study area. Areas were then identified where restoration objectives can be most easily met through the use of natural ignitions. Areas were also identified within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands.

Results

We developed and used a GIS model, BurnPro, to estimate the average annual probability of burning and to help assess the feasibility of WFU as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. We used this modeling approach to evaluate the existing fire management plans at each of 5 study areas. Our analyses generated new information that will be helpful for long-term fire and fuels management planning. Each landscape has unique spatial configurations of fuel, ignitions, and topography, and the approach used by BurnPro accounts for the spatial topology and context of each study area. Furthermore, we were able to address cross-boundary influences of fire management. We found that our approach to modeling the probability of burning with BurnPro is suitable for a range of climate regimes.

The project supported planning and management at a number of sites: Gila/Aldo Leopold Wilderness Area (Gila National Forest), Great Smoky Mountains National Park, Selway-Bitterroot Wilderness Area (includes Nez Perce, Clearwater, Lolo and Bitterroot National Forests), Sequoia-Kings Canyon National Parks, and Yosemite National Park. We evaluated WFU strategies as outlined in fire management plans and identified areas where restoration objectives can be most easily met through the use of natural ignitions. We also identified areas within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands. In addition, we provided information on risks and opportunities of WFU to improve risk assessments.

Our modeling approach was documented in a conference proceedings paper and we are currently working on peer-reviewed journal article. We presented the BurnPro model and resulting analyses at 5 scientific conferences, including one invited presentation. The exposure at national conferences generated considerable interest in BurnPro from the fire management community. For example, as a result of response to our poster presentation at the 2nd

International Wildland Fire Ecology and Fire Management Congress in Orlando, FL, November 2003, we experimentally released a development version of BurnPro for use on the Cloud Peak Wilderness in northeastern Wyoming. More recently, we were asked to develop lecture materials for a unit in Module VI of Technical Fire Management (administered by Washington Institute and Colorado State University). Over the next few months, we plan to present results to management staff at other workshops and training sessions, including the Rocky Mountain Area Fuels and Fire Use workshop and the Northern Rockies Training Center's Managing Wildland Fire for Resource Benefit course. The model is also being evaluated for use in planning hazardous fuels reductions on the Colorado Front Range.

The interest of the research community has also been piqued and we have several opportunities for improving, testing and applying BurnPro. Further development and testing on BurnPro is needed and would be facilitated if any of the following opportunities are funded. We are working with collaborators from the University of Georgia to submit a proposal to NASA in January 2005 that includes further application of BurnPro as a decision support planning tool for Great Smoky Mountains National Park. The USDA Forest Service Rocky Mountain Research Station's Boise Aquatics Lab has a pending JFSP proposal to develop a decision support tool that will likely utilize BurnPro. The Canadian Forest Service has also expressed interest in comparing BurnPro to their regional probability of burning model, BurnP3. Finally, we see promise in using BurnPro to help parameterize fire regimes in landscape vegetation simulation models.

Deliverables

The specific deliverables outlined here exceed our initial proposed list. Electronic and hardcopy versions of all reports and articles will be submitted to the Joint Fire Science Program office.

- Final reports to each study area
    - All maps, data and model output created for each pilot study area are being provided to the participating agencies along with a final report. Provided materials include a copy of BurnPro program code and associated documentation. Data provided include historical weather, historical ignitions, and coverages of fuels and expected rate-of-

spread. *The review of these study area final reports will be completed by February 11th, 2005.*

  - Final report contains a chapter that serves as a guidebook for replicating the results we obtained using the model BurnPro and/or for conducting additional analyses to explore alternative fire management strategies. *This guidebook represents an **addition** to the original proposed list of deliverables.*

- Publications

  - Miller, C., B. Davis. Modeling the probability of burning to help evaluate fire use strategies. In preparation. *Due to recasting of objectives (see Goals and Objectives, Chapter 1), the focus of this paper was changed from the proposed topic, which was to evaluate availability of natural ignitions for restoring fire regimes. To be submitted to peer-reviewed journal Spring 2005.*
  - Davis, B., C. Miller. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society of Photogrammetry and Remote Sensing (CDROM). *Originally intended for Fire Management Today.*

- Presentations

  - Poster presentation: 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL, November 2003.
  - Poster presentation: National Fire Plan Conference, Reno, NV, February 2004.
  - Oral presentation: Symposium on Science and Monitoring, Denver, CO, September 2004.

  *The following presentations represent **additions** to the original proposed list of deliverables*:

  - Invited oral presentation: American Society for Photogrammetry and Remote Sensing, Denver, CO, May 2004.
  - Invited oral presentation: Technical Fire Management, Bothell, WA, October 2004. *Lecture notes and slide presentation were provided in course materials.*
  - Poster presentation: Mixed Severity Fire Regime Conference, Spokane, WA, November 2004.

- Other communication and additional deliverables

  - Two rounds of site visits included presentations to fire and resource management staffs at each of 5 study areas.
  - Site visit and presentation to fire and resource management staff for potential study area (Grand Canyon National Park).
  - "Research in a Nutshell" – a two page synthesis of project findings

- Project website http://leopold.wilderness.net/research/fprojects/F002.htm

All presentations, the published conference proceedings paper, the Nutshell, and a draft of the BurnPro guidebook chapter are provided here in the Appendices. After reviews are completed February 11, 2005, an example of one of the final reports to the study areas will be forwarded to the JFSP office. Similarly, the final draft of the journal article will be forwarded upon submission.

Lessons Learned

Our original intent was to directly compare our probability of burning estimates to historical fire frequencies as a way to determine whether natural ignitions are sufficient for restoring natural fire regimes. We soon realized that it was impossible to make this comparison because our probability of burning estimates are based on a snapshot of current fuel conditions and cannot be compared to historical fire frequencies that occurred under very different (and quite unknowable) vegetation and fuel conditions. Instead we focused on answering "*where are restoration objectives most easily met through the use of natural ignitions, and where are challenges expected to be greatest?*" and worked to identify areas on each landscape that are most influenced by the suppression of fires on adjacent lands. We also originally intended to produce information that would be used to develop fire management plans (FMPs) and delineate WFU zones. However, the study areas available to us already had FMPs with delineated WFU zones. Therefore, we evaluated these FMPs rather than help to design them.

Our approach required substantial data about fire, fuels, and weather, and we selected study areas that met these requirements. From our perspective, there are obvious advantages to using familiar study areas where prior research has developed the required data. However, we note that there is also a tradeoff of lost opportunities to learn from new study areas when we continue to study the same iconic parks and wildernesses time and time again. For example, these areas we selected tend to be those with established FMPs and active WFU programs, and may not represent a full range of management challenges.

Although we selected well-studied sites with excellent data sets, we encountered problems with data availability. For example, we waited several months for new fuels data layers for both Yosemite and Great Smoky Mountains National Parks. If the project time line had been less than 3 years, we may not have been able to accommodate these delays.

Underlying this project is a principle that fires do not necessarily stop at administrative boundaries, and therefore, neither do the impacts of fire management activities. As such, we encourage efforts to look beyond a unit's boundaries when developing fire management plans. Sequoia-Kings Canyon National Park was the only study area for which we had data that extended far beyond a single administrative unit and this is due to the interagency planning efforts of the Southern Sierra Geographic Information Cooperative, previously funded by JFSP. We do recognize that we may have squandered several opportunities to foster interagency cooperation and collaborative planning during this project. In retrospect, we should have invited staff from neighboring management units to share in our discussions during our site visits.

Working in multiple study areas was an advantage because it allowed us to develop a more robust approach. For example, our approach to calculating the probability of burning from two sub-probabilities allowed us to handle sites with different precipitation regimes. However, we found that working in so many study areas posed several logistical challenges. In particular, we underestimated the difficulty we would have with scheduling site visits for so many study areas.

We did not anticipate doing so much model development as part of this project, but we needed to resolve some conceptual issues with BurnPro. These efforts were time-consuming, although we feel they were very worthwhile as they resulted in an improved tool and more meaningful analyses.

The interest in the model BurnPro that was generated during this project gave us additional insight for future applications and has encouraged us to continue developing the model. We did not anticipate this level of interest or the time required to respond to requests for information. The guidebook we developed should reduce reliance on our expertise in the future and allow management staff to conduct additional analyses on their own. A continued concern of ours is how to respond to requests for a tool that is still under development and testing and has not been formally released. We consider any delivery of the tool to date as experimental and have urged caution with using and interpreting the results.

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Chapter 1

Introduction

Purpose and Need

Wildland fire and fuels managers face unique challenges and opportunities on unroaded lands which include more than 105 million acres of federally designated wilderness. Reduced access to the interiors of these areas limit the ability to apply prescribed fire, thinning and other mechanical methods for fuels management. Further, manipulative methods for fuels management may be inappropriate for use in designated wilderness, and are limited by current legal and policy constraints. Current federal interagency fire policies facilitate the use of lightning-caused natural ignitions for wildland fire use (WFU). Unroaded areas and areas managed as wilderness provide unique opportunities for applying WFU as a fuels management strategy while satisfying legal and policy mandates to restore natural or historical fire regimes and ecosystem conditions. But can WFU successfully restore historical fire regimes?

In many wilderness areas, current fuel conditions may preclude the use of wildland fire because of excessive risks to natural resource values within the wilderness or to social values in the adjacent wildland urban interface (WUI). In some areas, especially small wilderness areas with extensive WUI areas, WFU may never be feasible. Even in larger unroaded areas, there will always be an argument to suppress some natural ignitions because of these risks. Ignitions outside of these areas that otherwise would immigrate into wilderness are usually suppressed, further limiting the amount of natural fire that can occur. Before investing limited time and resources in developing and implementing a fire management plan, wildland fire and fuels managers need information and tools to understand where they are most likely to meet management objectives and where to expect their greatest challenges.

This project helped evaluate the feasibility and effectiveness of WFU as a strategy for managing fuels and restoring historical fire regimes. The project directly addressed the research needs described in Task 1 of RFP 2001-1 to “evaluate the impacts of alternative management strategies” (specifically WFU) “on fire regimes in unroaded areas, wilderness areas, and other areas managed for similar purposes.” The information produced resulted in “improved understanding of the options for restoring and managing fire in unroaded, wilderness, and similar areas” and provided a “tool for evaluating and understanding management and restoration goals in unroaded, wilderness, and other areas with restricted access.”

Project Description

We developed and used an approach to help assess the feasibility of WFU as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. We used 5 wilderness areas and national parks as study areas to develop our analysis approach, which we used to evaluate the existing fire management plans at each of the study areas. We were particularly interested in evaluating the impact of suppressing ignitions from outside designated WFU zones that otherwise would have immigrated into these areas. Our evaluation identified areas where restoration objectives can be most easily met through the use of natural ignitions. We also identified areas within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands.

We conducted two rounds of site visits to each study area so that fire management staff could provide input and feedback on our approach and analysis results in the form of expert knowledge. At the request of fire and resource management staff, we provided additional analyses to improve their assessment of the risks and opportunities from WFU.

Goals and Objectives

The goal of this project was to develop an approach to assess the feasibility of wildland fire use (WFU) as a strategy for restoring the process of fire and managing fuels in wilderness and other unroaded lands. With this approach, we sought to directly support the development of new Fire Management Plans

(FMPs) and to help evaluate current FMPs as they apply to wilderness management objectives. There is a common assumption that fire restoration can be achieved in an area if natural ignitions are allowed to burn. But this assumption ignores the contribution of naturally ignited fires that would have immigrated into the area from outside. This study provides a better understanding of the ability of a FMP to achieve its goal of restoring natural fire regimes and provides new information for future FMP revisions.

Our original intent was to develop information about the risks and benefits that could result from naturally ignited fires, and then use this information for FMP development to delineate zones where WFU can be reasonably considered. In those areas where WFU can be considered, we then intended to assess whether there are enough natural ignitions to restore the historical fire frequency. As described below, we modified this original intent and subsequent analysis approach in two ways.

First, the study areas we selected already had approved FMPs with delineated WFU zones. Therefore, we did not develop information to *design* FMPs, but instead we developed information to *evaluate* the existing FMPs. Although we didn't use our analyses of risks and benefits to delineate WFU zones, we did develop these analyses to meet specific requests from managers. Therefore, we did not use the risk-benefit analyses to determine "Where can WFU be considered given the current conditions of fuels in the study area and the risks to ecological and social values both within and outside wilderness or park?" Instead, we used these analyses to improve the assessment of risks and benefits for prioritizing fuels treatments and prevention planning.

