FINAL REPORT

Programmatic Analysis of Fuel Treatments:
from the landscape to the national level

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ROI: return on investment
VA: value added, AKA, V
NPS: National Park Service
SEKI: Sequoia and Kings Canyon National Park
GLAC: Glacier National Park
BICY: Big Cypress National Preserve
SHEN: Shenandoah National Park

iii. Keywords

Programmatic scale, landscape scale, National analysis, planning, preparedness, wildland fire budgeting, fuel treatment, economics, decision support, spatial planning, appropriation.

iv. Acknowledgements

Many thanks to our cooperators and collaborators in the Department of Interior including the National Park Service, the Bureau of Land Management and the U.S. Fish and Wildlife Service for their support and collaboration. While we believe that this research shows substantial advancement in the science of budgeting and planning that directly applies at all levels, it rests on a history of work from many dedicated individuals. They held a vision of a more robust process that would provide sound, defensible budgeting along with full support for integrating ecosystem values with the traditional priories on life and property.

Abstract

The importance of cost effective fuel treatment programs has appeared consistently in federal directives (FLAME ACT, National Cohesive Strategy, U.S Department of Interior Office of Policy Analysis) as a priority. Implementing cost effective fuel treatment programs requires a spatially explicit and integrated systematic approach that can be applied to the landscape, program and national scale. This research directly addresses this need and the 'Programmatic scale' question of Task 1 of the JFSP Project Announcement FA-FON 14-5. The objectives of this study were three-fold. The first objective was to generate cost effective fuel treatment programs at the landscape scale and their impact on the preparedness program. The second objective was to quantify the interrelationship between the fuel program and preparedness program by budget alternative at a landscape scale to provide mangers with the fuel and preparedness budgets that achieve the highest return on investment (ROI) for any combination of budgets. The third objective was to form cost effective national and regional fuel treatment programs based on the data collected from the landscape analysis that considers national and regional policies. Using four ecologically distinct study sites across the United States the research demonstrates how a landscape level analysis is applied to a national analysis to generate a national budget that promotes the highest return on investment meeting the objectives of this research. The landscape analysis consists of identifying fuel treatments that promote the highest ROI while taking into account policy guidance for managing vegetation and fuels. The treatment locations are identified at each study site for a set of budget alternatives. The value added for each budget alternative was estimated by comparing the pre-treatment and post-treatment landscapes. The post-treatment landscape for each budget alternative was used to determine the effects on preparedness at increasing preparedness budget alternatives. The data was recorded as discrete combinations of fuels and preparedness budgeting. These discrete data points were applied to a programmatic analysis. A smooth three-dimensional surface was created using translog production functions (production functions) unique to each study site. A gradient method was applied to the production functions to increase the budget along the direction of the

highest investment returns. A national analysis was generated by combining the preparedness and fuels budget reallocations determined from the program analysis for each of the individual study sites to create national budget allocations for each study site for each of the fuels and preparedness programs that maintain the landscape consideration for policy guidelines. The resulting output can guide managers to cost-effective budget allocation for wildland fire programs that yield the greatest value added without disrupting the workforce and the capital equipment allocations. The research demonstrates several key findings that include: the use of a common performance metric of ROI that can be applied from the landscape, to a program and to a national scale while reflecting DOI policy; the generation of programmatic valued production functions for fuels and preparedness as well as funding gradients to guide budget decisions along the surface; and lastly an extension of these methods that demonstrate how a national budgeting application can be generated.

1 Objectives

This project directly addresses the 'Programmatic scale' question of Task 1 of JFSP Project Announcement FA-FON 14-5. The research demonstrates how cost-effective fuel treatment programs can be generated at the landscape scale, contribute to spatially explicit and integrated with fuel programs across the nation to form a national or regional program budgeting system. A program analysis was generated by including considerations for both the fuels and preparedness programs and quantifying the relationship between these budgets. The program analysis can then be used to information a national analysis. The project demonstrates how fuel treatment programs in the context of preparedness programs respond to changes in funding levels on a landscape and nationally and potentially regionally. The objectives of this research were as follows:

Objective 1: Cost effective fuel treatment programs at the landscape scale
We will locate fuel treatments across the landscape to generate the greatest net benefit. Landscape fuel treatments will be modeled by budget level and the economic performance of each is quantified.

> *This objective was met and augmented with preparedness considerations.* We identified fuel treatment locations across four different and diverse landscapes to generate the highest return on investment (ROI)[1] by budget alternative. Further, we quantified how fuel treatments impact preparedness programs for each fuel treatment budget alternative and with increasing preparedness budgets. Maps locating the fuel treatments, summary graphics with respect to value added for both fuel treatments and preparedness budget alternatives and fuel types have been provided in this report. A sample from BICY depicting how rates of spread and intensity were altered by the fuel treatments is included.

[1] ROI is an abbreviation for "return on investment" and as used in this analysis, it denotes the value added or return as compared with its cost of production or funding.

Objective 2: Cost effective program at the landscape scale:

This objective was added and met. During the study, it became evident that it was necessary to quantify the interrelation between the fuel program and preparedness program by budget alternative at a landscape scale to provide mangers with the fuel and preparedness budgets that achieve the highest ROI for any combination of budgets. Methods and summary graphics depicting this relationship are included in this report.

Objective 3A (Formally Objective 2A): Forming cost effective national and regional fuel treatment programs

We will construct a national program by importing results of the landscape analysis in objective 1. The national program will promote cost effective fuel treatments across all landscapes and relevant budget levels. Cost effectiveness will be demonstrated nationally by budget level and accounted for by region.

This objective was met and augmented with preparedness considerations. Using the results from objective 2, we combined the preparedness and fuels budget reallocations from the program analysis to construct a national program that promotes cost effective programs across all landscapes and relevant budget. We structured the national program to ensure that changes to national budgets mitigate potential disruption to landscape programs. This methodology can be applied to a regional or national scale. A summary graph has been included in this report that shows the impact of alternative budgets on performance.

Objective 3B (Formally Objective 2B): Implementing and Analyzing Alternative Fuel Treatment Policies:

We build upon objectives (1) and (3A) to implement national policies that often accompany appropriations language. Federal appropriation language can include requirements or initiatives focusing funds on three kinds of fuel treatments; life and property, resilient landscapes, and maintenance treatments. We will formulate and implement a national allocation system that implements such policies and analyze their impacts at multiple scales.

This objective was met. This study used a structured elicitation and valuation process that included resource management officials from each study site to identify the resources (human and natural) that were positively or negatively affected by fire. The fire-induced value changes at different intensities/severities for each of these resources were explicitly quantified and the return interval for the resource vegetation types that are sensitive to time since last fire/treatment was included. The changes in intensity/severity and fire return interval on the post-treatment landscapes was captured in the post-treatment set of resource values capturing the impact of these policies. These value changes are applied from the landscape to the national scale. These values reflect national prioritization as implemented at the landscape level. Policy initiatives within the DOI's Office of Policy Analysis (USDOI 2012) were also addressed by using a common performance metric (ROI) across all values and across a diverse geographic set of study sites, by guiding cost-effective decisions and budget allocations and by guiding decisions that will promote ROI without unduly disrupting programs and workforce.

2 Background and Purpose

The importance of fuel treatment programs is reflected in the federal budget and in legislation. For example, in the President's 2015 draft budget, resilient landscapes are allocated 30M (United States Office of Management and Budget 2015). The importance of maintenance treatments was highlighted in the 2015 budget "degradation of fuels on lands previously treated should be minimized". Cost effective fuel treatment programs appear consistently as a federal priority as demonstrated by the FLAME ACT (2009) that requires "A system to ensure that the highest priority fuels reduction projects are being funded first" and the Healthy Forest Restoration Act (2003) that makes hazardous fuels reduction its first priority. Subsequently, the National Cohesive Strategy documents (Wildland Fire Leadership Council 2011, 2012 and 2014) each address the importance of a systematic approach to fuel treatments in the context of restoring and maintaining fire resilient landscapes as a national management objective. Key obstacles to this objective were identified in the U.S Department of Interior Office of Policy Analysis (2012) that reviewed current fire programs and the wildland fire literature. An important obstacle identified in the report is the inability to address the effects that fire management variables have on changes to the value of the underlying natural capital.

