

Project Title: Evaluating approaches to mapping burn probabilities for a quantitative wildland fire risk analysis framework.

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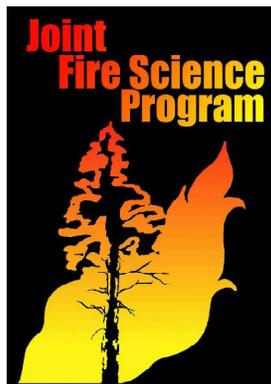
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ABSTRACT

This final report summarizes a collaboration that brought together experts in burn probability (BP) modeling and wildland fire risk analysis to compare and evaluate BP models, and ultimately incorporate these into a risk analysis framework. The project built on and extended the work from JFSP project #01-1-1-05. This project evaluated and tested three different independent models that generate BP maps as output for their operational use in risk analysis. The project quantified the relative sensitivity of the three BP models to different inputs, enhanced our understanding of the factors that affect BP at the landscape scale, and yielded concrete improvements to BP models for operational use in quantitative risk analysis. The findings of this project have greatly enhanced our capability to reliably estimate BP and use this information in an applied setting. For example, our analyses have pinpointed which inputs can be further generalized (“shortcuts”) and which ones require more detail (i.e., “real world” variability). Land managers will benefit from this project by having a more robust measure of the expected losses and gains (both ecological and financial) resulting from wildland fire upon which to base decisions. This final report summarizes findings to date and lists the proposed and accomplished deliverables. A wealth of information pertaining to the project has been disseminated through published articles, poster and oral presentations, a PhD dissertation, and workshops with land managers. Furthermore, the knowledge learned throughout this project will be synthesized in a forthcoming General Technical Report.

BACKGROUND AND PURPOSE

Burn probability (BP) is the spatially explicit likelihood that a cell (i.e., pixel) on a raster landscape will burn. BP models consider ignition locations, topography, weather conditions, and the rate and direction of fire spread on a landscape. Predictive models of BP, which are based on the physical factors that control fire behavior and spread, have enormous potential to support strategic fire and fuels management planning decisions at landscape scales, especially when combined with information on values and expected effects in assessing fire risk (Finney 2005). This project built on and extended the work from JFSP project #01-1-1-05 in a collaboration that brought together experts in BP modeling and in wildland fire risk analysis to compare and evaluate BP models, and incorporate their methods into a risk analysis framework.

Spatially explicit information on the probability of burning is necessary for virtually all strategic fire and fuels management planning activities, including conducting wildland fire risk assessments, optimizing fuel treatments, and prevention planning. The BurnPro model that was developed in JFSP project #01-1-1-05 has the ability to estimate BP at each point on the landscape, making it possible to evaluate wildland fire risk in a quantitative manner using the well established probabilistic methods from the actuarial sciences (Finney 2005). BurnPro received considerable interest from fire planners and managers, but as the final project report for project #01-1-1-05 stated (Miller and Parsons 2005), a number of technical issues limited its application for quantitative wildland fire risk assessments.

After project #01-1-1-05 was completed, significant technical advances related to the problem of estimating burn probabilities had been made by developers of other BP models (Finney et al. 2006, Parisien et al. 2005). Although BurnPro and these other models are similar in that they generate BP maps as output, the inputs that drive each model (e.g., spatial ignitions, weather, duration of burning period) differ significantly. Furthermore, the landscape-scale factors that determine spread patterns—and thus the manifestation of BP—were not well understood (Mermoz et al. 2005). There was therefore a need to understand the relative sensitivity of each model to the different inputs and their concomitant effect on the output estimates of BP.

The project accomplished the following objectives:

1. Compare BurnPro with at least two other BP modeling approaches (Burn-P3 and Randig-FlamMap) and evaluate the accuracy, practicality, and effectiveness of each model for mapping BP in different fire regimes.
2. Assess the spatial factors that affect BP at the landscape scale to better understand why some landscapes are inherently more likely to experience fires and how landscape modifications resulting from fuels modifications (e.g., fuel treatments, prescribed fire) and fire management activities (e.g., fire suppression, wildland fire use) can affect BP.
3. Incorporate the improved BP models into an operational framework for assessing wildland fire risk using the existing ArcFuels software (ongoing JFSP #03-4-1-04, Ager 2005) and demonstrate this application. ArcFuels will be modified to run one or more of the BP models and combine their outputs with resource value data to provide an automated method for calculating risk.

STUDY DESCRIPTION AND LOCATION

To accomplish our first two objectives, we used a combination of artificial and real landscapes. To accomplish our third objective, we used an additional real landscape.

Artificial landscapes

A series of simple artificially generated landscapes were used to compare the BP models and investigate the relative importance of environmental factors (i.e., inputs) affecting BP across the landscape. The landscapes differed in the dominance and spatial configuration of fuel types, and in the density and spatial pattern of ignitions. Non-spatial settings, such as variability in weather and the length of time that fires burned were also included in the study design.

Three simulation experiments focused on how ignitions, fuels, and weather influence the average landscape BP, as well as the spatial patterning of BP. Simulation scenarios were designed to discern the influences of so-called top-down (weather) and bottom-up (fuels and ignitions) drivers of fire regimes. The ‘ignitions experiment’ examined the influence of ignition patterns and the interactions of this factor with mean fire size and wind direction. The ‘fuels experiment’ examined the effect of fuel patterns and interactions with ignition patterns and mean fire size. The ‘weather experiment’ assessed the effect of wind direction constancy and fire size distribution on BP and interactions with fuel patterns.

In this study, 66 simulations were run using each of the models BurnP3 and FlamMap-Randig. After examining BurnPro output from a subset of these simulations, we chose not to run the full set of 66 because FlamMap-Randig and BurnP3 produced more realistic BP patterns. To assess the degree of influence of environmental variables (and interactions between them) on BP, we evaluated the relative departure of BP values from scenarios using nonrandom or nonuniform inputs (i.e., patterned ignitions, patterned fuels, and directional wind) against scenarios with random or uniform inputs (i.e., random ignitions, uniform fuels, and random wind). In addition, we evaluated the relative departure of BP within spatial features such as fuel patches and zones of high ignitions to provide a coarse measure of the influence of that particular feature on BP. A generalized linear model (GLM) framework was used to partition the explained variance in BP among the experimental factors and their second-order interactions within each experiment. A factorial design revealed effects of interactions among factors. A full description of the experiment and methods can be found in Parisien et al. 2010 (Deliverable #7790).