Second, when we first proposed this project, we intended to directly compare our probability of burning estimates to historical fire frequencies as a way to determine whether natural ignitions are sufficient for restoring natural fire regimes. However, we subsequently realized that such a direct comparison would not be valid or meaningful. Our probability of burning estimates are based on a snapshot of fuel conditions (in this case current fuels) and are therefore not comparable to historical fire frequencies that occurred under very different (and quite unknowable) vegetation and fuel conditions. We considered developing probability of burning estimates for different historical fuel "scenarios" as a way to work around this fundamental limitation, but discussions with fire management staff convinced us instead to identify areas on the landscape that are most influenced by the elimination of imported fires. Therefore, instead of answering the question "*are there enough natural ignitions to restore the historical fire frequency?*" we focused on answering "*where are restoration objectives most easily met through the use of natural ignitions, and where are challenges expected to be greatest?*"

As such, our primary research objective was to determine how well we can expect current or proposed WFU strategies to achieve the restoration of natural fire regimes. We hoped to answer the following questions:

- How does suppression of lightning-caused ignitions that occur *outside* WFU zones affect our ability to achieve the restoration of fire *inside* the WFU zones? In other words, what is the effect of eliminating the importation of fires that start on adjacent lands?
- Where eliminating the importation of fires appears to pose the greatest challenges for achieving restoration objectives, what are some management alternatives?

A secondary objective was to evaluate the risks and opportunities from WFU fires. We assessed the risk and opportunity that lightning ignitions from the WFU zone might pose to different values of interest in the study area. We evaluated risks to areas such as the WUI or and ecologically sensitive areas, and we evaluated expected benefits to areas that are inhabited by fire-dependent species. This information can help with prevention planning, prioritizing fuel treatments, and anticipating where to expect the greatest conflicts with other management objectives when implementing a WFU program.

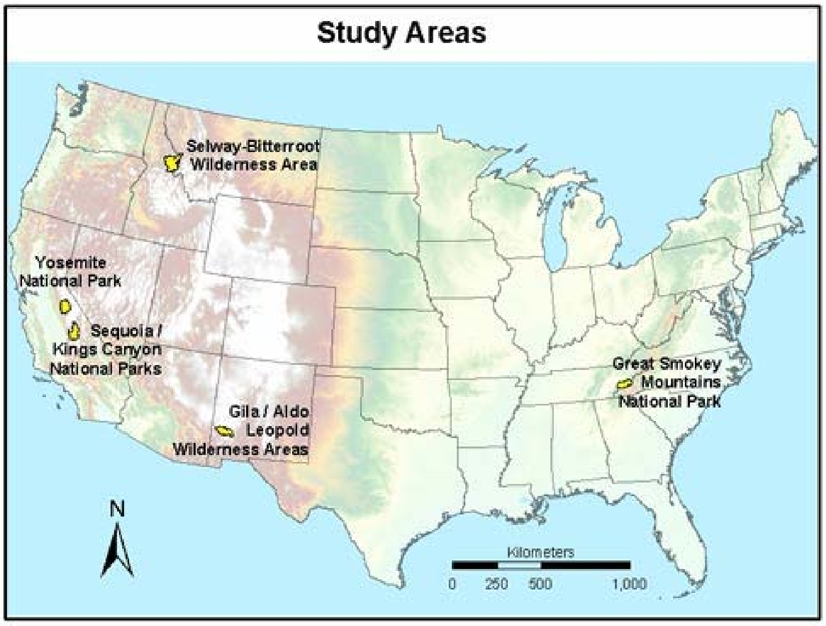
Chapter 2 Study Areas

Site Selection

Study sites were selected for the availability of fire history and fuels information, local expertise, and for prior collaborative relationships that we had with managers and other cooperating researchers. In addition, we sought to include study areas that had management challenges that we could help address through meeting our project objectives. Most of the study areas we selected had experienced a relatively large number of fires in the 20th century and therefore provided important data for validating the modeling component of this project. The most important factor that drove our study area selection was the availability of fuels and fire data. We settled on 5 high quality study areas that met our criteria (Figure 1): Gila/Aldo Leopold Wilderness, Great Smoky Mountains National Park, Selway-Bitterroot Wilderness, Sequoia-Kings Canyon National Parks, and Yosemite National Park. Selection of Great Smoky Mountains National Park was a direct response to the JFSP Governing Board's request to include a site in the eastern US. All five study areas had existing Fire Management Plans with designated WFU zones.

Other eastern sites we explored were Everglades National Park and Okeefenokee National Wildlife Refuge. However, after discussions with resource and fire management staff from these two units, we decided not to include these study areas in this project. We felt that our project objectives were not a good fit for the management challenges facing these units. In addition, the fire regime characteristics at both these sites are considerably different from our other mountainous forested study areas, and we were not confident that our modeling approach would adequately represent these sites.

Figure 1. Location of project study areas.

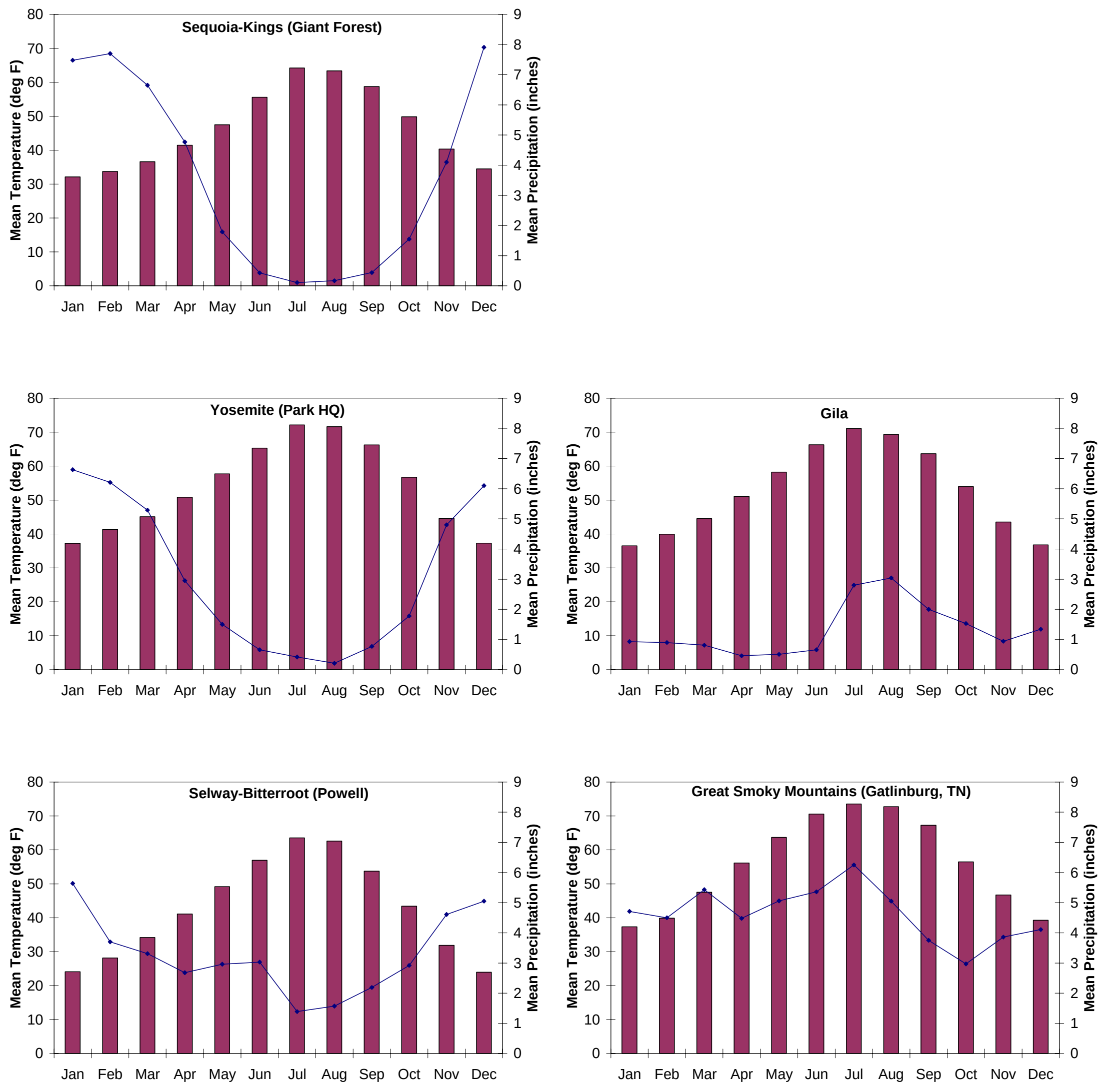


We originally proposed to include Glacier National Park as a study area because of expected collaboration with a proposed project with Dr. Michael Medler. However, because that project was not funded, those collaborative opportunities did not materialize. We considered Grand Canyon National Park as a sixth study area, but due to staffing changes at the park, we had difficulty coordinating with their staff and obtaining the required data in a timely manner. To avoid further delays with the project, we decided not to pursue this study area.

In addition to our five formal study areas, we had two "ad hoc" study areas where portions of our analysis approach were used and demonstrated. The first was the Bitterroot National Forest, adjacent to and part of the Selway-Bitterroot Wilderness and was done as part of JFSP project #99-1-3-16. The second was the Cloud Peak Wilderness in northeastern Wyoming, where, in response to a request from fire management staff, we experimentally released a development version of the BurnPro model and preliminary documentation of our procedures.

Distribution of precipitation is a key difference among our five study areas (Figure 2) and the study areas will be described for the following precipitation patterns: Summer-dry, Summer-monsoon, and Summer-moist.

Figure 2. Annual precipitation and temperature patterns for the five study areas.



Summer-Dry

Sequoia-Kings Canyon National Parks, Yosemite National Park and the Selway-Bitterroot Wilderness fall into the summer-dry category. These study areas have relatively cool moist winters and warm dry summers with most annual precipitation occurring outside the summer months. Therefore, during the growing season, plants are largely dependent on water that is stored in the form of snow or deep in the soil. As can be seen in Figure 2, the pattern in Sequoia-Kings Canyon and Yosemite is very dramatic with virtually no precipitation at all during

July and August. The Selway-Bitterroot has a similar, albeit less pronounced, pattern.

Sequoia-Kings Canyon National Parks are located on the western slope of the Sierra Nevada in central California. Combined acreage for these two parks is 349,500 ha (863,300 acres). Elevations range from (420 to 4410 m (1380 to 14,470 feet). Vegetation ranges from the foothill grassland and chaparral, through ponderosa pine, to the mixed conifer zone, to red fir and lodgepole pine and finally to high elevation pine near treeline. Generally, fire frequency increases toward drier environmental positions, and as fire frequency increases, fire severity tends to decrease (Caprio and Swetnam 1995). Lightning is most common on higher elevations, but can still be significant at lower elevations. In the past, lightning ignitions may have been supplemented by burning by native Americans and by sheepherders during the late 1800s. Fire suppression since the early 1900s has disrupted the fire regime allowing dead fuel to accumulate and understory tree density to increase. Currently, the fire and fuels management program at the Parks seeks to restore and maintain the natural fire regime in a manner consistent with firefighter and public safety. This program includes the use of prescribed fire, managing unplanned fires for the benefit of ecological values, and fire suppression. Because Sequoia-Kings Canyon has been actively involved with interagency fire management planning (Southern Sierra Geographic Information Cooperative; JFSP project # 99-1-3-04), we extended our analysis beyond Park boundaries and used the watershed boundaries that this planning effort has adopted. Our study area is the Kings and Kaweah watersheds, a very large landscape (782,700 ha; 1,932,600 acres) managed by multiple agencies including the US Forest Service, Bureau of Land Management, and state and local governments.

Yosemite National Park is approximately 100km north of Sequoia-Kings Canyon National Parks. It is 303,000 ha (750,000 acres) in size and ranges in elevation from 660-3950m (2100-13000 feet). Vegetation in Yosemite is similar to that in Sequoia-Kings Canyon, but Yosemite has less foothill and low elevation vegetation. Fire regimes and the history and management of fire in Yosemite is also similar to that of Sequoia-Kings Canyon NPs. Seventy-five percent of the park is managed to allow wildland fires to burn in a prescribed natural fire zone with another 8% in a conditional zone where fires have been allowed to burn under some conditions.