While this research is focused on the planning and budgeting for fuel treatment programs, we performed the analysis in context with the preparedness programs at the landscape and national scales. The interactions between the programs affect the planning and budgeting at the landscape scale and the national budget allocations for fuels depend on the relative productivity of the preparedness program. For example, fuel treatments for hazardous fuel reduction typically reduce fire intensity and spread rates of future fires (Stratton 2004). Reduced spread rates improve the ability of the firefighting operation to contain fires successfully in initial attack, and lower intensities often reduce expected losses across the full range of resources at risk. Fires contained in initial attack are typically much less costly than those that spread. Attempts to control fire risk often rely on these two interrelated programs (fuels and preparedness programs) that require a similar set of resources, including crews, equipment, and planning.

3 Methods and Results

The methods and results are designed and organized by scale. The data and analytical process used to generate the fuel treatment and preparedness analyses at the landscape scale is described first, followed by the program analysis that is used to support the national analysis. The equations and surfaces generated from the program analysis are used to inform the national analysis. Figure 1 provides an overview of the steps involved in each analysis that transition from the landscape scale to the national scale. Each analysis level and the corresponding methods and results are described in further detail below.

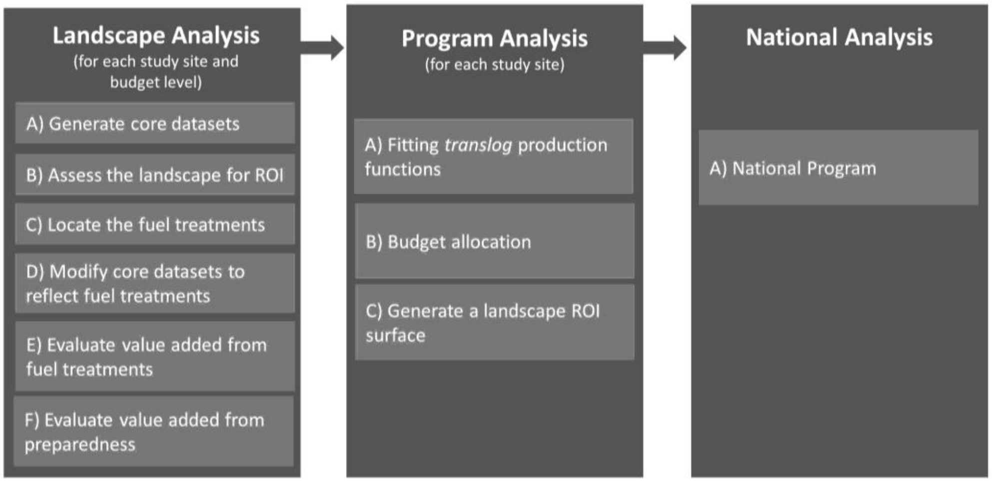

Figure 1. Overview of steps for modeling cost effective fuel treatments at the landscape, program and national scales.

3.1 Study Sites

Four study sites (figure 2) were selected to build and demonstrate the regional, program and national analyses reflecting a diverse set of landscapes. The study sites are situated in the west and southeast regions of the National Cohesive Strategy and include: Sequoia and Kings Canyon National Parks (SEKI), Glacier National Park (GLAC), Big Cypress National Preserve (BICY), and Shenandoah National Park (SHEN)[2]. BICY is located in southern Florida between Miami and Naples and the 729,000 acre landscape is comprised of tropical and temperate plant communities including; pine forest, mixed grass prairie, cypress forest, mixed hardwood hammocks and marsh (Big Cypress National Preserve, 2010). SEKI is located in the western Sierra Nevada mountain range in California. The parks comprise almost 900,000 acres and contain sequoia groves, montane forest, subalpine woodlands, oak woodlands and chaparral (Sequoia and Kings Canyon National Parks, 2011). GLAC is over one million acres in size and is located in the northwest corner of Montana along the spine of the Rocky Mountains bordering Canada. The landscape is comprised of moist coniferous forest, dry coniferous forest, barren and sparsely vegetated rock and ice and small sections of deciduous forest, and wet meadows and fens (Glacier National Park, 2010). SHEN is located in the Mid-Atlantic region of Virginia, north of Washington D.C. straddling both the North

2 We had originally proposed use two other study sites, one from the northeast and one from Okefenoke. These proved to be unviable due to data restrictions and personnel changes. In collaboration with our federal cooperators the study sites of Glacier National Park and Shenandoah National park were substituted to retain the regional and ecosystem diversity originally envisioned.

and South Appalachian mountain range. The 200,000 acres park is comprised mainly of chestnut oak and red oak forest with smaller sections of tulip poplar, cove hardwood, spruce-fir forest as well as small areas of grasses, sedges and rushes (Shenandoah National Park, 2017)

Figure 2. Location of study sites (identified in orange) across the United States.

The study sites were selected to represent a diverse set of environmental conditions, resources, vegetation and values. Figure 3 represents the difference in the composition of fuel models available for treatment at each study site.

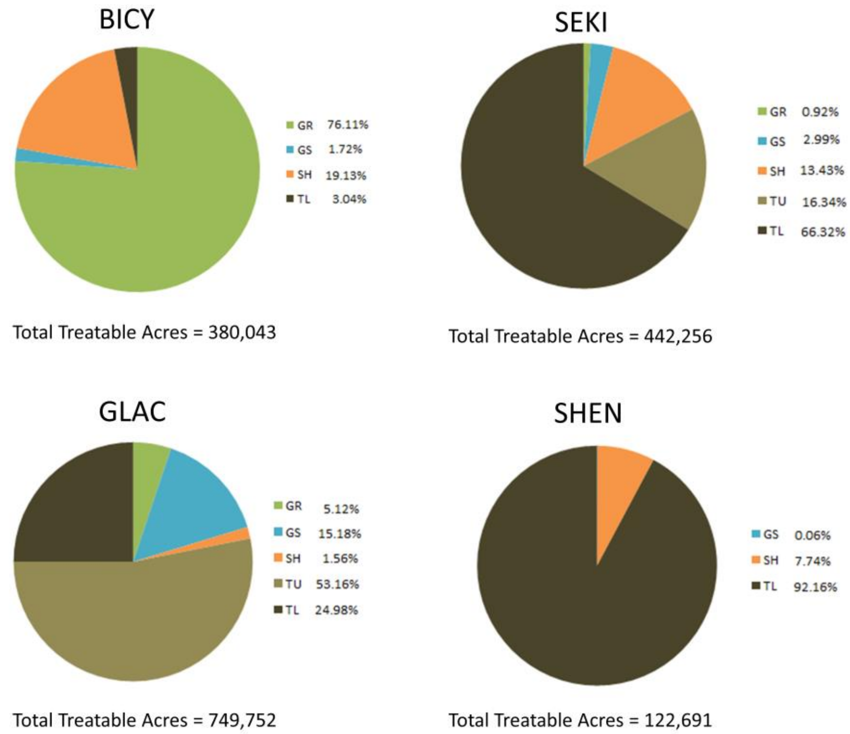

Figure 3: Proportions of treatable fuels (Scott and Burgan) at each study site. GR represents the grass fuel model numbers, GS represents the grass-shrub fuel models, SH represents the shrub fuel models, TU represents the timber-understory fuel models and TL represents the Timber-litter fuel models.

3.2 Landscape Analysis Methods

Four core datasets were assembled for each of the study sites to generate a pre-treatment landscape to estimate the potential to add value to the landscape through fuel treatments (either for hazardous fuels reduction or ecosystem benefit). Treatment locations were selected for each budget alternative at locations where fuel treatments had the highest potential to add value. For each budget alternative, a post-treatment landscape was generated that reflected the effects of the fuel treatment. The value added for each budget alternative was estimated by comparing the pre-treatment and post-treatment landscapes. The post-treatment landscape for each budget alternative was used to determine the effects on preparedness. Increasing preparedness budgets were also evaluated against each post-treatment landscape for each study site to assess the impact of preparedness budgets.

3.2.1 Generating Required Data Sets:

We used four core datasets to generate the landscape analysis. The first data set represents the spatial fire behavior for each study area. The second data set estimated the value change of fire effects and fuel treatment costs. The third data set reflects the temporal analysis that informed the valuation (values can depend upon time since last fire or treatment) and estimated the ignition density (used in burn probability calculations). The fourth dataset was comprised of the inputs required for the preparedness calculations.