Real landscapes

Although artificial landscapes were useful for identifying the effects of single variables, the BP approach was designed to be applied to real landscapes, where fire spread is subject to substantial natural variability. A set of 4 real landscapes that represent different fire-prone biomes of western North America were used to investigate the environmental factors affecting BP (Table 1). The landscapes represented gradients of mean fire sizes (e.g., small surface-fire regime v. large crown-fire regime), fire frequencies (e.g., short v. long fire-return-interval), and topographic characteristics (e.g., flat v. mountainous terrain) and are described below. The landscapes were:

1. Wood Buffalo National Park in Alberta and the Northwest Territories, Canada
2. The southern Sierra Nevada in California, USA
3. The Selway-Bitterroot Wilderness Area in Idaho and Montana, USA
4. The Gila and Aldo Leopold Wilderness Complex in New Mexico, USA.

Table 1. Environmental attributes of the four study area landscapes.

Study area attribute	Wood Buffalo National Park	Southern Sierra Nevada	Selway-Bitterroot Wilderness	Gila and Aldo Leopold Wilderness Complex
Area (ha)	4,480,000	572,000	655,000	319,000
Latitude, Longitude (deg)	59.4 N, 112.8 W	36.8 N, 118.8 W	46.1 N, 114.8 W	33.2 N, 108.3 W
Mean annual precipitation, cm (range within study area)	36 (32 – 54)*	95 (41 – 155)**	121 (68 – 204)**	58 (41 – 103)**
Mean January temperature, °C (range within study area) ***	-21.6 (-19.4 - -23.3)*	7.6 (-9.1 – 10.3)**	-5.9 (-10.4 – -1.6)**	1.3 (-2.0 – 4.0)**
Mean July temperature, °C (range within study area) ***	16.6 (13.3 – 17.5)*	17.2 (5.9 – 28.0)**	14.9 (11.1 – 21.0)**	20.0 (14.4 – 24.4)**
Vegetation	Mixedwood boreal forest, wetlands	Shrubland and woodland; mixed conifer forest;	Pine forest; mixed conifer forest; subalpine	Grassland, shrubland and woodland; pine

		subalpine forest	forest	and mixed conifer forest
Fire season	May to mid-September	mid-May to mid-October	July through September	April through September
Mean elevation, m (range within study area)	283 (163 – 965)	2116 (212 – 4297)	1751 (480 – 3091)	2275 (1462 – 3314)
Mean slope, degree (std. dev.)	0.5 (1.5)	18.7 (10.3)	21.3 (8.9)	15.1 (8.8)
% study area with nonfuels (i.e., fuel breaks)	11.7	16.6	9.5	10.7

* McKenney et al. 2006 (average for 1980-2005)

** Daly et al. 2002 (PRISM; average for 1971-2000)

*** Mean temperature calculated by averaging the mean monthly high and mean monthly low temperature

Because of the complexity inherent to real landscapes, it was necessary to use a different approach than that used with artificial landscapes to isolate the relative importance of environmental factors than that used for artificial landscapes. The Burn-P3 model was used to examine WBNP and the Randig-FlamMap model was used for the three US study areas. We created a BP surface for each study area using all available inputs which we called the “control.” We then created six additional BP surfaces for each study area where one of the major inputs was randomized or homogenized (Table 2); we called these “treatments.” Subtracting the BP map of a given treatment from that of the control, we evaluated the patterns in BP attributable to a factor of interest while taking into account the effect of all other variables. The relative importance of each environmental factor is undergoing statistical control and being tested using structural equation models, a technique that accounts for complex relationships among factors. Results will be reported in two refereed journal articles currently in preparation (Parks et al. “Factors controlling burn probability in three western US fire prone landscapes” and Parisien et al. “Environmental controls on the burn probability of a fire-dominated boreal landscape”).

Table 2. Environmental factors and the associated experimental treatment for simulations involving the four real landscapes.

Environmental factor	Experimental treatment
Fuel configuration	Three random fuel grids were created. Fuels were randomly distributed according to their observed proportion on the landscape; areas of non-fuel were maintained. The resulting BP grids were averaged.
Topography	Flat
Ignition pattern	Randomly distributed
Weather variability	Random wind direction; uniform wind speed, temperature, and relative humidity.
Duration of burning variability	All fires burn the same number of hours
Fuel breaks	Three fuel grids were created, each with areas of non-fuel (water, barren, etc.) converted to random fuel types according to their observed proportion on the landscape. The resulting BP grids were averaged.

Wood Buffalo National Park (WBNP):

Canada's largest national park is located in northern Alberta and southern Northwest Territories, Canada. It is managed by Parks Canada and is subject to very limited anthropogenic pressure. Although the elevation ranges from 163 m to 965 m, most of the park is remarkably flat except for two small hills. The climate is cold continental and is characterized by long cold winters and short warm summers. There are frequent and intense firestorms in the summer. The vegetation of WBNP is representative of the mixedwood boreal forest; the park is a complex and patchy mosaic of wetlands, forest (jack pine, white spruce, black spruce, tamarack, aspen, and balsam poplar), rivers, and lakes. The fire season generally runs from May through mid September, with the peak fire activity June through August. In normal to wet years, fire predominantly burns in conifer forest types where the wetlands act as barriers to fire spread. In drier years, wetlands can carry fire and the landscape is more conducive to large fire events. Fires, which are highly episodic, are mainly crown-renewing and can achieve very large sizes (>100,000 ha).

Southern Sierra (SS):

The SS study area is located in the southern Sierra Nevada in California, USA. The study area encompasses a dramatic physical gradient with elevations ranging from 212 m to 4297 m. The area experiences a Mediterranean climate, where there is virtually no rain during the summer and fall, except for occasional thunderstorms. The amount of precipitation and the proportion falling as snowfall generally increases with elevation. The natural vegetation at the lowest elevations, which are typified by hot, dry summers, consists of a mosaic of grassland, oak woodland, and chaparral shrubland. As elevation increases, the vegetation transitions into mixed conifer forest, then to red fir and lodgepole pine, and finally subalpine

forests and alpine grassland and shrubland. The occurrence of exposed rock or scree, which act as natural fuel breaks, increases with elevation. The fire season generally runs from mid-May to mid-October, with the highest fire incidence occurring June through September. However, fire season length generally decreases with increasing elevation. Fire severity and frequency varies throughout the study area depending on vegetation type with grasslands and woodlands experiencing surface fires, chaparral experiencing crown fires, and the conifer belt experiencing a low to mixed-severity fire regime whereby many fires are non-lethal surface fires, but under suitable weather and fuel conditions, lethal surface fires and stand-replacing crown fires occur.