The Selway-Bitterroot Wilderness is located on the border of north-central Idaho and western Montana. We buffered the 0.5 million-hectare (1.2 million-acre) designated Wilderness to obtain a study area of 1.1 Mha (2.7 M acres). Elevations range from 430-3070 m (1410 to 10,060 feet). The climate ranges from inland-maritime in the northwestern part of the Wilderness to a continental rain shadow climate in the southern and eastern portions (Finklin 1983). The vegetation ranges from open stands of ponderosa pine at lower elevations, to mixed conifer forests at intermediate elevations, to whitebark pine, alpine larch, and Engelmann spruce at higher elevations (Habeck 1976). The area experiences a mixed severity fire regime: many fires are nonlethal surface fires but under suitable weather and fuel conditions, lethal surface fires and even stand replacing crown fires occur (Brown et al. 1994). The fire season typically runs from late June to mid-September; during this time, lightning-caused fires accompany frequent thunderstorms. Within the wilderness boundary, unplanned ignitions are often allowed to burn, although if a threat is perceived to the wildland-urban interface outside the wilderness, fires within the wilderness will be controlled (Law et al. 1997).

Summer Monsoon

The Gila-Aldo Leopold Wilderness in west-central New Mexico experiences a summer monsoonal precipitation pattern. Annual precipitation is low, and a rainy season typically begins at the end of July. We buffered the 226,000 ha (558,000 acre) Gila Wilderness and 81,800 ha (202,000 acre) Aldo Leopold designated Wildernesses to obtain a study area of 576,000 ha (1.4 M acres). The area ranges in elevation from 1380m to 3310m (4,510 to 10,860 feet) and features steep mountains, rough deep canyons, flat mesas, large river channels and flood plains. Vegetation ranges from desert scrub at the lowest elevations, through pinon-juniper woodlands and ponderosa pine and Douglas fir forests at middle elevations, to subalpine forests at the highest elevations. Fire management objectives are to return fire to its natural role in the wilderness ecosystem to the maximum extent possible, consistent with safety of persons, property, and other resources. The risks and consequences of wildland fire within wilderness, or escaping from wilderness are to be reduced to an acceptable level. The Gila National Forest, which manages these wilderness areas, experiences the highest fire occurrence nationwide. In the 10 year period from 1988 to 1998, approximately 67,923 ha (167,711 acres) have been managed with the use of fire.

Summer-moist

The Great Smoky Mountains National Park falls into the category of summer-moist. Annual precipitation is approximately 140 cm (55 inches), and is evenly distributed throughout the year. There is no dry season to speak of, although the warm temperatures of the summer months create more evapo-transpirative demand for plants. Stretching over 200,000 hectares (493,800 acres)of the Southern Appalachian Mountains, Great Smoky Mountains National Park is one of the largest protected areas in the eastern US. A primary goal of park management is to preserve the native plants and animals found in the park. In order to do so, it is necessary to preserve the natural processes that perpetuate them, including fire. To help counteract the negative impacts of fire exclusion the park has adopted a number of new fire-related policies. These include recognizing the role of naturally ignited wildfire in maintaining the health of Southern Appalachian ecosystems, establishing the management practices which include WFU, in which naturally ignited wildfires are allowed to burn in designated areas under prescribed conditions. Although the fire season is approximately 10 months long, natural ignitions tend to occur April through August.

In addition to being our only eastern US study area, it was our only site with extensive deciduous forest, which means that fire behavior fuel models must include “leaf-off” and “leaf-on” versions. Fuels data were originally developed by researchers at the University of Georgia for the leaf-off condition, which accurately represents fuels from approximately mid-October through mid-April. As such, it was necessary to adapt the leaf-off fuel models to approximate leaf-on conditions.

Chapter 3 Methods

To assess the feasibility of WFU as a strategy for restoring historical fire regimes, the frequency and location of ignitions, as well as their likelihood for spreading, must be evaluated. We used a GIS-based approach to estimate the probability of burning for every location on a landscape (Davis and Miller 2004, Miller 2003). For the WFU zones identified in Fire Management Plans, we estimated the probability of burning based on all natural ignitions in the study area. Ignitions falling outside of approved WFU zones were removed from the analysis and the probability of burning was recomputed. From these analyses we quantified the effect of eliminating the importation of fires that start on adjacent lands. We also combined the information on probability of burning with information on resource values to improve assessments of risks and benefits.

This section briefly describes the GIS model and the analyses we conducted to evaluate FMPs and to identify risks and opportunities for WFU. Detailed description of an earlier prototype of the GIS model is available in the literature (Miller 2003). A description of the version we used for this project is provided in Davis and Miller (2004) (see Proceedings Paper, Appendix A), in lecture notes (see Technical Fire Management, Appendix B) and is currently being prepared for a peer-reviewed journal article. Finally, detailed procedures for data development and running BurnPro are included as a guidebook in a chapter in the final reports to each study area (see Guidebook, Appendix A).

Probability of Burning

Information on where fire is most likely to occur within a landscape is valuable for assessing risk, prioritizing fuel treatments and prevention planning. Planning for WFU is also aided with an understanding of where the most frequent opportunities for WFU are within a landscape as this information can be used to develop fire management plans and to support the go/no-go decision.

Probability of burning is not the same as probability of ignition. Several regional assessments have derived and used probability of ignition, whereby the number of ignitions per unit area is computed for a particular time period (e.g., Northern Region Cohesive Strategy, http://www.fs.fed.us/r1/cohesive_strategy/datafr). Information about probability of ignition is very useful for assessing risk at a coarse scale, but it is not very useful finer scales such as the mid-scale and/or project level. Probability of burning depends on the probability of ignition, but it also depends on how fire spreads in a spatial context. The methods we developed for estimating probability of burning are intended to help with planning at the mid scale and/or project level.

Probability of burning as we define it here is also different from probabilities generated in RERAP. RERAP is a non-spatial analysis tool applicable to a single fire incident (FRAMES 2003). The probability of burning that we derive and use to evaluate fire management plans represents the cumulative probability of many events, averaged over many years. The intended planning horizon (several years to decades) is different from RERAP's single incident timeframe.

BurnPro

BurnPro is a GIS model that estimates the annual probability of burning for every pixel on a raster landscape (Davis and Miller 2004, Miller 2003) and considers ignitions, rate of fire spread, time available for fire spread, and topography, all in a spatial context. BurnPro uses topography, historic weather, current fuel model data and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might spread from any ignition point. It computes the probability of burning for each pixel as the product of two "sub-" probabilities: 1) the probability that fire reaches the location before the *end of the fire season* (*PEnd*) and 2) the probability that fire will reach the location before a *fire-stopping event* (*PStop*). As such, it integrates the timing and location of ignitions, rate of spread of fire (as it is affected by fuels, topography and weather), length of fire season as it varies over elevation, and frequency of fire-stopping events (i.e., rain) during the fire season.

What BurnPro does:

- Provides an estimate of *average annual probability* of burning for every cell on a raster landscape using data from many years and multiple events that would occur under a range of weather conditions.
- Generates *continuous* values (not categorical).
- Although BurnPro generates numerical values representing probability, these should be interpreted only as *relative* values.

Several GIS data layers are required to run BurnPro, and developing some of these requires the use of other analysis tools:

- Monthly ignition point coverages. These data are commonly available from http://famweb.nwcg.gov/weatherfirecd

- Rate-of-spread and direction-of-maximum-spread grids for selected percentile weather conditions. Rate-of-spread and direction-of-maximum-spread grids are generated from FlamMap (http://fire.org/nav.mas?pages=flammap&mode=1). Percentile weather conditions are determined using Spread Component Index generated from FireFamilyPlus (Bradshaw and McCormick 2000).

- Elevation (m) grid, e.g., from a digital elevation model (DEM).

- Average length-of-fire-season grid. This can be derived in a number of ways, including using Daymet variables like growing-degree-days (http://daymet.org), using drought-days computed by FACET (Urban et al. 2000), or simply by using expert judgment about how fire season varies across the landscape.

BurnPro also requires some information about rain and wind:

- Frequency of fire-stopping precipitation events, by month. The average monthly frequency of fire-stopping events can be determined using FireFamilyPlus (Bradshaw and McCormick 2000). These events might be defined as a certain amount of rain within a given time period (e.g., 0.5 inches of rain within a 5-day period).

- Frequency distribution of wind directions. Daily observations of wind directions can be analyzed using a simple spreadsheet program like Excel to determine the relative proportion of observations falling into 8 compass directions.

BurnPro is intended to support long-term processes such as fire management planning. It is not suitable for most incident management applications, but can be useful for the type of pre-planning that supports a go/no-go decision. For more details on BurnPro, please see materials in Appendix A, including the conference proceedings paper as well as lecture notes describing the approach.

Key Variables

Historical weather data. We used data from representative weather stations for each study area (Table 1). In an attempt to capture the weather of the study area as a whole, we sought data from multiple stations across a representative range of elevations. In the case of Yosemite, however, data from only one weather station (Crane Flat) were used, due to anomalies in the data from other potential weather stations. This one station, which falls near the average elevation for the park, was judged to be representative by the fire use specialist who uses data from this station for fire behavior modeling in Yosemite.

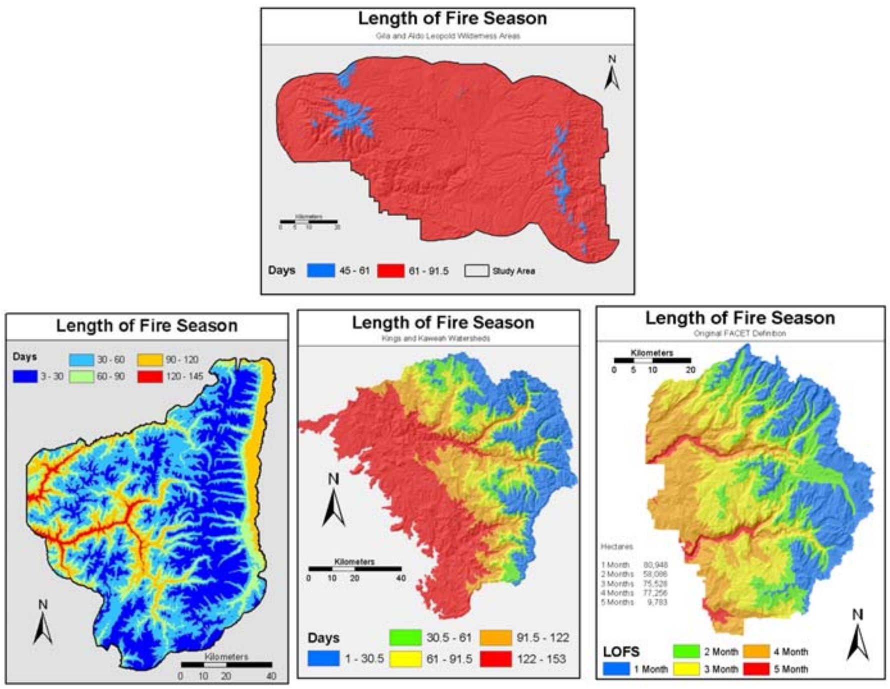
Table 1. Sources for historical weather data

Study Area	Weather Station	Elev (m)	# Years	Period of Record
Gila/Aldo Leopold	Bearwallow	3034	10	1994-2003
	Beaverhead	2043	29	1975-2003
	Gila Center	1738	29	1975-2003
Great Smoky Mountains NP	Cherokee	1037	12	1989, '91-'94, '96-'97, '99-2003
	Indian Grave	823	12	1989, '91-'94, '96-'97, '99-2003
Selway-Bitterroot	Hell's Half Acre	2474	29	1975-2003
	Moose Creek	750	29	1975-2003
	Powell	1039	29	1975-2003
	Westfork	1338	29	1975-2003
Sequoia-Kings Canyon NP	Ash Mountain	518	26	1977-2002
	Park Ridge	2299	26	1977-2002
	Pinehurst	1238	26	1977-2002
Yosemite NP	Crane Flat	1850	21	1979-1999

Length of fire season. Longer periods of time available for fire to spread should lead to higher probability of burning. This length of time—the length of fire season—varies across a landscape according to elevation, aspect, topographic position, etc. In this project, we accounted only for variation with elevation. Although we used a fairly complicated soil-water-balance model (Urban et al.

2000) and its estimates of “drought-days” for different elevations to approximate how length of fire season varies with elevation, there are many other possible ways to map fire season across the landscape. For example, estimates of growing-degree-days from Daymet (http://daymet.org) could be used as a proxy for length of fire season, or expert knowledge/opinion of the area could be used.

Figure 3. Length of fire season derived from drought-day estimates by a soil-water-balance model (Urban et al. 2000) for Gila/Aldo Leopold Wilderness (top center), Selway-Bitteroot Wilderness (bottom left), Sequoia-Kings Canyon NP (bottom center), and Yosemite NP (bottom right). Note: Length of fire season does not vary in Great Smoky Mountains NP for the months modeled (April-August) as they are a subset of the overall fire season (February-November).