1) Spatial Fire Behavior Data Set:
We used fire simulator software (FlamMap5) to estimate the fire behavior characteristics across each study site's landscape (Finney 2006) using a constant weather and fuel moisture condition (Appendix D). The fire modeling landscape was generated using LANDFIRE (2014) data and augmented with Park specific data where available. A consistent 90th percentile weather condition was used across all study areas and was estimated using data provided by the National Predictive Service Program (PDS). Wind speeds were adjusted using the 'probable maximum 1-minute speed' in the wind gust estimating table developed by Crosby and Chandler (2004) based on the guidance of Stratton (2006). FlamMap's geospatial outputs of spread rate(m/min), fire intensity (BTU/ft2), maximum spread direction (degrees) and flame length (m) were used as the fire behavior inputs into the model.

2) Fire Effects on Values and Fuel Treatment Costs Dataset:
We used the Marginal Attribute Rate of Substitution (MARS) valuation system (Rideout et al. 2008, Rideout et al. 2014a and b) to estimate the relative marginal values (RMV) of fire effects on resources and property on each study site. In MARS, fire effects on value are explicitly a function of fireline intensity and ecosystem condition as shown in Rideout et al. (2014a).

RMV = RMV(fireline intensity/severity, ecosystem condition, fire affected resource).

We used three steps to estimate RMV's. Using a structured elicitation process that included resource management officials from each study site, the resources (human and natural) whose values are positively or negatively affected by fire were determined. Second, the fire-induced value changes at different intensities/severities for each of these resources were explicitly quantified. Third, the return interval for cover types who's RMV is sensitive to time since last fire/treatment was determined as treatment effectiveness degrades in these study areas. Each RMV was spatially located on the study sites. A raster cell containing multiple fire affected resources will have multiple RMVs. For these cells, the RMVs were summed to reflect the net value of the fire on that cell.

Fuel treatment costs are key component of determining return on investment (ROI). Fuel treatment costs vary extensively depending upon scale, cover type, ecosystem condition (maintenance vs. restoration), type of treatment (prescribed burning, chemical and mechanical), broad fuel types (such as grass like, tree like and shrub like), accessibility and region. Relative fuel treatment cost reflecting these different conditions were obtained from local planners for the study sites. The treatment costs were applied spatially and combined with the RMVs to estimate the fuel treatment ROI for each cell.

3) Temporal Dataset:
Fire history information including ignition locations and fire perimeters where obtained for each study site. The ignition locations were used to support estimates of ignition probability (using ArcGIS 10.1) for each raster cell and were used internally within the model in burn probability calculations (Rideout and Wei, 2013). The fire perimeter polygons were converted to rasters to generate a ‘time since last fire’ input.

4) Preparedness Datasets
Preparedness analysis inputs included eliciting the amount of time a fire can burn before reaching its escape size from fire management specialists. Resource arrival time for each cell on the landscape to its nearest dispatch location was estimated using a national cost surface supplied by the National Park Service and ESRI’s ‘Cost Distance’ tool. The post-treatment rate of spread estimated by FlamMap5 was used for each study site. Loss producing cells were generated from the RMVs.

These four core datasets were processed using STARFire (Rideout et al. 2017) to simulate burning conditions and calculate the expected value added from burning for each raster cell and the effects of the treated surface on preparedness.

3.2.2 Establishing the budget alternatives:

The FY2014 fuel treatment budget and preparedness budget was provided by NPS for each study site. The preparedness budget alternatives where expanded from current at 30%, 50% and 70% and decreased from current at 30%, 50% and 70%. The current budget was included and a zero budget was dubbed the baseline (Table 1A). The maximum preparedness budget (plus 70% of current) was used as the maximum fuel treatment budget alternative. This was converted into an acre budget by cell size (240m x 240m) and then monetized to a dollar budget. For this reason, the maximum fuel treatment dollar budget may not match the maximum preparedness dollar budget for each study site exactly. The maximum fuel treatment budget was then reduced by 80%, 60%, 40% and 20%. The current budget and the baseline were included (Table 1B).

Table 1A. Preparedness budget alternatives by study site.

	Preparedness Budget ($)						
Study Site	-70%	-50%	- 30%	Current	+ 30%	+50%	+70%
SEKI	533,188	888,646	1,244,104	1,777,292	2,310,480	2,665,938	3,021,396
GLAC	104,744	174,573	244,402	349,145	453,889	523,718	593,547
BICY	267,959	446,598	625,237	893,195	1,161,154	1,339,793	1,518,432
SHEN	116,976	194,961	272,945	389,921	506,897	584,882	662,866

Table 1B. Fuel treatment budget alternatives by acres and dollars for each study site.

	Fuel Treatment Budget							
	Acre Budget				Dollar Budget ($)			
	SEKI	GLAC	BICY	SHEN	SEKI	GLAC	BICY	SHEN
Current	1,751	114	51,624	313	532,746	7,839	394,383	58,400
20%	1,993	982	62,014	612	599,108	117,535	346,048	129,937
40%	3,886	1,765	123,630	1,167	1,206,037	235,421	692,201	262,085
60%	5,466	2,348	204,717	1,765	1,810,270	354,877	1,038,210	394,935
80%	7,017	3,003	282,402	2,306	2,414,361	473,934	1,384,409	528,160
100%	8,896	3,530	287,014	2,975	3,020,283	592,384	1,427,844	660,085

3.2.3 The potential to Add Value through Fuel Treatments:

Each study site's landscape was evaluated for the potential of each raster cell to add value if treated by fuels or through preparedness. The model accounts for fuel treatment to add value by restoring the ecosystem to a more desirable condition through hazard fuel reduction. Such treatments can reduce the burn probability on raster cells that have the potential to harm life and/or property or damage natural or cultural resources. This potential is estimated by probabilities and by the RMVs. The maximum expected value added is equal to the sum of the RMVs on a cell adjusted for burn probability. The maximum expected value added was calculated for each cell on the landscape as in (1) (Rideout et al. 2014b).

$$\sum_m \sum_j P_m * RMV_{(m)j} + \sum_n \sum_j (1 - P_n) * RMV_{(n)j} = MaxExp\,ValueAdded_L \qquad (1)$$

The first part of the equation defines the expected maximum potential value added for protection. We add this to the potential value added for beneficial fire effects and summed across all raster cells. In (1), m = 1 to m raster cells on the landscape (L) with damaging fires, n = 1 to n raster cells on the landscape with beneficial fires and j = 1 to J RMVs present in each raster cell. $P_{(m \text{ or } n)}$ denotes the probability of the m or n^{th} raster cell burning and $RMV_{(m \text{ or } n)j}$ denotes the j^{th} RMV for raster cell m or n. This computation was applied to each cell and processed across the landscape for each study site to quantify the overall fire management condition of the overall landscape. This was performed again after treatment (3.2.5) to estimate the value added from a pattern of fuel treatments.

3.2.4 Locating Fuel Treatments to Promote ROI:

The fuel treatment costs were applied to the potential value added assessed in (1) for each raster cell to estimate the ROI if treated. A 'current' fuel treatment budget was provided for each study site. For each budget alternative, the raster cells that return the highest ROI are identified until the budget is expended. The first three core data sets were updated to reflect the physical effectiveness of the fuel treatments and the landscape was reprocessed (STARFire, 2017). This defined the post treatment simulated burning condition and the post treatment expected value added of burning. The fire history data set was updated with the treatment perimeters. The resulting changes to fire intensity and time since last fire influenced the system selection of RMVs used in the analysis. Post treatment fire behavior data was generated in FlamMap5 by updating the fire modeling landscape (e.g. updated fuel models, etc.).

3.2.5 Evaluating the Fuel Treatment Cost Effectiveness:

The difference between the expected value of the pre (5.2.3) and post treatment landscapes (5.2.4) approximated the value added by a fuel treatment application across the landscape. This was calculated for each budget alternative and expressed as a net benefit (return-cost).

3.2.6 Estimating the Effect of the Fuel Treatment on Preparedness:

The reduction in spread rates resulting from the fuel treatment are assessed in the post treatment landscape (5.2.4). Reduced spread rates improve the ability of the firefighting operation to contain fires successfully in initial attack. This relationship is captured in the Preparedness module in STARFire. STARFire's Preparedness module compares fire spread rates with arrival times for deployed resources using principles of diminishing returns and standards for initial attack success (Rideout et al. 2016). The preparedness module adjusts the initial attack success rate to affect burn probability calculations. This alters the potential value added (5.2.3) and estimates the impact of preparedness for each budget alternative.