Selway-Bitterroot Wilderness (SBW):

The SBW study area straddles the border of western Montana and north-central Idaho, USA. The study area encompasses the entire Selway-Bitterroot wilderness, as well as adjacent Forest Service lands that are managed for wildland fire use. Elevations in this topographically rugged and complex study area range from 480 to 3091 m. The climate ranges from inland-maritime in the northwestern portion of the study area to a continental rain shadow climate in the southern and eastern portions. Vegetation ranges from open stands of ponderosa pine at lower elevations to mixed conifer forests at intermediate elevations and whitebark pine, alpine larch, and Engelmann spruce at higher elevations. The fire season generally runs July through September; during this time, lightning-caused fires accompany frequent thunderstorms. The area experiences a mixed severity fire regime: lower-severity surface fires are common in the lower elevations and patchy, stand-replacing fires become more common as elevation increases, although stand replacing fires may occur over the entire study area during extreme years.

Gila and Aldo Leopold Wilderness Complex (GILA):

The GILA study area is composed of both the Gila and Aldo Leopold wilderness areas; due to road intrusions into and between the wilderness areas, this study area contains two narrow stretches of non-wilderness. GILA is entirely managed by the Forest Service except for some small private inholdings and a relatively small parcel managed by the Park Service (Cliff Dwellings National Monument). The area ranges in elevation from 1461 to 3314 m and features steep mountains, rough deep canyons, flat mesas, large river channels and flood plains. Vegetation consists of from desert scrub and grasslands at the lowest elevations and piñon-oak-juniper woodlands at higher elevations. Above the woodlands, the vegetation transitions to stands of ponderosa pine, Douglas fir, white fir, subalpine fir, Englemann spruce, southwestern white pine, and aspen. The fire season runs April through September. However, because the rainy season is usually July through August, mid-summer fires are rare unless the summer rains do not develop. Fires in GILA are generally low-severity surface fires, but fire severity tends to increase with elevation.

Demonstration landscape

The demonstration landscape encompasses the Deschutes National Forest near Bend, Oregon, with 1,600,000 acres of USDA Forest Service lands and 400,000 acres of private lands. It has diverse topography and fuels, and contains a relatively high density of human and ecological values including numerous urban interfaces, old growth forests, and habitat for species listed as threatened or endangered under the Endangered Species Act. Located in the high lava plain physiographic and geological province, the area is characterized by young

lava flows of moderate relief interrupted by scattered cinder cones and lava buttes. The vegetation on this basin and butte dominated landscape varies considerably with elevation, topography, and substrate. The relatively flat pumice plains are generally dominated by dense stands of lodgepole pine. Vegetation on the buttes gradually changes with elevation to include ponderosa pine and Douglas-fir at elevations below 2000 m, and Shasta fir, mountain hemlock, and western white pine between about 2200 and 2400 m. In the western, higher elevation (>2400 m) portion of the study area, mountain hemlock, western white pine, and lodgepole pine are the most common tree species. Approximately 50% of the Forest is administered according to the Northwest Forest Plan where the primary management goal is the creation and conservation of spotted owl habitat. A recent assessment noted that the most immediate need within areas protected for their late successional and old-growth forest characteristics known as Late Successional Reserves was to reduce the risk of uncharacteristic loss of existing late and old structured stands that are imminently susceptible to insect attack or wildfire (USDA Forest Service 2002).

BP at specific flame length classes was estimated by simulating 50,000 wildfires under burn conditions that replicated recent severe wildfire events on the Forest. BP represented the likelihood that a 90-m resolution pixel would burn assuming randomly located ignitions within the study area. The simulation outputs were summarized for selected management designation, conservation reserves, and ecological conditions. These outputs included: (1) Average BP, (2) average flame across simulated fires, and (3) average size of fire generated by an ignition within the polygon. Also summarized was the ratio of fire size to BP, a new metric termed “source-sink” ratio. This ratio is a new way to describe the spatial topology intrinsic to a fire regime.

KEY FINDINGS

BP estimates can be made for a greater diversity of fire regimes and fire environments than ever before

Several improvements were made to the BP modeling framework as a result of this project. There is now greater flexibility in the inputs required to run the BP models, which allows users to incorporate much more natural variability into simulations. As a result, BP maps can be estimated and used for risk analysis on almost any fire-prone North American landscape. The improvements to the model resulted from not only the scientific experiments described above, but also from cross-pollination of the three BP models.

In particular, two new features were added to Randig-FlamMap to more accurately estimate BP: (1) user-specified non-random ignition patterns and (2) the ability to use weather conditions (wind speed and direction) that can vary from one burn period to the next. The functionality of Burn-P3 was also greatly increased. In addition to greatly optimizing the computation, two major features were added to the program: (1) the ability to calculate and report fire behavior outputs such as fire intensity and flame length (as in Randig-FlamMap), and (2) a “batch” function that is useful for conducting multi-scenario studies. Batch functions greatly facilitate the multi-scenario approach required to appropriately evaluate the importance of environmental factors on BP.

Enhancements were also made to the operational risk analysis framework. Several new functionalities were added to ArcFuels to facilitate the processing of BP outputs for risk analyses. These included new computer code to automate the calculation of expected net value change (i.e., risk) so that the probable effects of fuel treatments on resources of concern can be measured. To facilitate the processing of large landscapes for risk analysis, new formats for Randig-FlamMap outputs were created.

In spite of complex fire-environment relationships, it is possible to isolate the influence of individual environmental factors.

The spatial likelihood of fire is controlled by a large number of environmental factors, all of which may interact with one another. As such, isolating the effect of individual factors on BP is a difficult task. The use of heuristic artificial landscapes allowed us to examine to what extent the effect of environmental factors could be disentangled. This was fairly straightforward for extremely simple landscapes and inputs. However, certain combinations of simplistic inputs resulted in highly complex “emergent” patterns that could not be simply explained by looking at the individual effects of their components.

The generation of complex BP patterns from simple inputs on artificial landscapes underscored the challenge of isolating the role of environmental factors on real landscapes. Confronting and disentangling the inherent complexity required sophisticated statistical techniques. Structural equation modeling, a technique that allows the specification of highly complex model “structure,” allowed us to evaluate the “unique” contribution of a given environmental factor when taking into account the effect of all other factors affecting fire.

We gained valuable insights into the manner in which the combinations of factors generate landscape fire patterns. For example, we found that the effect of variable weather, which, in conjunction with fuel configuration, played a much larger role than anticipated in the spatial patterning of BP. Although these techniques get much closer to isolating the role of individual environmental controls in real landscapes, they also provide greater appreciation for the strong inter-dependence among these factors. In fact, our results suggest that categorizing fire regimes as either fuels- or weather-dominated may be a gross oversimplification of complexity.