Frequency of fire-stopping precipitation events. Less frequent heavy rain events should lead to higher probability of burning. We used the FireFamilyPlus event locator and historic weather data to determine number of times the area experiences a fire-stopping rain event (Table 2). In all but one of our study areas, we defined a fire-stopping event as an occurrence of more than 0.5 inches of rain within a 5-day period. In Great Smoky Mountains National Park, we defined a fire-stopping event as 1.5 inches of rain within a 5-day period.

Table 2. Number of fire-stopping rain events							
Study Area	Apr	May	Jun	Jul	Aug	Sep	Oct
Gila/Aldo Leopold	--	0.33	0.68	2.23	--	--	--
Great Smoky Mtns NP	1.72	1.49	1.90	1.48	0.98	--	--
Selway-Bitterroot	--	--	2.43	1.29	1.40	1.25	--
Sequoia-Kings Cyn NP	--	--	0.21	0.06	0.04	0.40	0.66
Yosemite NP	--	--	0.49	0.21	0.11	0.99	0.60

Ignitions. A higher frequency or density of ignitions should lead to higher probability of burning. Furthermore, ignitions that occur early in the season have a longer opportunity to burn. Therefore, all other factors being equal, the more ignitions occurring early in the season should lead to a higher probability of burning. Historic ignition data are available from http://famweb.nwcg.gov/weatherfirecd. These data contain geographic location (latitude/longitude), date, and cause (e.g., lightning- or human-caused). We separated these point datasets by month of occurrence and imported them into a GIS database. From these monthly point coverages, we calculated ignition densities using the POINTSTATS function in ArcInfo (ESRI 1998) and created up to 5 density grids to represent low to high density classes for each month of occurrence (Figure 4). For example, if there were 4 months in the fire season (e.g., June-September) and 5 density classes, the result was 20 ignition grids. Separating the data by density class allows BurnPro to weight results when calculating the average annual probability of burning (the last step in the BurnPro approach). Weights are assigned according to frequency of occurrence (i.e., density of ignitions). For example, probabilities generated using density class 5 are weighted 5 times more heavily than those generated using density class 1. We used 15 years or more of ignition data, and usually started with data from 1986 because spatial location accuracy before 1986 is generally very poor (Table 3).

Figure 4. Lightning ignitions and corresponding ignition density grid for the Gila/Aldo Leopold Wilderness.

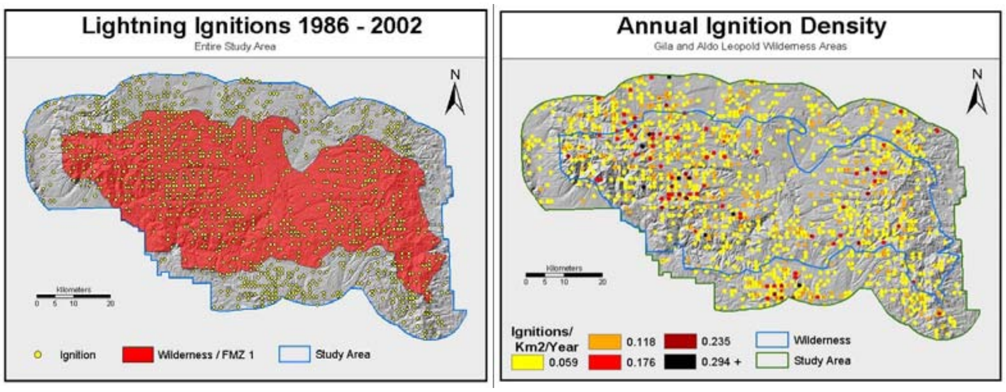


Table 3. Lightning ignition data				
Study Area	# Ignitions (entire study area)	# Ignitions (WFU zone only)	#Years	Period of Record
Gila/Aldo Leopold	1721	1044	17	1986-2002
Great Smoky Mtns NP	34	27	17	1986-2002
Selway-Bitterroot	2888	1221*	17	1986-2002
Sequoia-Kings Cyn NP	952	184	19	1981-2000
Yosemite NP	720	529	17	1986-2002

*Ignitions in the Selway-Bitterroot WFU zone include all from the Interior zone plus ignitions after July from the Early Season/Drought zone.

Rate- of-spread (ROS). Rapid fire spread should lead to higher probability of burning. We used FlamMap to calculate rate-of-spread (ROS). FlamMap provides a snapshot of expected fire behavior for every pixel on a raster landscape based on current fuels, slope, aspect, fuel moistures conditioned under specified weather conditions, and constant wind. Because FlamMap calculates ROS for static conditions, we made multiple runs to account for potential fire spread under a variety of weather conditions and wind direction. As such, we ran FlamMap multiple times to represent ROS under 8 different wind directions and 4 different percentile weather categories (Table 4). Percentile weather categories were determined using the Spread Component (SC) index (Bradshaw et al. 1983). For example, to account for 8 wind directions (N, NE, E, SE, S, SW, W, NW) and 4 weather categories (low: 0-79% SC, moderate: 80-89% SC, high: 90-97% SC, extreme: 98-100% SC), we ran FlamMap to create

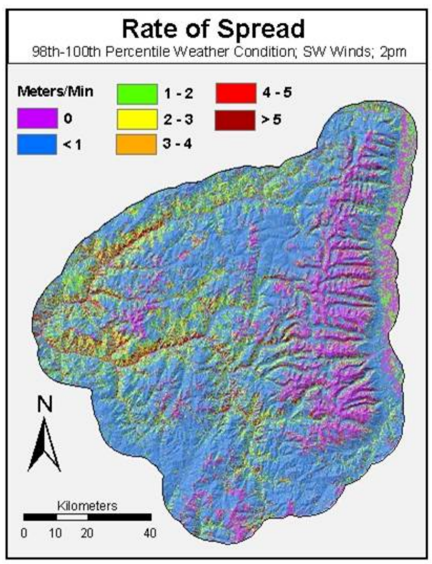
32 ROS grids (Figure 5). The frequency distribution of the 8 wind directions and the percentiles for the weather classes are used by BurnPro to weight the probability results accordingly when the annual average is computed (e.g., note that a 99th percentile weather condition occurs only 1% of the time).

Table 4. Definition of percentile weather categories

Study Area	Low	Moderate	High	Extreme
Gila/Aldo Leopold	0-79	80-89	90-97	98-100
Great Smoky Mtns NP	0-41	42-92	93-98	99-100
Selway-Bitterroot	0-79	80-89	90-97	98-100
Sequoia-Kings Cyn NP*	0-14	15-89	90-97	98-100
Yosemite NP	0-79	80-89	90-97	98-100

* Categories for Sequoia-Kings Canyon NP were defined by the SSGIC planning effort.

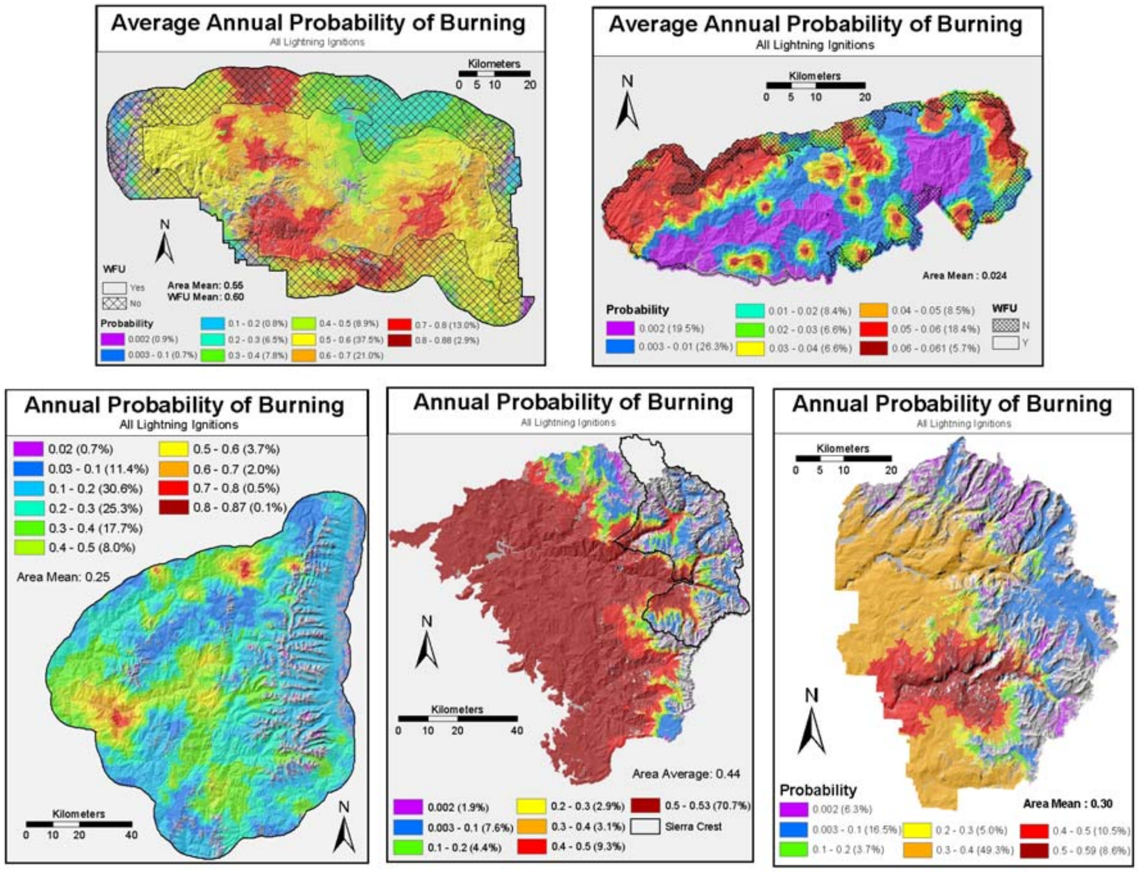
Figure 5. One of 32 rate-of-spread grids for the Selway-Bitterroot Wilderness representing rate-of-spread under the extreme weather category and southwest winds.



Cumulative spread time (CST). The longer it takes fire to reach a location, the lower the probability of burning should be. To compute the number of days for fire to spread from ignition locations to all other points on the landscape, BurnPro uses the ArcInfo function Pathdistance (ESRI 1998). Pathdistance is a least-accumulative cost spreading algorithm that computes the *cheapest* path and *total cost* of traveling to each cell in a grid. Instead of *cost*, we are interested in *time*. BurnPro uses Pathdistance to find the path of least resistance across the landscape and to compute the total time it takes to travel that path. Pathdistance requires a Source grid and a Cost grid. In BurnPro, the Source grid is one of the ignition density grids and the Cost grid is Time, which is derived from any one of the ROS grids with simple arithmetic. For any pixel on the raster landscape, there are almost an infinite number of paths that fire could take to get there but there is only one *quickest* path--the path that results in the lowest cumulative spread time (CST). BurnPro uses the algorithm in ArcInfo's Pathdistance function to generate CST grids for each unique combination of ignition (source) grid x Time (cost) grid. If there were 20 ignition grids (4 months x 5 density classes) and 32 Time grids (derived from 32 ROS grids), 640 CST grids were generated (20 ignition grids x 32 Time grids).

BurnPro computes the probability of burning for each pixel as the product of two "sub-" probabilities: 1) the probability that fire reaches the location before the *end of the fire season* (*PEnd*) and 2) the probability that fire will reach the location before a *fire-stopping event* (*PStop*). Both *PEnd* and *PStop* depend on knowing how long it would take fire to spread to a location, and therefore both are computed using CST. To compute *PEnd*, CST is compared to the length of fire season. Currently, the Weibull function is used for this: *PEnd* = $\exp[-(\text{CST}/\text{season length})^{\eta}]$ where η is a parameter derived from the distribution of season lengths and reflects the interannual variation in season length. To compute *PStop*, CST is essentially compared to the average length of time between fire-stopping rain events. Each of the CST grids is used to compute these two sub-probabilities, which are then multiplied together to derive the annualized probability of burning (Figure 6). The annual distribution of precipitation for the study area determines whether *PEnd* or *PStop* dominates the computation for average annual probability of burning. In Summer-wet and summer-monsoon areas, *PStop* tends to dominate the computation for probability of burning. In summer-dry, *PEnd* is dominant.

Figure 6. Average annual probability of burning for Gila/Aldo Leopold Wilderness (top left), Great Smoky Mountains National Park (top right), Selway-Bitterroot Wilderness (bottom left), Sequoia-Kings Canyon National Park (bottom center), and Yosemite National Park (bottom right).