3.3 Landscape Analysis Results

Fuel Treatments were identified across the landscape that would promote the highest ROI for each budget alternative. The value added from treating the landscapes was estimated and the impact of the treatments on the range of preparedness budget alternatives was assessed. These results were used to generate the Program Analysis in 5.4.

3.3.1 Locating Fuel Treatments to Promote ROI

The areas on the landscape for each study site that return the highest ROI for each budget alternative are displayed in figure 4. The dark pink areas represent the highest priority acres for treatment as they generate the highest ROI. As the fuel treatment budget increases the potential to treat more acres increases with diminishing ROI (less pink areas on the map). Some areas were excluded from treatment selection and are represented by the dark grey cells in the inset map.

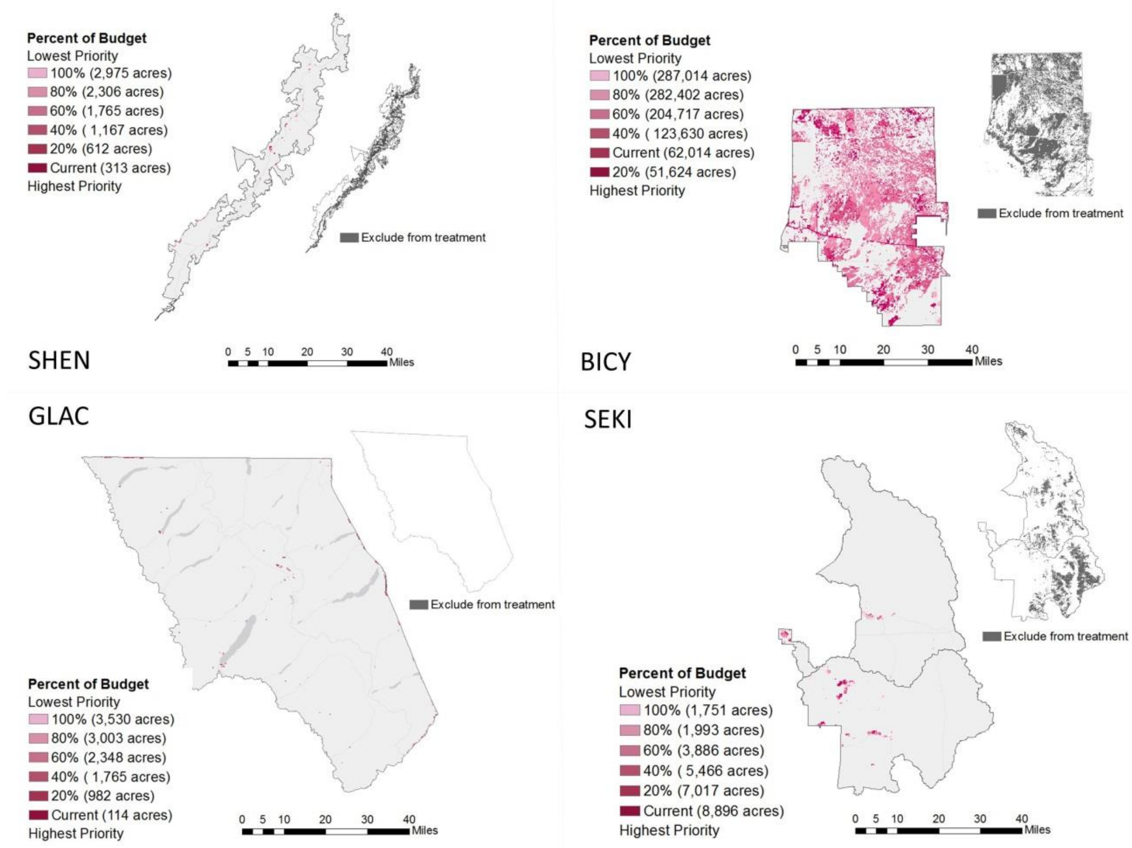

Figure 4. Fuel treatment locations by budget alternative at each study site. Areas that are colored in a darker pink represent areas that are a higher the priority for treatment. The areas colored in grey in the inset maps represent the areas where fuel treatments would not occur and were excluded from the analysis.

The types of fuels selected for treatment varied by study site based on the cellular expected ROI. This included the cell's RMV's, burn potential, relative cost of treatment and treatable fuel model at each study site. The grass fuel model represented the highest proportion of cells treated at BICY, the timber-understory fuel model represented the highest proportion of cells treated at SEKI and GLAC and the timber-litter fuel model represented the highest proportion of cells treated at SHEN (figure 5).

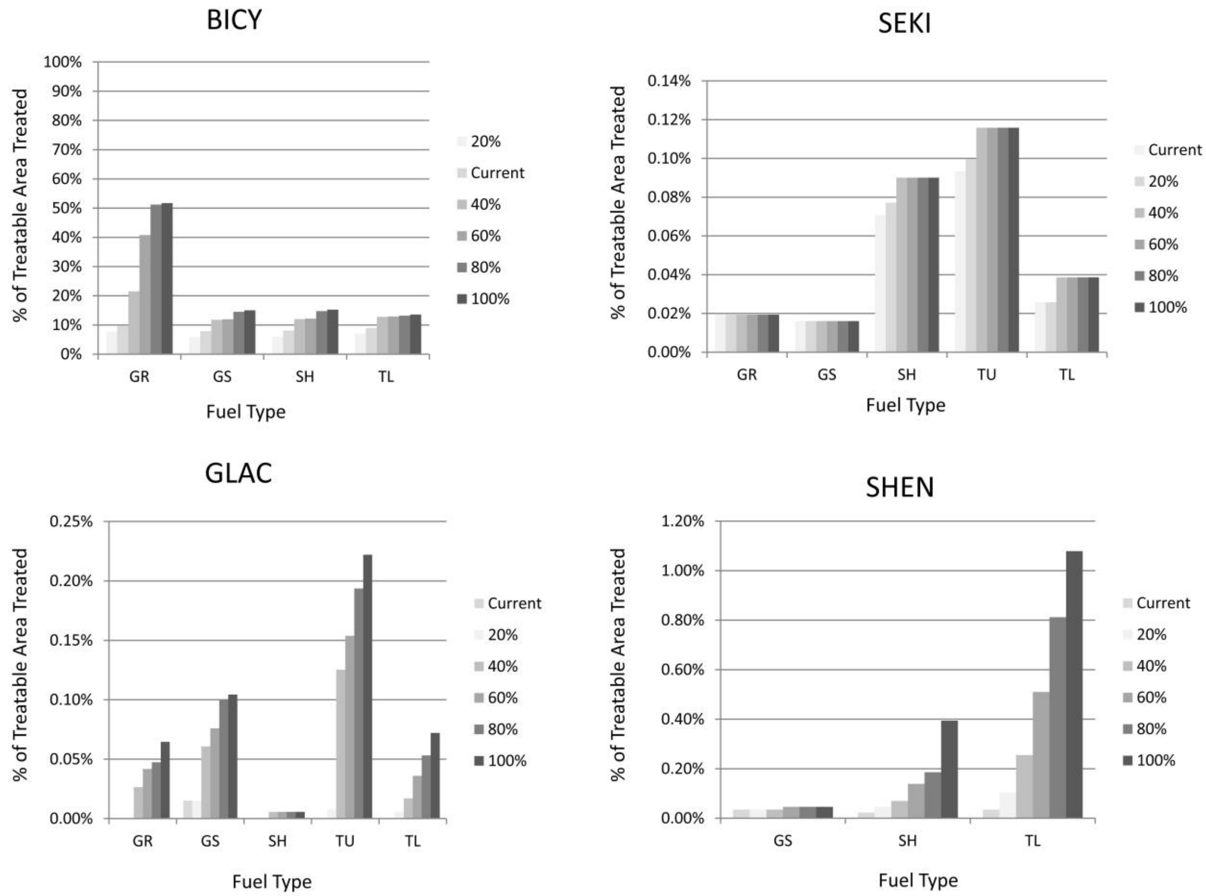

Figure 5. The percentage of treatable area selected for treatment by budget alternative for each fuel type (Scott and Burgan). Fuel models are: GR representing the grass fuel model, GS representing the grass-shrub fuel model, SH representing the shrub fuel model, TU representing the timber-understory fuel model, and TL represents the timber litter fuel model.