We have a better understanding of the factors contributing to BP and fire regimes.

This project deepened our knowledge of the environmental controls on BP, and more generally on fire regimes. Empirical studies of fire-environment relationships are typically limited by the short temporal extent (<100 years) of fire history and environmental data. The BP simulation modeling approach successfully complemented and enriched the body of empirical studies of fire-environment relationships.

Simulations on artificial landscapes that used highly simplistic inputs showed that combinations of these simple inputs (e.g., fuel patterns and ignition patterns) can yield highly complex BP patterns. In some cases, interactions among two or more input variables produced unanticipated BP patterns due to complex topological dependencies among fire

spread factors. Although we were surprised by some of these patterns, we were able to fully explain them.

Disentangling the environmental controls on BP requires distinguishing between direct and indirect effects of factors. For example, topography (elevation, slope, and aspect) influences BP via the direct effects of slope on fire spread, but also can indirectly influence BP via its influence on ignition patterns, vegetation (fuel) distributions, and weather (fuel moisture conditions). The experimental design for the real landscapes (Table 2) involved randomizing or homogenizing a single input factor at a time. This design allowed us to see the direct influence of topography as distinct from any indirect influence topography might have through ignition or fuel patterns.

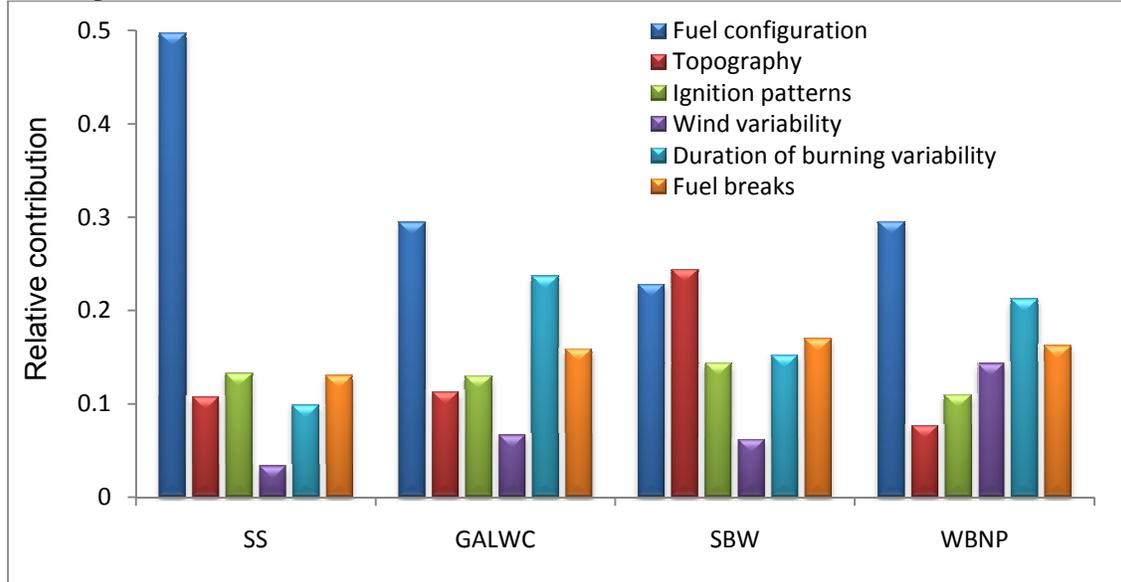
Results from this project highlighted the importance of environmental variability. We found that when we incorporated variability in the environmental inputs to the BP models (e.g., duration of burning, weather, ignitions), fire patterns were significantly altered on all the landscapes. In fact, the aforementioned improvements that we made to the BP models were a direct result of our greater appreciation of the impact of environmental variability.

Some inputs are disproportionately more important than others for BP mapping, but this varies among fire environments

The comparison of the four study area landscapes greatly improved our ability to “profile” fire environments for the purpose of BP and risk mapping. Not only did the inputs differ substantially among the study areas (Table 1), but the relative importance of these inputs on BP patterns differed (Figure 1). The relative importance of the environmental factors provides information about the controls on fire regimes and about the unique characteristics of the landscape itself. However, we must also emphasize that, even if an environmental factor contributes little to the overall patterns in BP across the landscape, it could play a crucial role in altering BP at the local scale, such as around communities (Beverly et al. 2010).

Fuel configuration is the most dominant factor contributing to BP patterns in all study areas except the Selway-Bitterroot Wilderness (SBW), where its steep topography appears to be slightly more important. Although the Southern Sierra (SS) also has very steep terrain, topography may appear to be less important there because the steepest slopes are at high elevations where fuel breaks are also prevalent. Non-burnable fuel breaks have a similar influence on BP patterns across all study areas (13 – 17%). Ignition pattern has a similar, moderate, influence on BP patterns across all study areas (11 – 14%). We were surprised that ignitions did not have a greater influence, but the reason for this is twofold. First, the spatial patterning of ignitions tends to be in areas where fuel breaks and/or less flammable fuels are prevalent, limiting the spread and size of fires (and thus BP). Second, the effect of ignition location is overwhelmed by the effect of long burning periods leading to very large fires; this is especially the case in WBNP. Wind directionality, which influences fire shape, has a negligible effect ($\leq 7\%$) in all study areas except WBNP where it contributes substantially (14%). We speculate that this is related to the potential for very large fires resulting from a combination of long burning periods and large “core areas” of flammable fuels.

Figure 1. The relative importance of model inputs on BP patterns for the four real landscapes.



Despite these differences among the four landscapes, some generalities can be made. First, spatial topology—that is, the spatial relationships in the fire environment—is extremely important in estimating BP. This was highlighted by the high relative contribution of spatial configuration of fuels across all four landscapes: at the scale of landscapes, fires are strongly controlled by the size and shape of fast-burning fuels and, conversely, of slow- or non-burning land cover. This point underlines the need for accurate spatial fuels data. Second, risk analyses need to acknowledge that fires can spread across large areas. That is, the fire environment of a certain location may have pervasive and far-reaching “downwind” effects. Furthermore, where fires can and do become large, ignition patterns become less relevant in landscapes, as short distance differenced in their specific location is dwarfed. Third, to be widely applicable across a diversity of landscapes, BP models need to account for many sources of variability. For example, even though wind variability may not have a large influence on BP patterns in one landscape (e.g., SS), it may be critical for another landscape (e.g., WBNP).