Key Assumptions

All models are built with underlying assumptions and the appropriate interpretation of model output requires an understanding of these assumptions. The most critical assumptions in BurnPro are mentioned here.

- The values in BurnPro's output grids represent average annual probability of burning. The probability of any event can range from 0 (certain it won't occur) to 1 (certain it will occur). For display purposes, the numbers output by BurnPro are converted to percentages and can range from 0.2 to 100%. Although BurnPro generates numerical values representing probability, these should be interpreted only as *relative* values. They do not represent absolute probabilities. It is appropriate to interpret a value of

0.50 as being 5 times greater than a value of 0.10, but a value of 0.50 should *not* be interpreted as indicating a 50 percent chance of burning.

- Estimates from BurnPro are based on long-term ignition and weather patterns and therefore should be used for *long-term planning* efforts rather than being interpreted for short-term purposes.

- The ROS spread grids that BurnPro uses to derive Cumulative Spread Time, and thus *PEnd* and *PStop*, are generated using maps of *current fuels*. The output from BurnPro does not take into account changes in fuels over time due to vegetation succession or disturbances. Because the probabilities represent the probability of burning given current fuels, these estimates are meaningful only so long as the underlying fuel data are valid.

- Rate-of-spread (ROS) calculations are based on twice-daily averages of ROS at 4am and 2pm. The impacts of weather variability at shorter time scales (e.g. a 2-hour wind event) are therefore not represented by BurnPro.

- Calculations by ArcInfo's Pathdistance algorithm are very dependent on how the ignition sources in the Source grid are distributed in space. If ignitions are close together in space, the least accumulative cost-distance paths derived by Pathdistance will tend to be quite short, CST values will tend to be low, and probability of burning will be high. Conversely, if ignitions are spread out widely in space, the paths will be long, CST values will be high and probability of burning will be low. Therefore, the length of the record used for historical ignitions will likely have an influence on BurnPro output, with longer records providing more ignition sources for the Pathdistance algorithm. Running BurnPro using randomly located ignitions instead of historical locations is a useful exercise for better understanding this influence.

- Ignitions are handled on a monthly basis and calculations of probability are based on the assumption that ignitions occur mid-month.

- Probability estimates near the edge of the study area are less reliable than those in the interior. This effect occurs because estimates near the edge can't account for the influence of ignitions outside the study area.

- The length of fire season used represents an average year. In extreme years, ignitions could occur in areas that aren't "in-season" in a normal year. BurnPro ignores ignitions that fall outside the season in a normal year.

- Historic weather data from one or a few weather stations are extrapolated to a large area.

- BurnPro's estimates are only as good as the quality of the input data. The better (more accurate, longer periods of record etc.) the input data the better the estimates of probability of burning.

Expert Knowledge

We conducted two rounds of site visits to our study areas. In the first round of site visits, we relied on fire management staff to identify data sets and parameters to use as input to the model BurnPro. We also learned where the most important values at risk are, and where lightning ignitions are, or are not, likely to be considered for WFU.

During the second round of site visits, we presented our analyses, obtained feedback, and took requests for additional analyses from management staff. In some cases, these additional analyses included revising the WFU zones to represent potential FMP revisions. In other cases, staff requested revisions to the WFU zones to more accurately reflect 'on the ground' realities that are not represented in the FMP. During the second site visit, we also discussed our estimate of expected burn probability with their expectations for achieving fire management objectives. In at least one case (Great Smoky Mountains National Park), it was clear that stated fire and land management goals are not achievable with lightning ignitions.

Evaluating Fire Management Plans

We used the model BurnPro to evaluate the risks, opportunities and challenges for WFU management in Great Smoky Mountains National Park. In particular, we used BurnPro to estimate the probability of burning from *all* lightning ignitions within the entire study area and compared this with the probability of burning from only potential WFU ignitions in areas where WFU is authorized in the Fire Management Plan (Table 5). By examining the difference between these two estimates, we highlighted places in the WFU zones where a natural fire regime would be dependent upon immigration of fires from outside the area. Through this comparison we identified those areas that are not likely to experience as much fire under current fire management strategies as they would under a natural fire regime. We used strategies outlined in the Fire Management Plan along with feedback from local managers to define potential WFU ignitions and the parameters necessary to run BurnPro for these analyses.

Table 5. Number of lightning-caused ignitions used to evaluate FMPs

	Size (hectares)		Total Lightning Ignitions (#)†	
Study Area	Entire Study Area	WFU Zone	Case 1 ("natural")	Case 2 ("current FMP")
Gila/Aldo Leopold	576,000	313,000	1721	1044
Great Smoky Mtns NP	219,000	175,000	34	27
Selway-Bitterroot *	1,098,000	499,000	2888	1221
Sequoia-Kings Cyn NP	722,000	169,000	952	184
Yosemite NP	303,000	251,000	720	529

* The Selway-Bitterroot WFU zone is defined as the Interior zone plus the Early Season/Drought zone. WFU Zone ignitions include all lightning ignitions from the Interior Zone and only late season ignitions from the ES/D zone.

† Lightning ignition counts reflect 17 years of data, except for Sequoia-Kings Canyon, where they reflect 19 years.

Identifying Risks and Opportunities

In addition to our evaluation of Fire Management Plans, we took a more direct look at some of the risks and opportunities of WFU. These analyses varied among the study areas according to values-at-risk for each site and to site-specific requests.

Our estimates of average annual probability of burning were overlaid with several values-at-risk to improve risk assessments. The estimates of probability of burning were also examined to determine where the greatest opportunities for WFU are. By overlaying our estimates with values-to-benefit, we identified where WFU is most likely to *benefit* specific resources.

Chapter 4

Results

We used estimates of probability of burning to determine how well current or proposed WFU strategies might be expected to achieve the restoration of natural fire regimes. In particular, we used these analyses to evaluate how, and where, suppression of lightning-caused fires on lands outside an approved WFU zone might affect the rate of burning within the approved zone. We also used estimates of probability of burning to evaluate selected risks and opportunities from WFU fires.

Evaluation of FMPs

To assess the feasibility of WFU strategies as outlined in the FMP for restoring natural fire regimes, we evaluated how suppression of lightning-caused fires on lands outside approved WFU zones might affect the rate of burning within these zones. By doing so, we asked: *what is the effect of eliminating the importation of these fires?*. Our main analysis consisted of running BurnPro with two different ignition cases ("natural" and "current FMP", Table 5) and comparing the difference between the two. We compared the area averages for the two cases and also calculated the absolute and relative differences on a pixel-by-pixel basis.

For the "natural" case, we ran BurnPro using all lightning ignitions that have occurred during the ~17-year period of record[1] in the study area. The resulting estimates of probability of burning are a proxy for what might be expected if there was no management intervention of the natural fire regime. There are two important caveats to the idea of using this "natural" case as a proxy for natural fire regime, however. First, it ignores ignitions that would have spread in from outside the study area. This is an edge effect that is more pronounced closer to the study area boundary. Ideally, we would have had a large buffer around each study area but in most cases, our fuels and ignition data only extended a short distance outside the park or wilderness boundary and we were unable to buffer the park or wilderness by very much. A second caveat is that these predictions are based on

[1] 17-years of ignition data used for all study areas except Sequoia-Kings Canyon NP, where we used 19 years of data

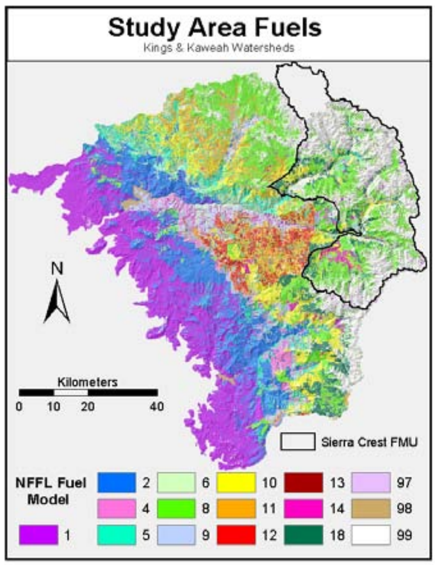
current fuels--fuels that have been influenced by human management such as suppression of naturally ignited fires. As a result, the vegetation composition and structure has been altered to varying and largely unknowable degrees. This would be particularly important if vegetation has changed over time from flammable types to inflammable or "fire-proof" types.

For the "current FMP" case, we ran BurnPro using only the ignitions that fell within an approved WFU zone as delineated in the FMP. These are zones that are typically managed for natural processes applying WFU as the primary tool. These results represent the probability of burning that we might expect under a strict implementation of prescriptions contained in the Fire Management Plan.

We compared the area averages for the "natural" and "current FMP" cases to evaluate how suppression outside the WFU zone affects the rate of burning within the zone (Table 6). In other words, by how much is the probability of burning reduced when we eliminate the importation of fire from outside the area that is being managed for natural processes? When ignitions outside the approved WFU zones are eliminated (i.e., the "current FMP" case) from the BurnPro analysis, the probability of burning is lower than when all ignitions (i.e., the "natural" case) are used (Table 6). This is not surprising: fewer ignitions should result in a lower probability of burning. However, the degree to which these values are reduced varies among the five study areas. For example, this reduction in the WFU zone area average for Sequoia-Kings Canyon is at least six times greater than for the other sites (e.g., a reduction of 0.06 in Sequoia-Kings Canyon compared to a reduction of 0.01 in Gila/Aldo Leopold, Selway-Bitterroot and Yosemite). There a couple of possible reasons for the large difference between the "natural" and "current FMP" cases for Sequoia-Kings Canyon. First, the study area is very large relative to the size of the WFU zone. Therefore, estimates of probability of burning derived for the "natural" case are based on many more ignitions than estimates derived for the "current FMP" case (Table 5). Second, the portion of the study area that is outside the WFU zone for Sequoia-Kings Canyon is at a relatively low elevation with a relatively long fire season (Figure 3). Furthermore, this portion of the study area contains considerable amounts of fast spreading fuels, such as NFFL fuel models 1, 2, and 5 (Figure 7). With a long fire season and fast spreading fuels, the area outside the WFU zone potentially exports a lot of fire to the higher elevation WFU zone.

Table 6. Probability of burning for the two cases used to evaluate FMPs				
	Averaged over entire study area		Averaged over WFU zone	
Study Area	Case 1 ("natural")	Case 2 ("current FMP")	Case 1 ("natural")	Case 2 ("current FMP")
Gila/Aldo Leopold	0.550	0.510	0.600	0.590
Great Smoky Mtns NP	0.024	0.022	0.023	0.021
Selway-Bitterroot*	0.250	0.150	0.260	0.250
Sequoia-Kings Cyn NP	0.440	0.310	0.230	0.170
Yosemite NP	0.300	0.290	0.260	0.250

Figure 7. NFFL fuels models for Sequoia-Kings Canyon study area.

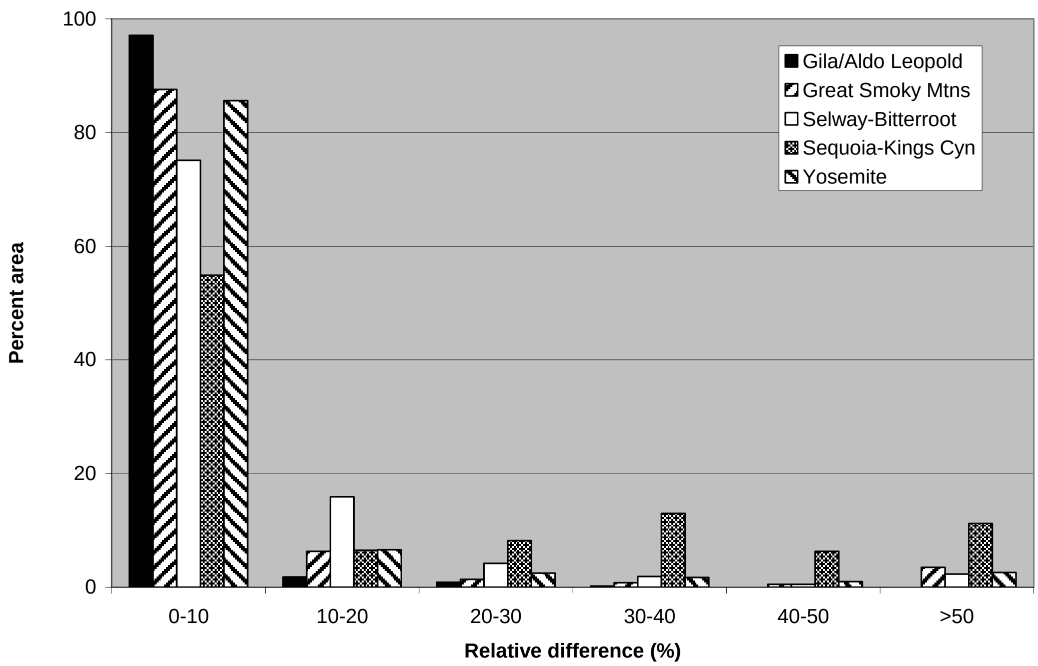


We also found that the degree to which probability of burning differs between the two cases varies greatly *within* a study area. On a pixel-by-pixel basis, we calculated the absolute and relative differences between the two ignition cases. The absolute difference was obtained by simply subtracting -- pixel by pixel -- one probability map from the other. While this is a simple and intuitive analysis, it can be somewhat misleading because the difference between two large values is perceived as the difference between two small values. For example, reducing the probability of burning by 0.10 from 0.50 to 0.40 does not represent the same degree of change as reducing the probability by 0.10 from 0.15 to 0.05. Therefore, we calculated the *relative difference* between the "natural" and "current

FMP" cases as the percentage that the probability differs between the two cases. For example, if the value for a pixel in case 1 is 0.06, and if the value for that same pixel in case 2 is 0.03, the relative difference is 50%. If the values are 0.06 and 0.04, the relative difference is 33%.