3.3.2 Evaluating the Fuel Treatment Cost Effectiveness:

The amount of value added from the treatments was calculated for each budget alternative at each study site (figure 6). BICY generated the most value added, followed by SEKI, GLAC and lastly SHEN.

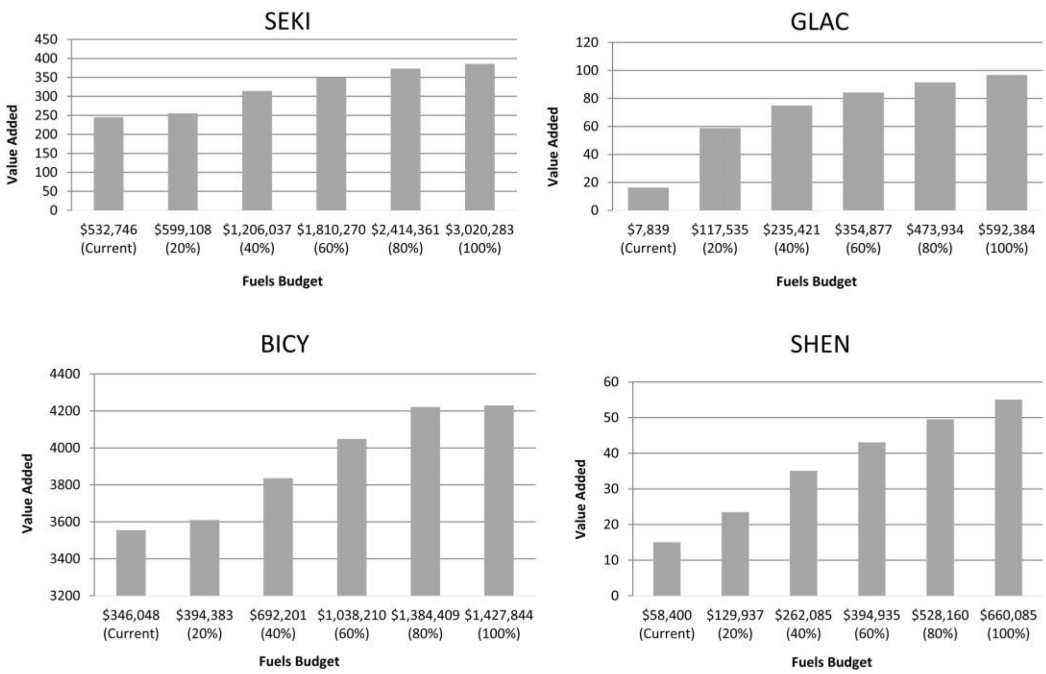

Figure 6. The amount of value added for each fuel treatment budget alternative by study site.

3.3.3 Estimating the Effect of the Fuel Treatment on Preparedness:

The fuel treatments reduced the spread rates and fire intensity across each of the study site's landscapes. These changes are most observable at BICY. Figure 7 compares the baseline landscape rate of spread (m/min) to the post-treatment rate of spread at each budget alternative. Figure 8 compares the pre-treatment flame lengths (feet) to the post-treatment flame lengths at each budget alternative. With increasing fuel treatment budget alternatives, the highest spread rates (darkest blue) and highest flame lengths (dark brown) are reduced across the landscape (lighter blue with respect to diminished rates of spread and lighter orange or yellow with respect to shorter flame lengths) in the treatment areas.

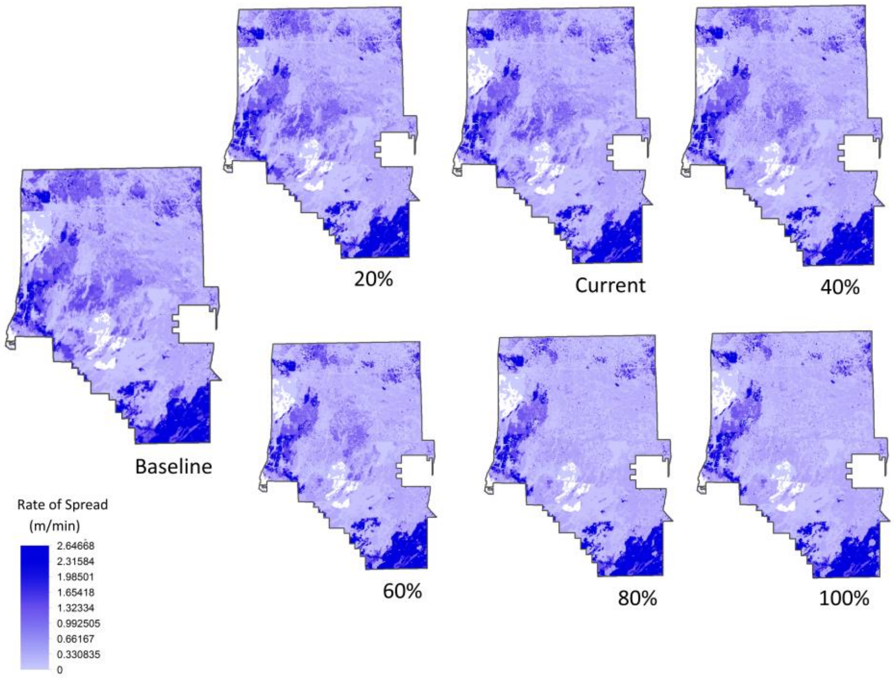

Figure 7. Comparison of the rate of spread at BICY to the post-treatment rate of spread by fuel treatment budget alternative. Areas in darker blue represent higher spread rates.

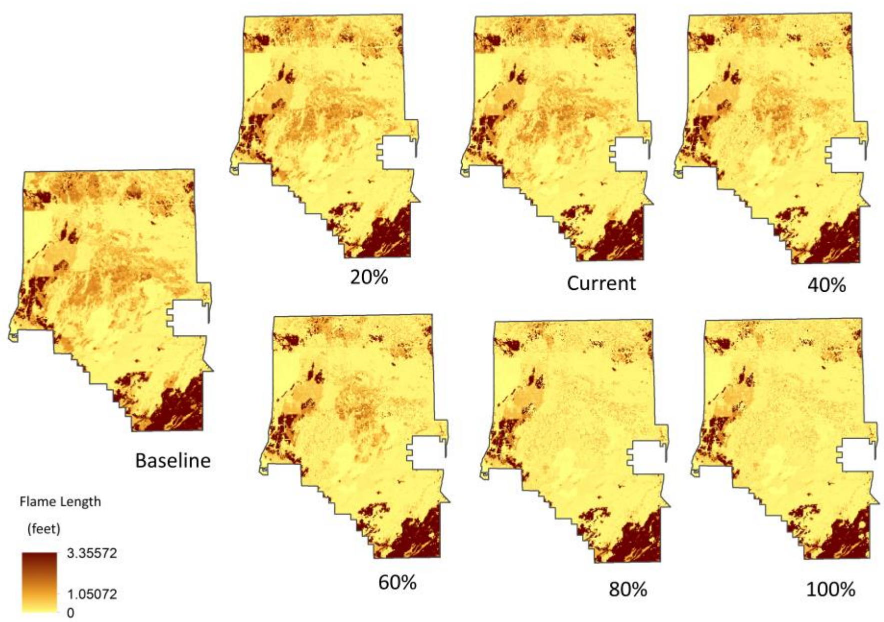

Figure 8. Comparison of the baseline flame lengths (feet) at BICY to the post-treatment flame lengths for each fuel treatment budget alternative. Areas in darker brown represent higher flame lengths and areas in lighter orange and yellow represent shorter flame lengths.

Reduced spread rates improve the ability of the firefighting operation to contain fire successfully in initial attack while lower intensities often reduced the expected losses across the full range of RMVs. The post-treatment landscape for each fuel treatment budget alternative was assessed for its impact on preparedness over the range of preparedness budget alternatives. Figure 9 shows the estimated value added by the preparedness program by preparedness budget alternative for each post-treatment fuel treatment budget alternative. For example, the bar "clumps" are fuel treatment budget levels while moving to a different clump means moving to a different preparedness budget. Figure 9 also demonstrates the interdependence in budgeting and planning between the two programs.