The effect of environmental factors on BP depends of the spatial scale of observation

A fire–environment relationship observed at one spatial scale may not hold at another (Parisien and Moritz 2009) and several studies have firmly established that controls on fire are scale-dependent (e.g., Cyr et al. 2007). To this end, we investigated how the scale of observation affects the relationships between BP and environmental variables in the Southern Sierra landscape. Results are reported in Parks et al. (“Scaling effects on fire likelihood in a southern Sierra Nevada landscape,” in review). We found that interactions among variables further complicated the scaling analysis, and therefore we needed to account for these interactions. In particular, we evaluated the extent to which topography interacts with fuels and ignitions on fire likelihood. Results illustrated how the relationship between fire likelihood and topography can obscure the effect of other factors that influence

fire ignition and spread. For example, on this landscape, a simple analysis would lead to the incorrect and nonsensical conclusion that ignitions are negatively related to fire likelihood. However, once we controlled for elevation, and the effect of other environmental factors was considered, this relationship between BP and ignition density became ecologically meaningful.

Generally, results reinforced that if one arbitrarily selects a single spatial scale of study from a continuum of meaningful scales, “the observer imposes a perceptual bias, a filter through which the system is viewed” (Levin 1992). Our results show that there may be more important information contained at the scale of a spatial neighborhood than that held at the scale defined by the raw data (e.g., pixel-based analyses) when explaining BP patterns. That is, spatial topology is an important consideration in explaining BP patterns, which is justified considering that fire is a contagious process. It is therefore important to examine the potential impact of spatial scale when initiating analyses of fire-environment relationships. We caution against transposing the reported scaling relationships to other landscapes because no two landscapes have the same spatio-temporal environmental characteristics and estimates of BP are extremely site-specific (Turner et al. 1989). Although our results are not transposable, the analysis framework we used can be applied elsewhere.

Spatial estimates of BP enable quantitative risk assessment for fuels management

BP combined with quantitative measures of loss/benefit provides a robust framework for planning fuels treatments at the landscape scale (Ager et al. 2007). The application of quantitative risk assessment tools to analyze the potential resource impacts from wildfire has been advocated in many recent papers. The anatomy of wildfire risk and a conceptual framework for its calculation was outlined by Finney in 2005. Specifically, risk defined as the product of: (1) the probability of a fire of a specific intensity i , $p(F_i)$, and (2) the resulting value change in financial or ecological value (ΔV_i).

$$Risk = \sum(p(F_i) * \Delta V_i)$$

The product is the *expected net value change*. When only losses are considered, risk is the *expected loss*. Wildfire risk can be mitigated by manipulating the probability of fire, $p(F)$, the probability of a fire of a specific intensity given that a fire occurs, $p(F_i)/p(F)$, or the effect of the fire on a specific value, ΔV_i .

Federal land management agencies have been slow to adopt risk-based approaches, largely because the modeling tools and framework for wildfire risk analyses have heretofore been lacking. We enhanced ArcFuels to facilitate risk analysis with a number of new features. We also added a section to the ArcFuels manual/tutorial on risk analysis.

The application of risk analysis to wildfire issues was made possible by Finney’s development of a minimum travel time (MTT) fire spread algorithm which makes it computationally feasible to simulate thousands of fires and generate BP and intensity maps over large areas (e.g. > 2,000,000 ha). The algorithm is embedded in a number of research and applied fire modeling applications (FlamMap, FSPro, FSIM) and extensive testing has shown that this algorithm can replicate large fire boundaries in the heterogeneous landscapes that typify much of the western U.S. These modeling developments have set the stage for operational application of wildfire risk analysis. What is now lacking are case studies to

demonstrate the calculation and interpretation of risk metrics in the context of fuels planning.

As part of this project and in cooperation with the Western Wildlands Environmental Threat Assessment Center (WWETAC), we conducted four case studies to advance the application of wildfire risk assessment to develop treatment strategies and evaluate fuel treatment alternatives. These four case studies are described below.

Wildfire Risk at the National Forest Scale. This case study applied risk assessment methods on the Deschutes National Forest to examine wildfire threats to conservation reserves in the context of forest scale planning (Ager et al. in prep). Specifically, we demonstrated the application of risk assessment tools to examine wildfire risk among and within an array of conservation reserves and other land management designations on the Deschutes National Forest. In particular, we posed three questions: (1) What is the relative wildfire risk among the array of management designations on the Forest; (2) Are specific conservation reserves contributing to wildfire risk and to the loss of other highly valued resources?; and (3) How do fuel treatments reduce wildfire risk when conservation reserves are excluded from treatment? Variation in BP among and within different land designations was relatively large, exhibiting large spatial differences in wildfire likelihood on the landscape. For instance, among 130 different forest-urban interface areas, average BP varied more than orders of magnitude from 0.0001 to 0.02. Average BP for nesting sites used by the endangered Northern spotted owl averaged 0.004 and varied from 0.001 to 0.01. The spatial topology inherent in BP estimates allowed sources and sinks of wildfire to be identified, and these affected the spatial pattern of risk on the demonstration landscape. In particular, conservation areas that were located on the lee side of non-burnable fuels such as lava flows and lakes showed markedly reduced BP. The case study also demonstrated the importance of fire intensity as a risk factor and the ability for the risk assessment framework to account for it. Most conservation reserves had lower *overall* BP than the surrounding managed forest, but they had higher BP for fires of *high intensity* than the general forest matrix. This work demonstrated the application of BP modeling for quantitative risk assessment for fuels management on federally-managed lands in the U.S. The analyses quantified spatial variation in BP that is useful in prioritizing fuels treatments and guiding other wildfire mitigation activities. The work also illuminated the potential conflicts between biodiversity conservation efforts on federally-managed lands and the high wildfire risk on fire-prone landscapes.

Case Studies on Risk Analysis for Fuel Treatment Planning. Two case studies demonstrated the use of risk analysis to measure the effects of fuel treatments on large trees, structures, and wildlife habitat (Ager et al. 2007, 2010). Formal risk analyses were combined with wildfire simulation methods to provide a framework to quantitatively measure performance of the fuel treatments. The first case study was on the Mt. Emily wildland-urban interface (WUI), Wallowa Whitman National Forest, the other on the Five Buttes planning area, Deschutes National Forest. The Mt. Emily study used BP and a risk framework to analyze treatment strategies on a typical WUI in eastern Oregon. The *expected* loss of large trees was determined for when fuel treatments were designed to reduce risk to structures rather than to reduce risk to large trees and old growth stands. The study highlighted tradeoffs between ecological management objectives on wildlands and the protection of residential structures in the urban interface. The Five Buttes case study examined the effects of different treatment intensities (area treated) on wildfire risk to Northern spotted owl habitat. Both case studies used BP and risk analysis to quantify off-

site fuel treatment effects that have not been analyzed in previous landscape fuel management studies.