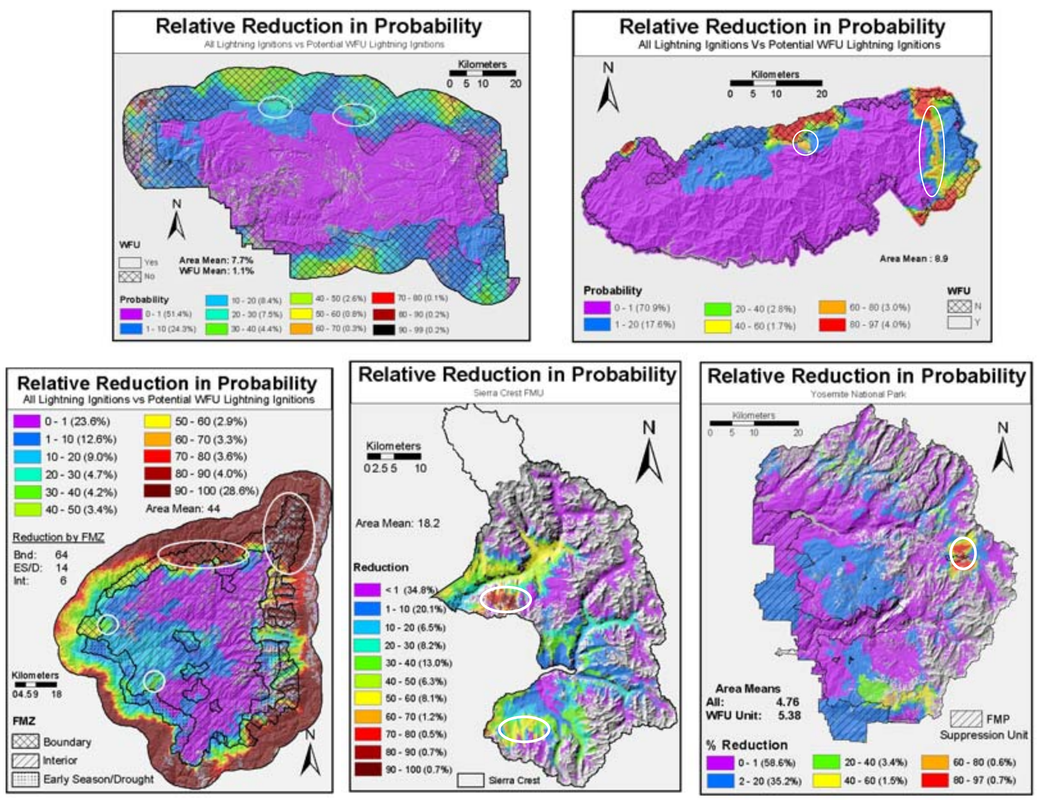
In general, the relative difference was low for the majority of area within the WFU zones. For example, the relative difference between the "natural" and "current FMP" cases was 10 percent or less for the majority of each of the WFU zones (Figure 8). For the Gila/Aldo Leopold, we found the relative difference between the two cases to be 10 percent or less for 97% of the WFU zone. This indicates that the impact of eliminating ignitions outside the WFU zone in the Gila/Aldo Leopold is minor. The relative differences for the WFU zone in Sequoia-Kings Canyon were considerably higher—for 10 percent of the WFU zone we found a relative difference of more than 50% (Figure 8).

Figure 8. Effect of eliminating importation of fires on the probability of burning in WFU zones as illustrated by relative difference between two ignition cases.



In each study area, we identified specific areas with higher relative difference between the two cases. These are areas where the impact of eliminating importation is relatively large, and where it might be more difficult to restore fire to a natural frequency due to management objectives of adjacent lands (Figure 9). In these areas opportunities for WFU should be maximized whenever possible and in some cases periodic prescribed burning over the long term may be warranted. In Yosemite, the effect of eliminating ignitions within a small area around Tuolumne Meadows in the east central part of the park is visible as an hourglass shape of red and orange which extends beyond the boundaries of a relatively small (~400 ha) suppression zone (Figure 9). Although there are numerous other small suppression zones in Yosemite, none of them are quite as large as the Tuolumne Meadows zone and so eliminating ignitions in those smaller areas for the “current FMP” case does not significantly affect the probability of burning in surrounding areas.

Figure 9. Relative difference in probability of burning between the two ignition cases for the Gila/Aldo Leopold (top left), Great Smoky Mountains (top right), Selway-Bitterroot (bottom left), Sequoia-Kings Canyon (bottom center), and Yosemite (bottom right) study areas.



In Sequoia-Kings Canyon and Yosemite NPs, managers can also compared these places where challenges might exist with analyses of Fire Return Interval Departure (FRID). Both parks currently use estimates of FRID to prioritize fuel management activities and to track their progress (Caprio et al. 1997, Keifer et al.

2000, Caprio and Graber 2000, van Wagtendonk et al. 2002). FRID is an estimate of the number of fire cycles an area has missed, and provides a coarse measure of deviation from natural conditions. Areas with high FRID values are defined as highly compromised by past suppression and in greatest need of fuel treatment. Therefore, managers may be interested in areas where both FRID and the relative difference between the two ignition cases are high. In such areas, the deviation of natural conditions indicated by the high FRID could very well be due to the past suppression of fires on adjacent lands that consequently eliminated the importation of fires.

These results provide useful feedback on current FMPs and WFU strategies and can help managers evaluate where the current FMP is likely to meet their expectations or where it might fall short. For example, are the potential WFU ignitions located in the WFU zone likely to burn the amount of area or burn with the frequency that managers expected they would? In a couple of the study areas, management staff asked us to modify the “current FMP” case to evaluate the effect of a potential revision to the FMP revision. Other times, staff asked us to modify the “natural” or “current FMP” cases to better account for realities that are not captured in the FMP.

Identifying Risks and Opportunities

We used our estimates of probability of burning to examine some of the risks and opportunities WFU may pose.

First, maps of probability of burning were overlaid with socio-economic or ecological values to identify where risks from fire are greatest. These areas might be then identified as priorities for fuel treatments or prevention planning. For example, for the Gila/Aldo Leopold Wilderness, we overlaid our estimate of probability of burning with information on Mexican spotted owl habitat and wildland urban interface (WUI) to assess the risk of WFU to both Mexican spotted owl and human life and property (Figure 10). For Great Smoky Mountains NP, we overlaid the probability of burning with the location of historic cemeteries, an important cultural resource that is potentially threatened by fire (Figure 11).

Figure 10. Analysis of risk from WFU to Mexican spotted owl habitat and wildland urban interface for the Gila/Aldo Leopold Wilderness.

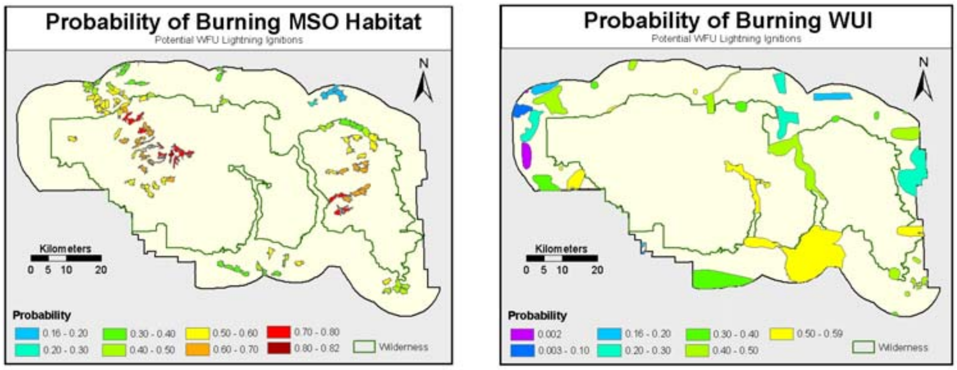
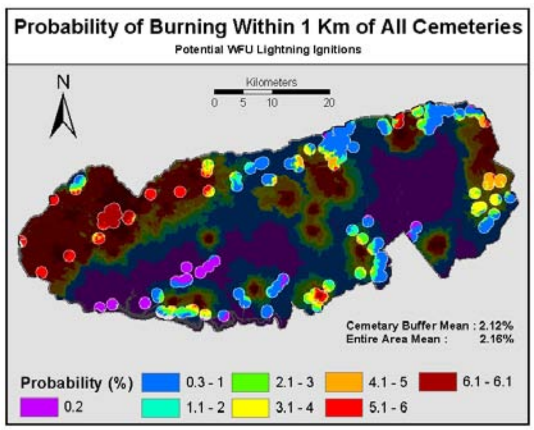


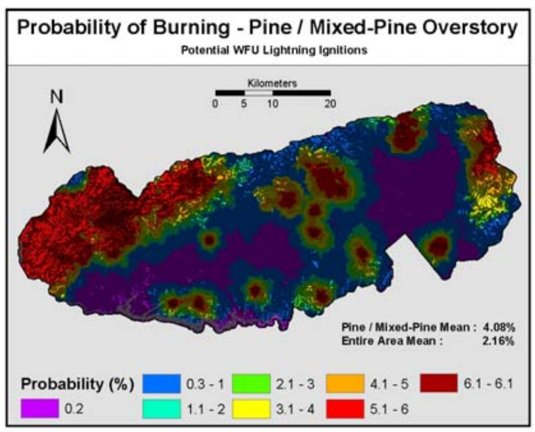
Figure 11. Analysis of risk from WFU to cemeteries in Great Smoky Mountains National Park.



The resulting map of probability of burning can also be viewed in terms of opportunities for WFU. WFU opportunities may be fairly common or frequent in areas with high probability of burning, whereas WFU opportunities are rare in areas with low probability of burning. This information can help inform the go/no-go decision. If a suppression decision has to be made in an area of high probability of burning due to external factors (e.g., national preparedness level, air quality concerns, etc.), managers can expect that another opportunity for WFU is likely to occur again relatively soon. On the other hand, in areas with low probability of burning, managers may want to more carefully scrutinize suppression decisions because of the rarity of such opportunities for WFU.

WFU also provides specific benefits to the resource and we used our estimates of probability of burning to identify some of these. For example, in Great Smoky Mountains NP there are estimated to be at least a dozen species of native plants and animals that benefit from fire. One of these species is Table Mountain pine, which has serotinous cones that open in response to fire, allowing the dispersion of their seeds onto the fire-cleared ground. Table Mountain pine has experience a decline in population over the past 100 years. For Great Smoky Mountains NP, we examined the opportunities for WFU to *benefit* the resource by overlaying the probability of burning with maps of fire-dependent yellow pine species as a whole (of which Table Mountain pine is an example) (Figure 12).

Figure 12. Analysis of benefits to fire-dependent pine species for Great Smoky Mountains National Park.

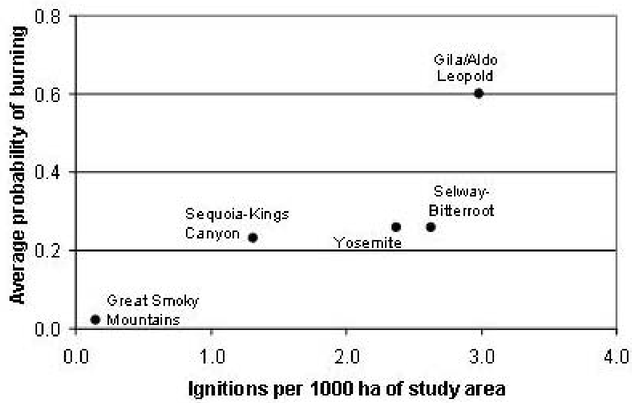


Management staff at all of the study areas were interested in seeing the probability of burning derived using *human-caused and* lightning-caused ignitions to help improve their risk assessments. In addition, the Gila National Forest requested additional analyses for the entire National Forest, an area of 1.5 Mha.