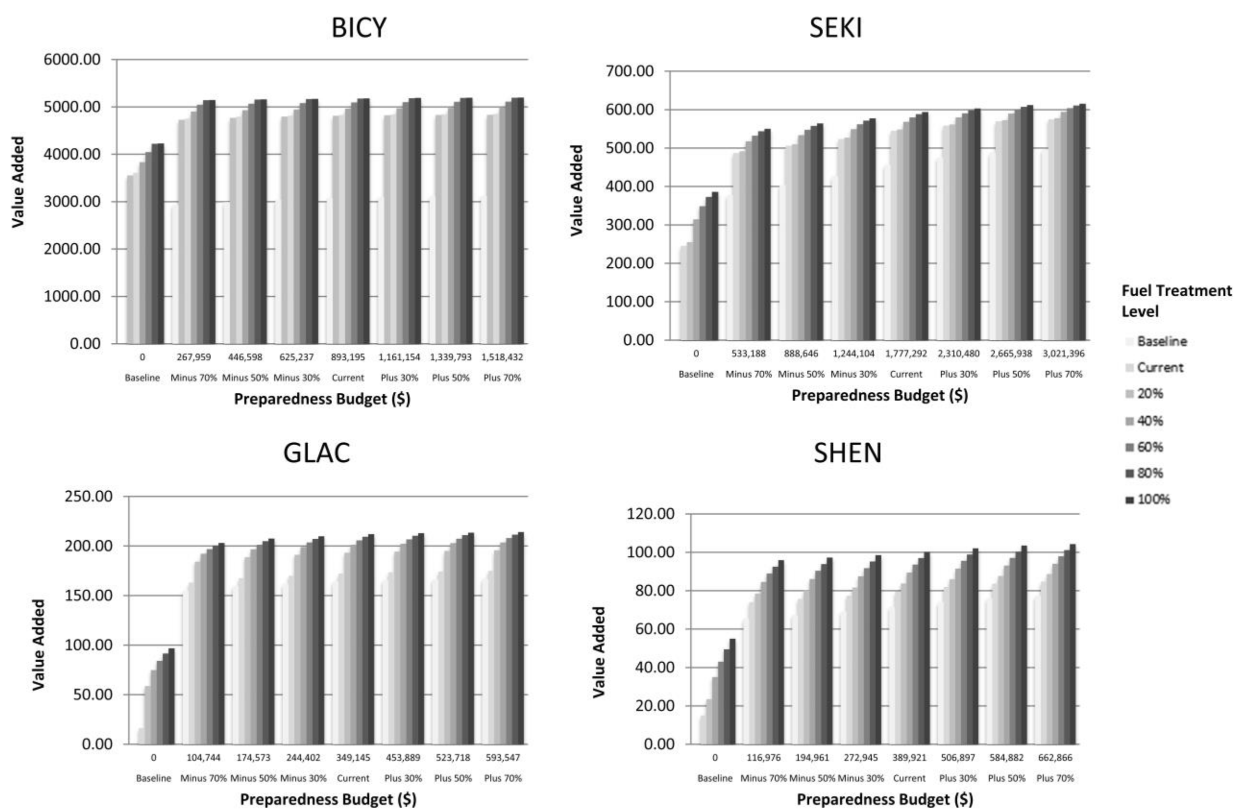

Figure 9. The amount of value added to each post- treatment fuel treatment (bar group) budget alternative by the preparedness program at each preparedness budget alternative.

The value added from each fuel treatment budget alternative (figure 6) and each preparedness budget alternative (figure 9) was recorded as discrete points. An example for SEKI is provided in figure 10. These data were generated for each study site as the basis for the program analysis (5.4)

			Value Added Fuel Treatment Scenarios						
			Baseline	Current	20%	40%	60%	80%	100%
		Fuels Budget =>	0	532,746	599,108	1,206,037	1,810,270	2,414,361	3,020,283
Preparedness Scenarios	Baseline	Preparedness Budget	0.00	245.04	255.42	314.44	348.56	372.92	385.83
	Minus 70%	533,188	377.72	487.17	491.67	517.59	532.64	543.73	550.34
	Minus 50%	888,646	403.68	505.98	510.10	533.91	547.68	557.84	564.02
	Minus 30%	1,244,104	427.08	523.49	527.29	549.33	562.04	571.42	577.23
	Current	1,777,292	455.93	545.27	548.68	568.61	580.04	588.49	593.83
	Plus 30%	2,310,480	474.67	558.52	561.64	579.97	590.42	598.17	603.18
	Plus 50%	2,665,938	488.45	569.57	572.53	590.01	599.93	607.30	612.12
	Plus 70%	3,021,396	496.05	574.73	577.56	594.33	603.83	610.89	615.56

Figure 10. The value added at SEKI for each fuel treatment budget alternative and each preparedness budget alternative.

Figure 10 shows the production of discrete combinations of fuels and preparedness budgeting and how they produce value added to the landscape. This discrete analysis will next be converted into a programmatic perspective by generating a smooth three-dimensional surface using a translog production function technology.

3.4 Program Analysis Methods

We fit a translog production function to the discrete surface (figure 10) to generate a smooth continuous surface that would serve as a foundation for the national analysis. The smooth continuous surface will allow interpolation for any combination of fuels and preparedness budget that the manager or planner might want to evaluate. Next, the path of steepest ascent in value added was estimated across the surface using the production functions in conjunction with a gradient method. The path of steepest ascent means always choosing an increase in fuels and preparedness planning that will generate the steepest increase in value added. The path of steepest ascent was overlaid on the econometrically estimated surface for each study site. The resulting output can easily guide managers to cost-effective budget allocations for wildland fire programs intended to yield the greatest value added without disrupting the workforce and capital equipment allocations by planning unit. The first step was to fit the translog production function.

3.4.1 Translog functions estimating value added from fuels and preparedness programs

There are many different types of production functions available, but we selected the translog production function due to its flexibility and potentially rich economic interpretations. For example, it does not restrict the values of the elasticity of substitution at any point in input space. This importantly allows for fuels and preparedness to take on either substitution or complementary properties as independent but related inputs. We supplied it with landscape (park) level data (as in figure 10) and then applied the R linear model operator to estimate a translog production function for each park. With respect to fuels (F) and preparedness (P), the translog production function has the general form:

$$\ln V_i = \ln A_i + b_{P,i} \ln P_i + b_{F,i} \ln F_i + b_{FP,i} \ln F_i \ln P_i \qquad (1)$$

where *i* denotes the index for each park and for each park *i*, ln denotes the natural log of the associated variable, V denotes the value added, A denotes the constant, P denotes the preparedness program budget, F denotes the fuels program budget, and FP represents the product of the fuels and preparedness program budgets. The terms, $\beta_{P,i,}$ $\beta_{F,i,}$ $\beta_{FP,i}$ are the regression coefficients to be estimated for the preparedness budget, fuels budget, and product of both program budgets, respectively, for each park. These coefficients either reflect different elasticities from the suppression preparedness investment and the fuel treatment investment, or the elasticities from the joint impacts of the two programs.

To directly calculate the value added in the fuel treatment and preparedness programs for park *i*, we express the exponential of equation (1) to directly show the value added in equation as in (2).

$$V_i = A_i * P_i^{b_{P,i}} * F_i^{b_{F,i}} * e^{\ln F_i * \ln P_i * b_{FP,i}} \qquad (2)$$

3.4.2 Budgets by applying the gradient to the valued translog production functions

Using the production functions for each park, we then applied the gradient method that increases the budget along the direction of the highest investment returns starting from the current budget level. We use the gradient method, because it reduces disruption to the current wildland fire program by rewarding proportional performance. Program budgets are increased proportional to the V increase in the fuels and preparedness programs for each park. For example, if the wildland fire program budget were to increase by $100 and the fuels program contributed 40 percent of the increase in the value added, then the budget allocation would increase the fuels program by $40 and the preparedness program by $60. Although somewhat technically involved, this represents a straightforward concept program budgeting and it is pragmatic. It also has inherent qualities of fairness and stability, all guided by value added, that are essential to managing a stable institution as large and complex as the USDOI.

We implemented the gradient method for each park separately by:

1. Calculating the marginal value added from each additional unit of investment from the current budget level.
2. Increase the total wildand fire program budget for park *i* by *x* dollar (a small amount); allocate this additional investment to each fire program proportional to the marginal value added from each program at each park; stop if the upper bound of the total possible budget amount is reached.
3. Go back to step 1) to update the marginal value added from all parks and programs that received a portion of the *x* dollars.