Application of Wildfire Risk Analysis to Examine Carbon Flux from Fuel

Treatments. This case study examined the effect of fuel treatments and wildfire on expected carbon flux at landscape scales using a risk framework. (Ager submitted, Cathcart et al. in press). We determined expected landscape-scale carbon dioxide emission offsets from fuels management activities. The study is part of the West Coast Regional Sequestration Partnership (WESTCARB) and is developing the methods on the 80,000 ha Drews Watershed of the Fremont-Winema National Forests in Lake County, Oregon. A number of recent studies have suggested short- and long-term carbon benefits from fuel treatments. Specifically, stand-level models show that fuel treatments reduce potential fire severity compared to non-treated stands, and therefore reduce carbon lost from emissions (it is assumed that a portion of the carbon removed by treatments is fixed in building materials, etc.). While informative, these analyses have limitations, including: (1) Wildfire probability is usually assumed to be 1.0, and thus carbon benefits are conditional on a fire burning the stand (i.e., no fire, no benefit) whereas actual wildfire probabilities from long term records for the western US average about 0.004 (1960 – 2006); and (2) The carbon benefits outside the treatment units from reduced BP and severity are not considered despite ample empirical and experimental evidence that offsite treatment effects are substantial for both wildfire likelihood and intensity. Our quantitative estimates of landscape BP that consider the spatial topology of fire represent an improvement over these stand-level analyses.

MANAGEMENT IMPLICATIONS

Managers and researchers alike will benefit from the broad body of knowledge generated by this project concerning the estimation of BP and its application in risk analyses. Spatial datasets were created for five study areas during the course of this project. Long-term planning of fire and fuels management will be enhanced by a better understanding of the factors that control BP. Understanding these controls is particularly important given current national efforts to mitigate the negative impacts of large wildfires. For example, there may be situations and landscapes where localized changes in fuels (i.e., fuel treatments) are not as effective as ignitions management. The results of this project will also encourage the integration of complex yet crucial topological inputs to long-term planning. That is, BP models can help us understand how changes in one part of the landscape affects fire ignitions and spread in other “downwind” parts of the landscapes. We argue that in many situations, the fire environment is too complex to “eyeball” the range of potential ways a fire may reach a certain point (e.g., community) on the landscape. Furthermore, our results will help pinpoint the situations or areas where fuel and ignition management may be useful in reducing risk, as well as the areas where the potential for mitigation is minimal.

In addition, our analysis of the relative importance of environmental factors on BP (Figure 1) could prove useful for prioritizing investments in acquiring, developing, or improving data. For example, the high relative importance of “fuel configuration” found for the Southern Sierra landscape suggests that investments in high quality fuels data are particularly

justifiable there. For other landscapes, such as the Selway-Bitterroot, results suggest that special attention to carefully mapping the non-burnable fuel breaks could reap rewards. The relative importance of “duration of burning” for the Gila-Aldo Leopold Wilderness and Wood Buffalo NP suggests that a focus on weather analysis to determine the conditions under which fires slow down or stop on their own might prove worthwhile. Furthermore, while the relative importance of ignitions was not overwhelming, it was notable in all of the study areas, suggesting that the creation and incorporation of spatially variable ignitions data would be valuable for any landscape undergoing BP analysis.

The outputs from quantitative risk analysis can be used to design and locate fuel treatment strategies. This approach builds on the Fire Regime Condition Class (FRCC), as FRCC is reflected in all of the risk factors that go into a quantitative risk analysis. The advantage is that risk analysis provides a quantitative measurement across a landscape that acknowledges the spatial topology of fire frequency, fire intensity, values-at-risk, and response functions of those values. The outputs and from risk analysis can be used to design fuel treatment strategies that target specific risk factors (BP, hazard) and spatial interactions with values-at-risk. The risk framework acknowledges the spatial topology of fire frequency, fire intensity, values-at-risk, and the effect of fires on values.

RELATIONSHIP TO OTHER RESEARCH

This project leveraged the completed JFSP #03-4-1-04, Developing an analysis and planning framework for district level fuels treatment planning (PIs Ager and McGaughey), which provided specialists and planners with an integrated set of landscape analysis tools for simulating alternative treatment scenarios through time and capturing the differences between various scenarios in terms of potential fire effects, insect mortality, visual impacts, financial outcomes, and other attributes. Improvements to ArcFuels facilitated the BP simulations, especially linkages to FlamMap. New features in Arcfuels provide the capability to perform risk analyses with FlamMap and FSIM outputs. The work in this project led to the development of new ArcFuels training manuals (see www.fs.fed.us/wwetac/arcfuels).

The improved ability to model BP reliably for the purposes of risk analysis that has resulted from this project has provided a foundation for the National Fire Decision Support Center (NFDSC). The NFDSC is improving risk models and protocols to provide real-time decision support for large fires that considers incident specific fire behavior, values-at-risk, performance, and decision analysis. The improvements in BP modeling and demonstration of risk analysis accomplished in this project benefit NFDSC’s efforts and in this way, will contribute to better risk-informed strategic and tactical decisions for wildland fires. Project staff and the NFDSC teamed up to produce the a national wildfire risk assessment for the Wildland Fire Leadership Council (Calkin et al. 2010).

The BP raster data that are generated using the Large Fire Simulator (FSim) developed for use in the Fire Program Analysis (FPA) effort, are comparable to those generated in this project. FSim uses historical weather data and current landcover data for discrete geographical areas (Fire Planning Units - FPU) and simulates fires in these FPU. Using these simulated fires, an overall BP and marginal BP at four fire intensities (flame lengths)

are returned by FSim for each 270m pixel in the FPU. This project used a smaller pixel size and more ignitions.

The demonstration case study conducted for this project is related to a recently created WWETAC research focus on wildland fire risk framework. The purpose of this research focus is to provide a consistent framework that can be used at a variety of different planning scales and that is tied to the Cohesive Strategy as mandated by the 2009 Flame Act. Case studies, like the Deschutes NF, are being used to demonstrate use of a wildland fire risk framework for an increasing diversity of values-at-risk (e.g., carbon, old growth, structures, habitat) at different planning scales (e.g., project, district, Forest, region).