Synthesis

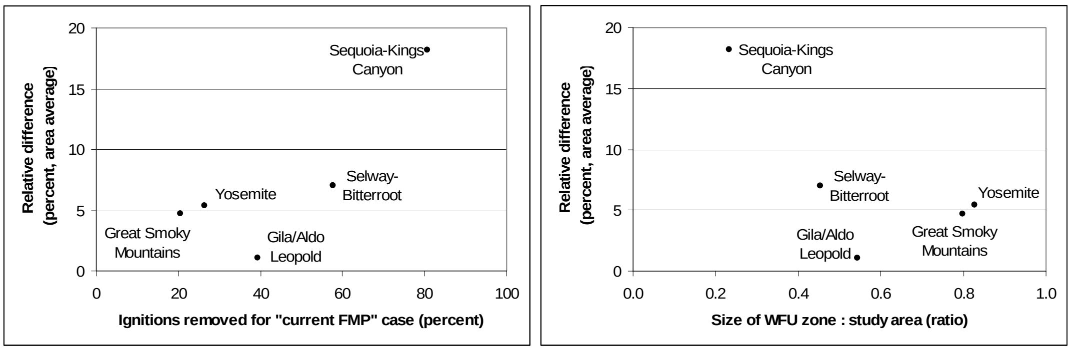
It was difficult to make direct comparisons among the five study areas because the the extent and definition of study area boundaries varied according to the data we had available. For example, the buffer areas around Selway-Bitterroot and Gila were much more generous (~10 km) than for Yosemite or Great Smoky Mountains NP, which had virtually no buffer. It is instructive, however, to examine the five study areas as a group. Figure 13 illustrates the differences among study areas in ignition densities and average annual probability of burning.

Figure 13. Comparison of study areas by probability of burning (averaged over the WFU zone) and density of ignitions for the study area ("natural" case).



Summer-monsoon and summer-moist. Summer precipitation influences the probability of burning for two of our sites: Gila/Aldo Leopold Wilderness and Great Smoky Mountains National Park. Gila/Aldo Leopold typically experiences a summer monsoon in late July that serves to limit the probability of burning. Frequent summer precipitation in Great Smoky Mountains National Park similarly limits the probability of burning at that site. Despite this similarity, the fire management and restoration challenges at these two sites are extremely different from one another. In terms of absolute probability of burning (Table 6, Figure 13), these two sites represent two different ends of the spectrum. Gila/Aldo Leopold has the highest density of ignitions, and therefore many opportunities for WFU and the highest probability of burning. Eliminating ignitions outside the WFU zone for the Gila/Aldo Leopold does not appear to have much of an effect on the average probability of burning within the WFU zone (Figure 14). Therefore, our analyses suggest that Gila/Aldo Leopold has a very good chance of maintaining natural fire frequencies with WFU, although there are resource values potentially threatened by fire that need to considered. Great Smoky Mountains, on the other hand, has the lowest density of ignitions, and therefore few opportunities for WFU and the lowest probabilities of burning (Figure 13). Although BurnPro's estimates should be interpreted only as relative probabilities, when we compared the absolute values for our study areas, it was apparent that Great Smoky Mountains NP has an exceptionally low chance of burning. For large portions of the interior of this park, BurnPro output suggests that there is little or no chance of burning from a lightning ignition. In comparison to Gila/Aldo Leopold, Great Smoky Mountains has virtually no opportunity to restore fire regimes through WFU and will likely continue to lose fire dependent species as a result. As such, an aggressive prescribed burning program is probably the park's best approach for achieving conservation objectives.

Figure 14. Effect of eliminating ignitions from outside the WFU zone, approximated by relative difference between the "natural" and "current FMP" cases. Relative difference is shown as a function of the number of ignitions removed from the analysis for the "current FMP" case and as a function of the size of the WFU zone relative to the size of the study area.



Summer-dry. The three remaining sites are in the summer-dry category and in these study areas, the elevational variation in the length of fire season is more important than summer precipitation for estimating probability of burning. These three sites have ignition densities and values of probability of burning that are intermediate between the Gila/Aldo Leopold and Great Smoky Mountains NP (Figure 13). Figure 14 illustrates the relative difference, averaged over the WFU zone for each study area. The relative difference between the "natural" and "current FMP" cases is one way to compare the impact of eliminating importation of fires. Because Sequoia-Kings Canyon and Yosemite NP have similar climates, vegetation, and fire regimes, we might expect them to be comparable. However, our analysis indicates that Sequoia-Kings Canyon has the greatest relative difference (Figure 14), suggesting that the importation of fires is more important there. This also suggests that suppression outside the WFU zone will limit the ability to restore natural fire regimes to the WFU zone more so in Sequoia-Kings Canyon than in Yosemite.

Model Development

We discovered problems in the original implementation of the model BurnPro and spent several months correcting these problems. For example, we discovered logical inconsistencies in the model regarding the assumed direction of fire spread and the whether the rate of spread referred to heading, flanking, or backing fires. We also discovered a logical fallacy in the assumed timing of the fire season for areas on the landscape with very short fire seasons (e.g., high elevations with a fire season <30 days). In addition to correcting these logical problems, we reprogrammed the model to make it more widely applicable and easier to use in multiple study areas. Another important modification we made was adding second sub-probability to account for fire-stopping precipitation events that may occur before the actual end of the fire season. Prior to this modification, the probability of burning was calculated solely from what is now the first sub probability—the probability that fire would reach a pixel before the end of the fire season.

Although these improvements were not anticipated in our original proposal, they provided more meaningful and defensible analyses for fire management planning. Furthermore, the development, testing, and use of BurnPro that was done within the scope of this project is an important foundation for what may become a widely distributed analysis tool.

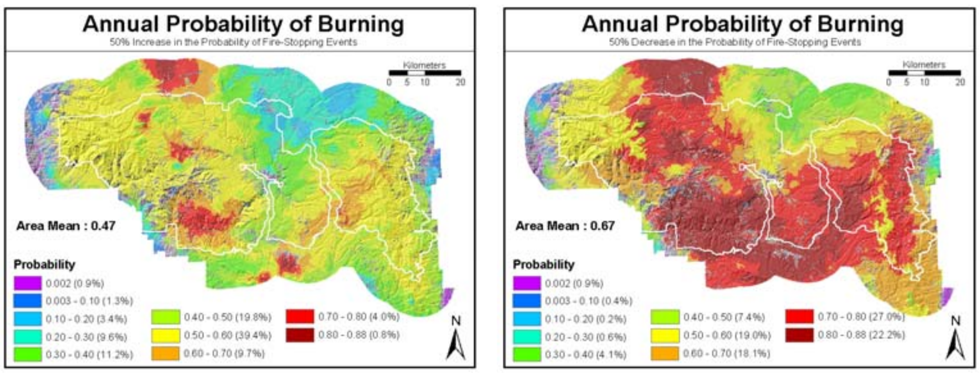
Sensitivity Analyses

Any model will have a degree of sensitivity to each of the variables within it. It is important to understand the model's sensitivity, particularly to those variables we are most uncertain about or for which we lack reliable data. Through an analysis of this sensitivity, we can prioritize our data needs and better understand the uncertainty of the model output. We conducted a sensitivity analysis of three important variables in BurnPro: frequency of fire-stopping precipitation events (which is used to compute *PStop*); length of fire season (used to compute *PEnd*); and rate-of-spread (which is used to compute CST for both *PEnd* and *PStop*).

Frequency of fire-stopping events

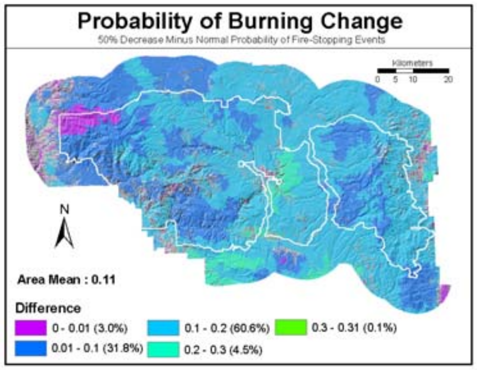
Increasing the frequency of fire-stopping events should decrease the probability of burning. For the Gila/Aldo Leopold Wilderness these events are defined as 0.5 inches of rain occurring in 5 days. To test the sensitivity of BurnPro output to this variable, we increased and decreased the monthly frequency of fire-stopping events by 50% and compared the resulting probability of burning (Figure 15) with the “normal” case.

Figure 15. Probability of burning estimates for the Gila/Aldo Leopold Wilderness with 50% increase and 50% decrease in the monthly frequency of fire-stopping events.



Changing the frequency of fire-stopping events does indeed affect the probability of burning and the difference is noticeable (Figure 15). Less frequent fire-stopping events result in higher estimates of probability of burning. When we examined the resulting from reducing the fire-stopping events by 50%, we found that probability estimates were increased by at least 0.10 for about 65% of the land area (Figure 16). Furthermore, the degree of this difference varies spatially within the landscape, indicating that the probability of burning for some places on the landscape is more sensitive than others when the frequency of heavy rains changes. These differences could indicate places on the landscape where fire frequencies may be more sensitive to interannual variability in precipitation.

Figure 16. Difference in probability of burning between the baseline case and a 50% decrease in the frequency of fire-stopping events for the Gila/Aldo Leopold Wilderness.



Length of fire season

Increasing the length of the fire season should increase the probability of burning. To test the sensitivity of BurnPro estimates to this variable, we increased the length of the fire season by shifting the fire season for Yosemite National Park uphill by 500m (Figure 17). This shift approximately doubles the amount of area that has a 4-month or longer fire season (Figure 18).

Figure 17. Original length of fire season and length of fire season shifted uphill by 500 m for Yosemite National Park.

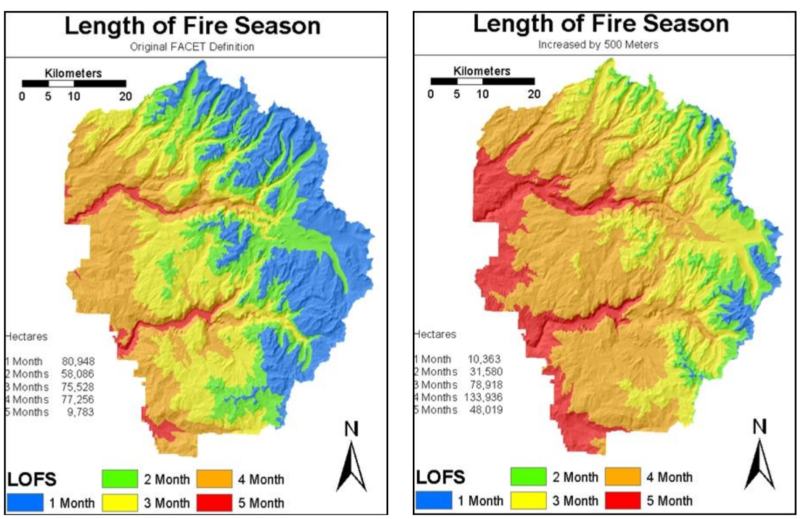
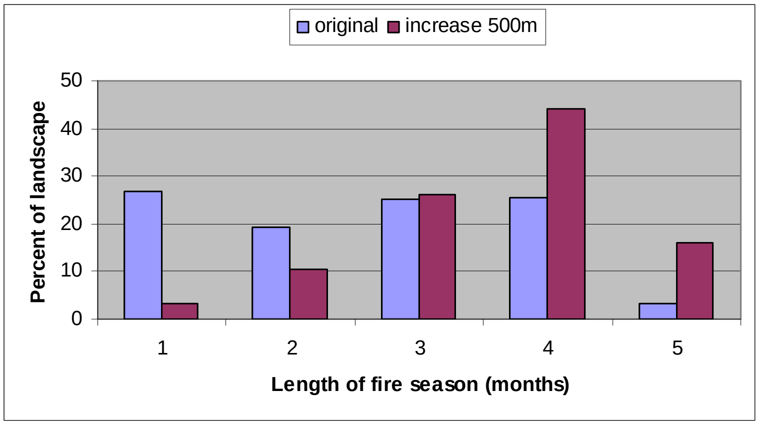


Figure 18. Distribution of original length of fire season and fire season shifted uphill by 500 m for Yosemite National Park.