To complete Step 1, we calculated the marginal value added from each increment of budget increase from the current budget level. The marginal value added for a given program for an individual park *i* is given by the partial derivative of the production function [3]for that individual park *i* with respect to that program. The general form of these partial derivatives with respect to fuels and preparedness, based on equation (2), is given by:

$$\frac{\partial V_i}{\partial P_i} = A_i * F^{b_{F,i}} * \left[b_{P,i} * P_i^{b_{P,i}-1} * e^{\ln F_i * \ln P_i * b_{FP,i}} + P_i^{b_{P,i}} * e^{\ln F_i * \ln P_i * b_{FP,i}} * \frac{\ln F_i * b_{FP,i}}{P_i} \right] \tag{3}$$

$$\frac{\partial V_i}{\partial F_i} = A_i * P^{b_{P,i}} * \left[b_{F,i} * F_i^{b_{F,i}-1} * e^{\ln F_i * \ln P_i * b_{FP,i}} + F_i^{b_{F,i}} * e^{\ln F_i * \ln P_i * b_{FP,i}} * \frac{\ln P_i * b_{FP,i}}{F_i} \right] \tag{4}$$

where equation (3) shows the partial derivative of the production function with respect to the preparedness program budget and equation (4) denotes the partial derivative of the production function with respect to the fuels program budget.

We then used Python to construct the path of steepest ascent that will help managers to cost-effectively allocate budgets to the Preparedness and Fuels programs. The fitted production function equations (Table 3) were put into the program and Python processed the partial derivative of each equation for each variable. Then to complete Step 2 of the process, we took the current budget values for each park and scaled them back by 10 percent to start the gradients. After scaling the current budget values back, we increased each park's budget by about $2000. Python allocated the new total budget to each of the programs in proportion to their marginal value added for each park. We had the Python code repeated this process to create the path of steepest ascent until the upper bound of the budget was reached.

3.4.3 Generating a landscape surface

The preparedness and fuel budget combinations from the original data were combined with the fitted value-added values calculated using the estimated production function equations for each study site. We used Matlab to interpolate and extrapolate these values to create a surface of all possible combinations of program budgets and their corresponding values. Using the gradient operation and the gradient method, Matlab charted the preparedness and fuels budget combinations that create the path of steepest ascent starting from the origin (0,0).

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3 While we are using translog production function technology, the dependent variable is value added (V). In this context, it is more properly referred to as a valued production function.

Once this was completed, we had a surface and path of steepest ascent that will easily guide managers for each planning unit to cost-effective budget allocations for wildland fire programs intended to yield the greatest value added without disrupting the workforce and capital equipment allocations.

3.5 Program Analysis Results

Here we show the results of applying the translog log valued production function and the gradient method to the landscape-level data. This application generates a programmatic budgeting and planning perspective that will serve as the foundation for the national analysis.

3.5.1 Estimating a production functions for each study site

Table 2 is a summary table of the coefficients for each of the variables for each park in the form of equation (1), where (1) is SEKI, (2) is GLAC, (3) is BICY, and (4) is SHEN. The results reflect the estimates with significant variables, represented by the asterisks next to the coefficient values. When running estimates that included the interaction variable (lnFP), the summary table for GLAC and SHEN showed that the interaction variable was not significant, leading to its exclusion in the final results. We also chose which variables to include based on whether their coefficients were positive or negative. Preparedness and fuels coefficients were required to be positive. This has to do with their positive relationship to value added. With a one dollar increase in fuels budget, value added will increase. The same can be said for the preparedness budget. We required the coefficient for the interaction variable to be negative since one dollar that goes toward fuels cannot be used for preparedness. The coefficients for the interaction variable for Glacier and Shenandoah National Parks were positive when included, giving another reason for their exclusion from the final results.

Table 2. Summary table of estimated production functions for each park where (1) is Sequoia and Kings Canyon National Parks, (2) is Glacier National Park, (3) is Big Cypress National Preserve, and (4) is Shenandoah National Park.

	Dependent variable:			
	lnV			
	(1)	(2)	(3)	(4)
lnP	0.045^{***}	0.091^{***}	0.017^{***}	0.076^{***}
	(0.001)	(0.007)	(0.0005)	(0.005)
lnF	0.023^{***}	0.024^{***}	0.036^{***}	0.023^{***}
	(0.001)	(0.006)	(0.0005)	(0.005)
lnFP	-0.013^{***}		-0.004^{***}	
	(0.001)		(0.001)	
Constant	6.314^{***}	5.453^{***}	8.532^{***}	4.637^{***}
	(0.005)	(0.040)	(0.002)	(0.029)
Observations	55	55	55	55
R^2	0.970	0.778	0.993	0.810
Adjusted R^2	0.969	0.770	0.993	0.802
Residual Std. Error	0.037 (df = 51)	0.200 (df = 52)	0.015 (df = 51)	0.154 (df = 52)
F Statistic	557.929^{***} (df = 3; 51)	91.246^{***} (df = 2; 52)	$2,576.398^{***}$ (df = 3; 51)	110.624^{***} (df = 2; 52)
Note:				$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

These results were applied in the form of equation (2) for each study site, shown in Table 3.

Table 3. A set of production functions to approximate the value added from different combinations of preparedness and fuels program budgets at the four national parks.

Park Name	Production Function Form
Sequoia and Kings Canyon	$V=552.2495P^{0.045}F^{0.023}e^{-0.013\ln P \ln F}$
Glacier	$V=233.4575P^{0.091}F^{0.024}$
Big Cypress	$V=5074.585P^{0.017}F^{0.036}e^{-0.004\ln P \ln F}$
Shenandoah	$V=103.2342P^{0.076}F^{0.023}$

To validate the production function fit, we compared the observed and estimated (fitted) values for each park (figure 11). The values approximated by the translog production functions were determined to be a good fit for each park.

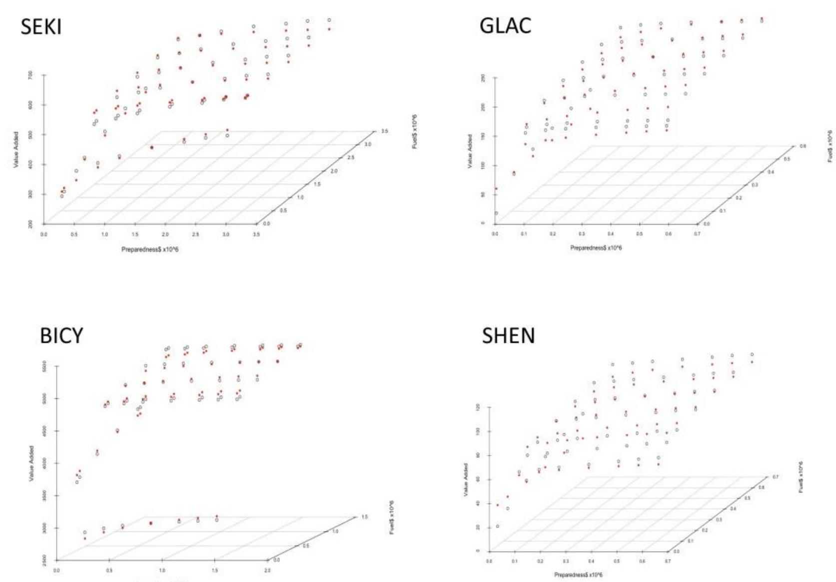

Figure 11. Comparison of the observed original data (black hollow spheres) and the estimated production function (red spheres) for Sequoia and Kings Canyon National Parks, Glacier National Park, Big Cypress National Preserve, and Shenandoah National Park.

We applied the gradient method to each park by using the production functions from Table 3 and the partial derivatives for each program (in each park). We started the gradient at the current program budgets less 10 percent, and expanded them to estimate the paths of steepest ascent. These are illustrated in figure 12.