The BP approach is most suitable at the spatial extent of landscapes (10^5 to 10^7 ha) whereas statistical climate gradient methods are appropriate for modeling fire likelihood for regional to global spatial extents (Krawchuk et al. 2009, Parisien and Moritz 2009). BP mapping is not appropriate beyond a certain spatial extent because the inputs and parameters to the models do not hold true for all parts of the study area. Climate gradient methods are appropriate at broader extents, producing statistical relationships between fire activity (presence/absence, area burned) and environmental controls (mainly climate-based) that exert their influence over large areas. Although BP and climate gradient models are designed for different spatial extents and incorporate different types of input data, there is an overlap in spatial extents at which they can be compared. A comparison of fire likelihood estimates are useful not only to provide some form of validation, but are also informative in outlining environmental controls that dominate fire regimes, regardless of spatial scale. This type of comparison would further deepen our knowledge of the controls on fire regimes.

FUTURE WORK NEEDED

Burn probabilities, as described here, represent an estimate of relative fire likelihood given a certain degree of natural variability in weather patterns, ignition density and ignition patterns. However, this project did not address the temporal (year-to-year) variability in fire likelihood, which may be much greater than the spatial variability in BP within a landscape. A logical next step in the study of BP thus consists of comparing inter-annual variability (mean BP) to the landscape-level spatial variability. Such a study would deepen our understanding of the sources and consequences of environmental variability on BP. From a practical standpoint, it could result in more effective management strategies. For example, fuels treatments may not be the most effective strategy for mitigating risk when extreme weather events create inter-annual variability in BP that is much greater than the intra-annual spatial variability. A more effective strategy in such a situation may be to focus on the management of ignitions.

Although substantial progress was made during the course of this project toward defining and identifying wildfire risk factors (e.g., BP and intensity), future efforts need to focus on the spatial pattern of values-at-risk (e.g., carbon, old growth forest, structures, habitat) and the development of response functions that represent the vulnerability of those values to fire.

Our results show the importance of fuel configuration in all study areas. As previously stated, quality fuels data are vital to producing a realistic BP grid. However, we observed large disparities between LANDFIRE fuels data and previously developed fuels data (Keane et al. 2000) for the GALWC study area, particularly in non-forested vegetation types. These disparities caused drastically different BP patterns, underscoring the need for high-quality fuels data for modeling BP.

Several features could be added to BP models to either improve BP estimates or to facilitate future research investigations. The first is incorporating spatial variability in burning conditions or fuel moisture values. Although other versions of FlamMap allow fuel moisture to be “conditioned” based on previous weather and topographic influences, the 64-bit version of Randig-FlamMap that we used in this project did not allow us to spatially vary these values. Instead, fuel moisture was homogeneous across the landscape and for every fire. Including the ability to condition fuel moistures or to input fuel moisture grids (potentially created elsewhere) would be a significant improvement to Randig-FlamMap. Considering that fire season length varies with elevation, fuel moisture input grids also could be used to represent landscape conditions at different points in the fire season, thereby incorporating these patterns for landscapes with large elevational gradients. Burn-P3 can incorporate some spatial variation in fire weather (and hence burning conditions) through the delineation of weather zones that use distinct weather streams for input, but these are usually coarse scale (e.g., ecoregion scale). Adding the ability for Burn-P3 to represent topographic influences and effects of solar radiation on burning conditions might improve its performance in topographically complex landscapes.

Incorporating spatial variability in wind direction and wind speed is another logical improvement to both Randig-FlamMap and Burn-P3. Programs such as Wind Wizard account for the effect of topography and create high resolution wind surfaces. As a result of this project, Randig-FlamMap was improved to allow for temporal variability in wind direction and wind speed for multi-day fires through the “weather scenario file,” but these wind fields are homogeneous across the landscape for each burning period. Similarly, within a geographically defined weather zone, wind fields are spatially homogeneous in Burn-P3. With an ability to select a high resolution spatial wind grid based on a probability distribution from weather station data, the BP models would then incorporate both spatial *and* temporal variability in winds.

The ability to save the ignition locations used in one BP simulation so that they can be input to subsequent simulations would be a useful feature for investigations using BP models. Burn-P3 has been recently updated to include this feature but the current version of Randig-FlamMap stochastically simulates ignition locations. If two simulations are executed with exactly the same input parameters, the resulting BP grids will be different, with the magnitude of this difference depending on a variety of factors such as the number of fires simulated and the size of the landscape. Although the difference is generally small, it can confound comparisons of alternative simulation scenarios (e.g., alternative landscapes). The ability to exactly replicate ignition locations among simulations would reduce ambiguity when comparing BP from alternative scenarios. This feature could also reduce the number of simulated fires (decreasing computation time) that are necessary when conducting simulation experiments for research purposes.

Finally, a feature allowing Randig-FlamMap to produce a GIS file (e.g., a shapefile) of each simulated fire perimeter would provide an additional and rich dataset for further analysis. Fire perimeters could be used to visually, or even quantitatively, validate model results as well as to more effectively calibrate input parameters. This feature will be added to Burn-P3 in the near future.

DELIVERABLES CROSSWALK TABLE

Proposed Deliverable (Type and ID)	Delivered	Status
Conference/ Symposia/ Workshop 8725 ("Presentation #1")	Parks, S.A., Parisien, M.-A., Miller, C. The most relevant spatial scale of environmental controls on landscape fire patterns in the southern Sierra Nevada mountains, California. Paper presented at U.S. International Association for Landscape Ecology annual symposium. Snowbird, Utah. April 12-16, 2009.	Completed
Conference/ Symposia/ Workshop 8726 ("Presentation #2")	Parisien, M. Environmental controls on the burn probability of a fire-dominated boreal landscape. Paper presented at 4th International Fire Ecology and Management Congress, Savannah GA, December 2009.	Completed
Refereed Publication 7790 ("Journal paper #1")	Parisien, M.-A., C. Miller, A.A. Ager, and M.A. Finney. 2010. Use of artificial landscapes to isolate factors controlling spatial patterns in burn probability. <i>Landscape Ecology</i> 25:79-94.	Completed
NonRefereed Publication 7791 ("Journal paper #2")	Miller, C., M.-A. Parisien, A.A. Ager, and M.A. Finney. 2008. Evaluating spatially-explicit burn probabilities for strategic fire management planning. <i>WIT Transactions on Ecology and the Environment</i> 119: 245-252.	Completed
NonRefereed Publication 8743 ("Technical Report")	Landscape scale burn probability modeling: a comparison of current techniques	In preparation
PhD Dissertation 8727	Parisien, M.-A. 2009. Evaluating controls on wildfires in North America at multiple spatial scales. Ph.D. dissertation filed August 12, 2009; conferred December 19, 2009.	Completed
Model/software/ algorithm 8742	ArcFuels was enhanced with new tools for analyzing BP and performing risk analyses (www.fs.fed.us/wwetac/arcfuels)	Completed