The effect of a longer fire season on annual probability of burning isn't very dramatic at a landscape scale (Figures 19 and 20), suggesting that BurnPro isn't very sensitive to length of fire season. Although this variable has a fairly high degree of uncertainty, results from this sensitivity analysis suggest that improving these data should not be a high research priority.

Figure 19. Probability of burning estimates for Yosemite NP derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.

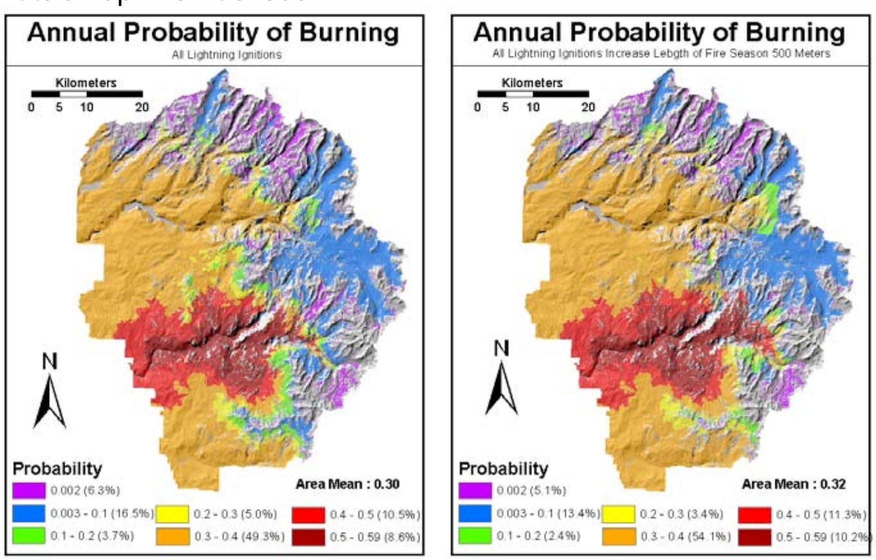
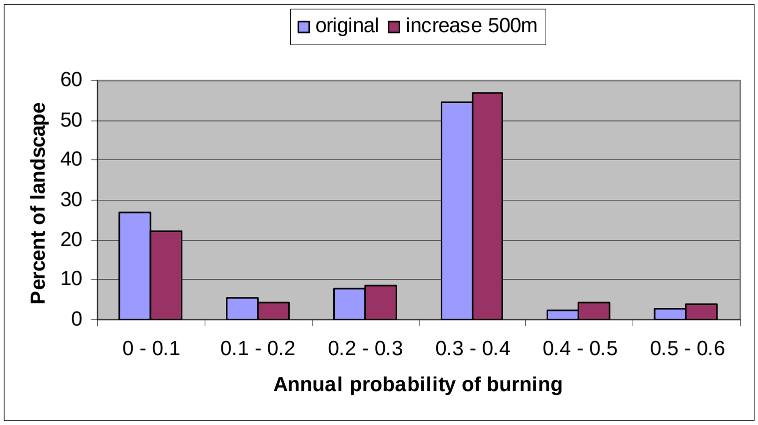
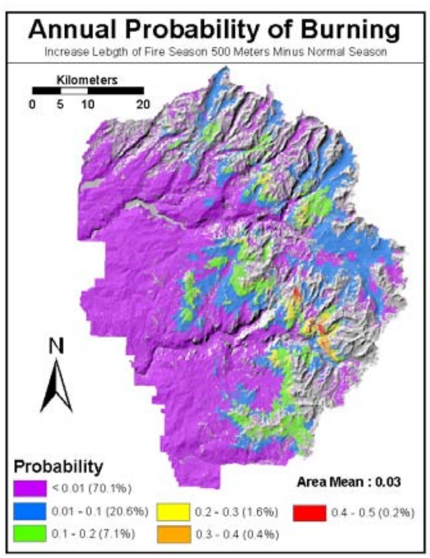


Figure 20. Distribution of probability of burning estimates derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.



However, direct point-to-point comparison reveals that certain places on the landscape are much more sensitive to this variable than others (Figure 21). The changing sensitivity to this variable across the landscape demonstrates the importance of the spatial configuration of fuels, topography, and ignitions and the need for approaches that explicitly account for this spatial context or topology.

Figure 21. Difference in probability of burning estimates derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.

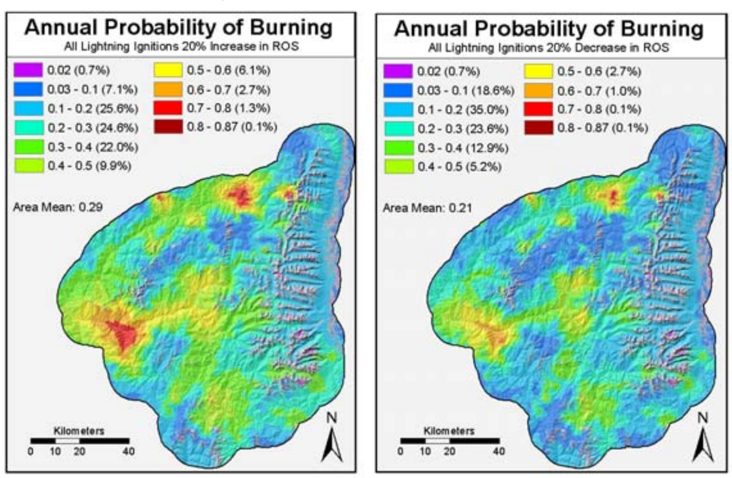


The results of this sensitivity analysis may have important implications for fire management under future climate change. Currently, most *lightning strikes* in Yosemite occur at higher elevations, but most *ignitions* occur at lower elevations because that is where fuel conditions are suitable for burning for long periods of time (van Wagtendonk 1993). If lightning patterns continue to remain the same and if conditions at higher elevations become dry enough to support fire for longer periods of time during the season, the park could experience a substantial increase in future rates of burning. However, since climate change also causes changes in vegetation and fuels, additional research on the complex interactions among climate, fuels and fire is needed to fully flesh out the management implications (Miller and Urban 1999).

Rate of spread

Finally, increasing the rate of spread should increase our estimates of the probability of burning. To test the sensitivity of BurnPro's estimates to this variable, we ran BurnPro for the Selway-Bitterroot Wilderness using rate-of-spread values that we decreased by 20% and again using rate-of-spread values that we increased by 20% (Figure 22).

Figure 22. Probability of burning for the Selway-Bitteroot Wilderness derived using 20% faster and 20% slower rates-of-spread.



The values for rate-of-spread that we use as input to BurnPro are computed using another model (FlamMap) and therefore come complete with their own degree of uncertainty. Through this sensitivity analysis, we can begin to understand the effect that uncertainties in other models might have on our estimates of probability of burning. The level of error in FlamMap's rate-of-spread predictions probably varies depending on fuel types. To improve future analyses of sensitivity, it would be advantageous to consult with the developers of FlamMap to design scenarios that consider varying degrees of error for each fuel type.

Chapter 5 Conclusions

Fire is a contagious process that responds to a multivariate landscape and is one that does not obey administrative boundaries. As such, effective fire management planning needs to account for the spatial context and configuration of landscape variables, and it needs to do so across administrative boundaries. In particular, effective planning needs to consider the effects that fire management activities on one side of a boundary can have on the other side of the boundary. Prior to this project, we know of no methods that could be used to evaluate such effects while accounting for a landscape's unique spatial configuration of fuels, topography and ignitions.

We developed methods for evaluating effects that fire suppression on one side of an administrative boundary might have on the other side of that boundary. We used these methods to evaluate how suppression of lightning-caused ignitions that occur *outside* WFU zones might affect our ability to achieve the restoration of fire *inside* the WFU zones. Specifically, we examined how eliminating the importation of fires that start on adjacent lands affects the predicted rate of burning for the WFU zone. Furthermore, we developed and demonstrated our approach using multiple study areas that have very different precipitation regimes. As such, the approach we developed is a robust one that can integrate information on summer precipitation patterns as well as patterns of season length over elevation.

Cross-boundary fire management planning requires cross-boundary information and data. We buffered around the boundaries of our study areas as much as possible, but in only one study area (Sequoia-Kings Canyon National Park) did we have a data set available to us that provided a true interagency perspective. This data set was the result of a previous project funded by the JFSP that created the Southern Sierra Geographic Information Cooperative (JFSP #99-1-3-04). This effort developed data that extend across administrative boundaries, thus allowing analyses and planning to also extend across boundaries.

Although we were unable to directly compare the estimates of probability of burning to historical fire frequencies (our original intent), we did identify specific places in each study area where restoration of natural fire frequency may be difficult because of the important influence of immigration of fires. This knowledge can help inform the go/no-go decision and we suggest that whenever possible, these areas receive the highest priority for WFU. If WFU is not possible, these are places where management-ignited prescribed fires might be warranted.

Originally, we expected to use the information generated to delineate fire management zones in fire management plans (FMPs). Although we believe this is a valid use of our analyses, the study areas we selected already had established FMPs and did not have a need for this application. Therefore, we used our analyses to evaluate these existing FMPs and to identify where the greatest challenges to meeting restoration objectives can be expected.

Developing a prediction tool that accounts for the spatial configuration of multiple variables on a landscape and the contagion of fire is not a trivial exercise. While we have developed one set of methods, we are certain these methods can be improved upon. We expect to collaborate with other researchers to compare and contrast other approaches for modeling the probability of burning. We expect that these efforts will not only require an understanding of what makes fires *start* and *spread* (i.e., the focus of much fire research to date), but also an understanding of how long fires can be expected to spread and what makes them *stop.* Therefore, we will encourage work that adapts the fundamental concepts in the incident support tool RERAP (Wiitala and Carlton 1994, FRAMES 2003) to longer time scales and multiple incidents.

Prospectus

The development, testing, and use of BurnPro that was done within the scope of this project is an important foundation for what we believe could become a widely distributed analysis tool. In particular, our experimental release of BurnPro for use on the Cloud Peak Wilderness and feedback from our lecture at the Technical Fire Management course have encouraged us to pursue the idea of a stand-alone tool. We have already identified several modeling issues that we need to address and resolve in BurnPro. By leveraging results from this project with continued support from the National Fire Plan, we hope to produce and release a user-friendly version of BurnPro in FY2006 for use by the fire and fuels management community.

Several opportunities for collaboration were generated as a result from this project. For example, BurnPro is being evaluated for use in the Front Range Fuel Treatment Project in Harris Park, Colorado. We have met with research partners (ESRI and the Colorado State Forest Service) and have provided a copy of the current model and preliminary documentation for this purpose. We are currently collaborating on a project proposal to NASA with researchers from the University of Georgia and management staff from Great Smoky Mountains National Park. The project would provide improved linkages between remotely sensed data and fire management decision support tools, including BurnPro. Another pending proposal (to JFSP) from the USDA Forest Service Rocky Mountain Research Station's Boise Aquatics Lab would likely utilize BurnPro in a decision support system for integrating aquatic species needs. We expect to test the individual functions in the BurnPro model and compare their behavior with other approaches, including "Monte Carlo" simulations of FARSITE, the Minimum Travel Time tool, and a model developed by the Canadian Forest Service (BurnP3).

Finally, management staff identified several additional applications for the probability of burning analyses. With the procedures we have provided in the guidebook, we expect they will be able to run the BurnPro model and conduct their own analyses.

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Appendix A

Publications

Proceedings Paper

Davis, B., C. Miller. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society of Photogrammetry and Remote Sensing (CDROM).

Research in a Nutshell

The feasibility of wildland fire use for restoring natural fire regimes, Aldo Leopold Wilderness Research Institute, http://leopold.wilderness.net.

Guidebook - *Draft*

Sample of Chapter 2 (methods and guidebook) from review draft of final report to Great Smoky Mountains National Park.

Appendix B Presentations

BurnPro Poster

Poster presented at 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL, November 2003 and National Fire Plan Conference, Reno, NV, February 2004.

Probabilty of Burning Poster

Poster presented at Mixed Severity Fire Regime Conference, Spokane, WA, November 2004.

Symposium on Science and Monitoring

Modeling the probability of burning to help plan for wildland fire use. Presented at Symposium on Science and Monitoring, Denver, CO, September 2004.

American Society for Photogrammetry and Remote Sensing

Modeling wildfire probability using a GIS. Invited presentation at American Society for Photogrammetry and Remote Sensing Conference, Denver, CO, May 2004.

Technical Fire Management

Lecture notes and slide presentation from Technical Fire Management, Bothell, WA, October 2004.