(“Arcfuels v1 and v2”)		
Training sessions* 8728	Workshop: Application of risk analysis for fuels treatment using ArcFuels. <ul style="list-style-type: none"> • Fremont-Winema NF; 2/28/2008; 15 attendees • Missoula, MT; 4/23-4/24/2008; 27 attendees • UC Berkeley; 5/1-5/2/2008; 25 attendees • Portland, OR; 11/2008; 46 attendees • National Forests from Region 1, Missoula, MT; 4/23/2009 - 4/24/2009; approx. 35 attendees • Deschutes and Ochoco National Forests, BLM, Bend, OR; 5/20/2009; approx. 15 attendees • AFE Fire conference, San Diego, CA; 12/3/2009-12/4 2009 	Completed
Dataset 8744 (“Data and BP maps”)	Input and resulting datasets to be delivered to appropriate management agencies and to RMRS data archive.	In preparation
Progress Reports for JFSP xxxx	Three progress reports for JFSP. Delivered in 2007, 2008 and 2009.	Completed
Final Report 2446	Final report outlining findings and deliverables.	Completed
-----Additional Products-----		
Additional Deliverable (Type and ID)	Delivered	Status
Poster 7272	Miller, C. Evaluating approaches for mapping burn probabilities, Joint Fire Sciences Program Governing Board visit, Lubrecht Experimental Forest, Montana, September 14, 2006.	Completed
Poster 7274	Miller, C., Parisien, M.-A., Finney, M., Ager, A.A. Evaluating approaches to mapping burn probability: phase I. Poster presented at the 2 nd Fire Behavior and Fuels Conference, March 26-30, 2007, Destin, FL.	Completed
Conference/ Symposia/ Workshop 7785	Parisien, M.-A. Environmental controls on the distribution of wildfire at multiple spatial scales. Paper presented at the Ecological Society of America conference, San Jose, CA, August 2007.	Completed
Poster 7787	Parisien, M.-A., Miller, C. The factors controlling burn probability in a large boreal landscape. Poster presented at the Ecological Society of America conference in Milwaukee, WI, August 2008.	Completed
Conference/ Symposia/	Miller, C., Parisien, M.-A., Ager, A.A., Finney, M. Evaluating spatially-explicit burn probabilities for	Completed

Workshop 7789	strategic fire management planning. Paper presented at the First International Conference on Modelling, Monitoring and Management of Forest Fires 2008 in Toledo, Spain, September 2008.	
Poster 7788	Parisien, M.-A., Miller, C., Ager, A.A., Finney, M., Moritz, M., Krawchuk, M. The factors controlling burn probability in a large boreal landscape. Poster presented at The '88 Fires: Yellowstone and Beyond conference in Jackson, WY, September 2008.	Completed
Poster 8739	Parks, S.A., Parisien, M.-A., Miller, C. Factors controlling burn probability in the southern Sierra Nevada mountains, California. Poster presented at California Association of Fire Ecology Pacific Coast Fire Conference. San Diego, California, December 1-4, 2008.	Completed
Invited Paper/ Presentation 7786	Parisien, M.-A. Evaluating controls on wildfires from landscape to global spatial scales. Talk presented at the USGS Menlo Park campus, June 2008.	Completed
Poster 8729	Parks, S.A.; Miller, C.; Parisien, M.A.; Finney, M.A.; Ager, A.A. Factors controlling burn probability in three western US fire prone landscapes. Poster presented at Association for Fire Ecology Conference, Savannah, GA, December 2009.	Completed
Invited Paper/ Presentation 7786	Parisien, M. Environmental controls on the burn probability of a fire-dominated boreal landscape. Talk presented at University of California, Berkeley, Geospatial Innovation Facility GeoLunch, Berkeley CA, December 2009.	Completed
Refereed Publication * 8740	Ager, A.A., Vaillant, N., Finney, M.A. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management. 259: 1556–1570	Completed
Training Manual* 8730	Fuel Treatment Planning with ArcFuels: Part 1: Grid Data. 60 p. Available online at www.fs.fed.us/wwetac/arcfuels	Completed
Training Manual* 8731	Fuel Treatment Planning with ArcFuels. Part II: Designing and Modeling Fuel Treatments with FVS 16 p. Available online at www.fs.fed.us/wwetac/arcfuels	Completed
Training Manual* 8732	Fuel Treatment Planning with ArcFuels. GIS Appendix. 66p. Available online at www.fs.fed.us/wwetac/arcfuels	Completed
Training Manual* 8733	Fuel Treatment Planning with ArcFuels: General Appendix. 16 p. Available online at www.fs.fed.us/wwetac/arcfuels	Completed
NonRefereed	Cathcart, J., Ager, A.A., McMahan, A.M, Finney, M.A.	Completed

Publication * 8735	(in press). Carbon offsets from fuel treatments using a risk analysis. Proceedings of the 2009 National Silviculture Workshop, Boise, ID. June 15-18. Rocky Mountain Research Station, General Technical Report RMRS-P-X	
NonRefereed Publication * 8736 (Abstract)	Ager, A.A, Finney, M.A, 2009. Application of wildfire simulation models for risk analysis. Geophysical Research Abstracts, Vol. 11, EGU2009-5489, 2009 EGU General Assembly 2009.	Completed
Refereed Publication * 8741	Ager, A.A., Finney, M.A., McMahan, A. Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. Submitted to <i>Natural Hazards and Earth Systems Science</i> .	In review
Refereed Publication 8737	Parisien, M.-A.; Parks, S.A.; Krawchuk, M.A.; Flannigan, M.D.; Gowman, L.; Moritz, M.A. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. Submitted to <i>Ecological Applications</i> .	In review
Refereed Publication 8738	Parks, S.A.; Parisien, M.-A. ; Miller, C. Scaling effects on fire likelihood in a southern Sierra Nevada landscape. Submitted to <i>International Journal of Wildland Fire</i> .	In review
NonRefereed Publication * xxxx	Ager, A.A., Reger, A. Wildfire risk to human and ecological values in Oregon and Washington and prioritization of fuels treatment opportunity. Gen Tech. Rep. PNW-GTR-XX. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station	In preparation
Refereed Publication * xxxx	Ager, A., Vaillant, N., Finney, M. Spatial patterns of wildfire risk factors and transmission among human and ecological values on a national forest in the Pacific Northwest, USA	In preparation
Refereed Publication xxxx	Parks et al. Factors controlling burn probability in three western US fire prone landscapes.	In preparation
Refereed Publication xxxx	Parisien et al. Environmental controls on the burn probability of a fire-dominated boreal landscape	In preparation

* Deliverable produced in cooperation with Western Wildlands Environmental Threat Assessment Center (WWETAC)

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