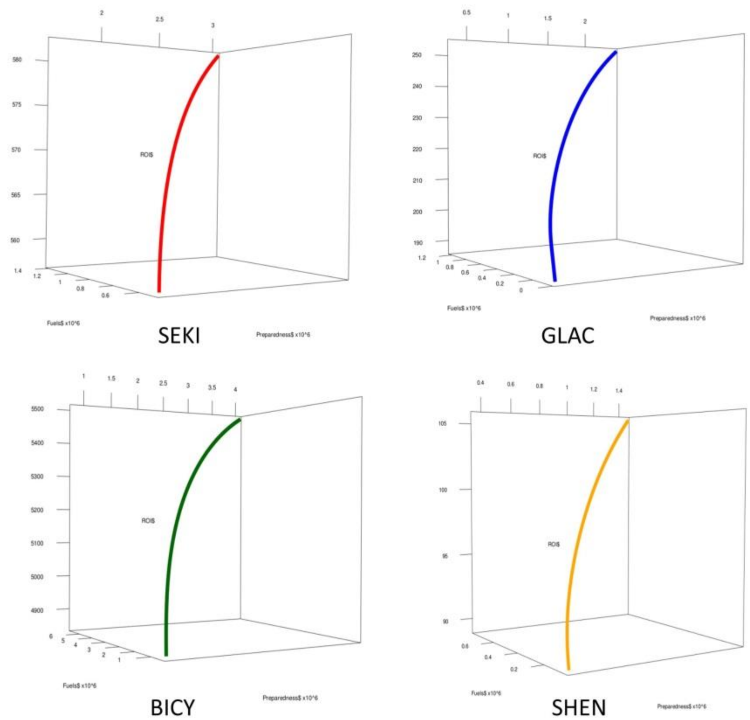

Figure 12. Paths of steepest ascent from, current budget levels, for Sequoia and Kings Canyon National Parks (red), Glacier National Park (blue), Big Cypress National Preserve (green), and Shenandoah National Park (orange). Paths show value added from investing in the preparedness and fuels programs yielding the greatest value added.

3.5.2 Generating a landscape surface

Combining the estimated value-added surfaces from the estimated production functions and the path of steepest ascent for each study site, we created a landscape surface as a visual depiction of all possible combinations of program budgets and outline the budget allocations that yield the greatest value added for managers for each study site.

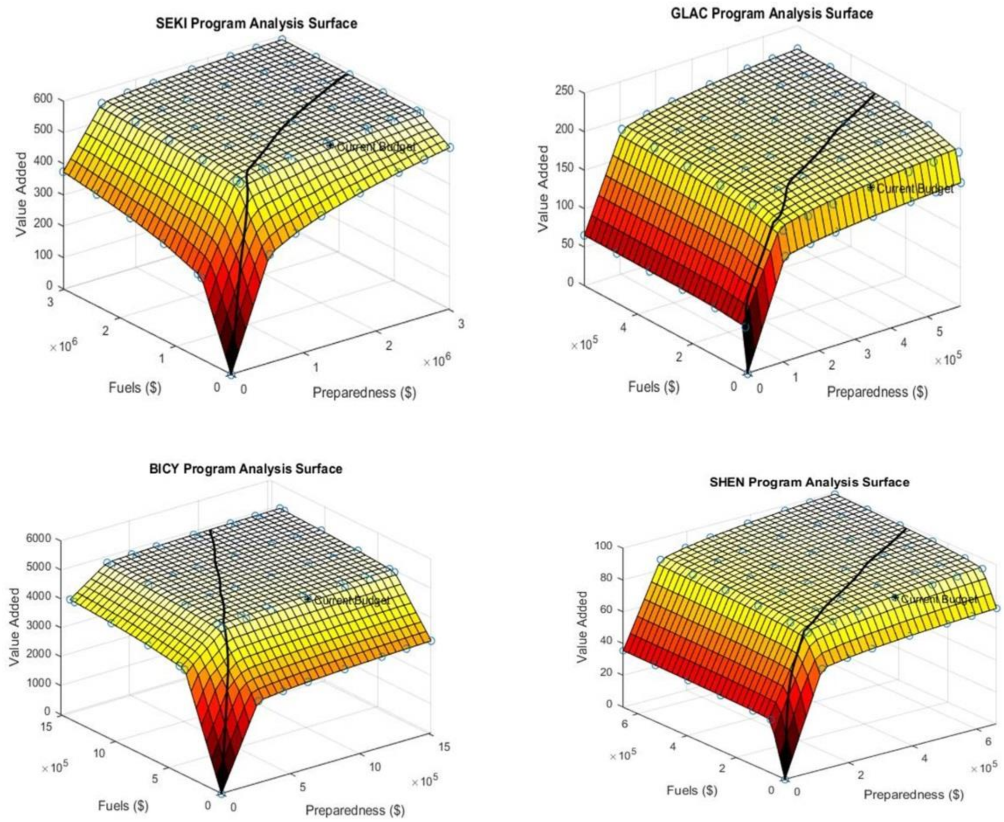

Figure 13. The interpolated surface of all possible program budget combinations based on the estimated production functions and the path of steepest ascent based on the gradient method starting from the origin (0,0), along with current budget, for SEKI, GLAC, BICY, and SHEN.

We applied the gradient method from the origin to generate the path of steepest ascent starting from (0,0) rather than the current budget. If the current budget had been used for the gradient method when combined with the surface, the path of steepest ascent would have gone through the current budget and been cut off by the surface. Figure 14 shows the path of steepest ascent generated from the origin (left line) as compared with the path of steepest ascent generated from the current budget (right line through the current budget). Since the paths and surfaces were created by the same production function the gradient method, they will converge as shown in figure 14 despite different starting points. The illustration represents an approximation such that the paths may not fully converge over the budget ranges displayed.

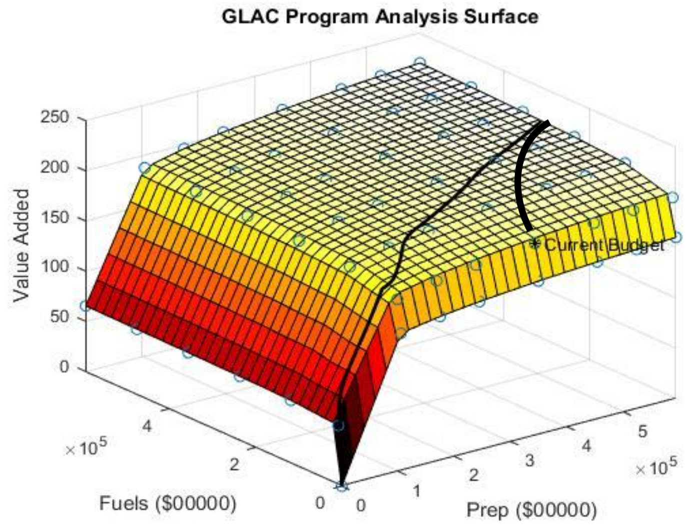

Figure 14. The path of steepest ascent starting at the origin (0,0) (left line) and the path of steepest ascent starting at the current budget (right line) for Glacier National Park.

At the landscape level, managers can use the information gathered above to cost-effectively allocate budgets by program, and in the case of fuels, they also have the information to spatially guide and defend allocations down to the pixel level. This is guided by the common performance metric of ROI. This spatially explicit information also lends itself well to populating fire management plans at the unit level or higher.

3.6 National Analysis Methods

To demonstrate the national program formation and appropriation, we used our four case study sites as a collection to demonstrate how national budget formation and appropriation would be guided by the advances funded by this research. The extension from four units to a large number is direct and requires no further conceptual or technical development. We will directly apply the concepts developed in the program-level analysis so they are not repeated. This will demonstrate how to appropriate funds from the nation to the units and to their programs guided by ROI and without being unduly disruptive to the workforce or to capital allocations. By following our previous development from the cell to the program (as demonstration of program formation) we can see how national program formation is achieved from the landscape level analysis.

We show how any relevant level of national appropriation can be allocated to each program in each study site. To accomplish this, we apply the value data established in the landscape analysis. Here, the program level gradient data are retained showing the gradient for each program by study site and used to form the national analysis. The process is as follows:

1. First, we calculated the addition to value added (V) obtained from each additional budget increment (from current) in each study site and each program. This estimates the increase in V from a small increment in budget.
2. We then increased the total (national) budget by a small increment and allocated it across the fire program in proportion to each program's contribution to the increase in value added. We continued until the upper bound of the total possible budget amount was reached.
3. Go back to step 1) to update the marginal value added from all study sites and programs that received a portion dollars.

We combined the preparedness and fuels budget reallocations from the program analysis for each of the individual study sites to create the national budget levels (Figure 15).

3.7 National Analysis Results: a four-unit demonstration.

Figure 15 shows the preparedness and fuels budget reallocations for each of the individual study sites across different national budget levels. As the total national budget increases, the various study site program budgets increase in proportion to the value added that they contribute.

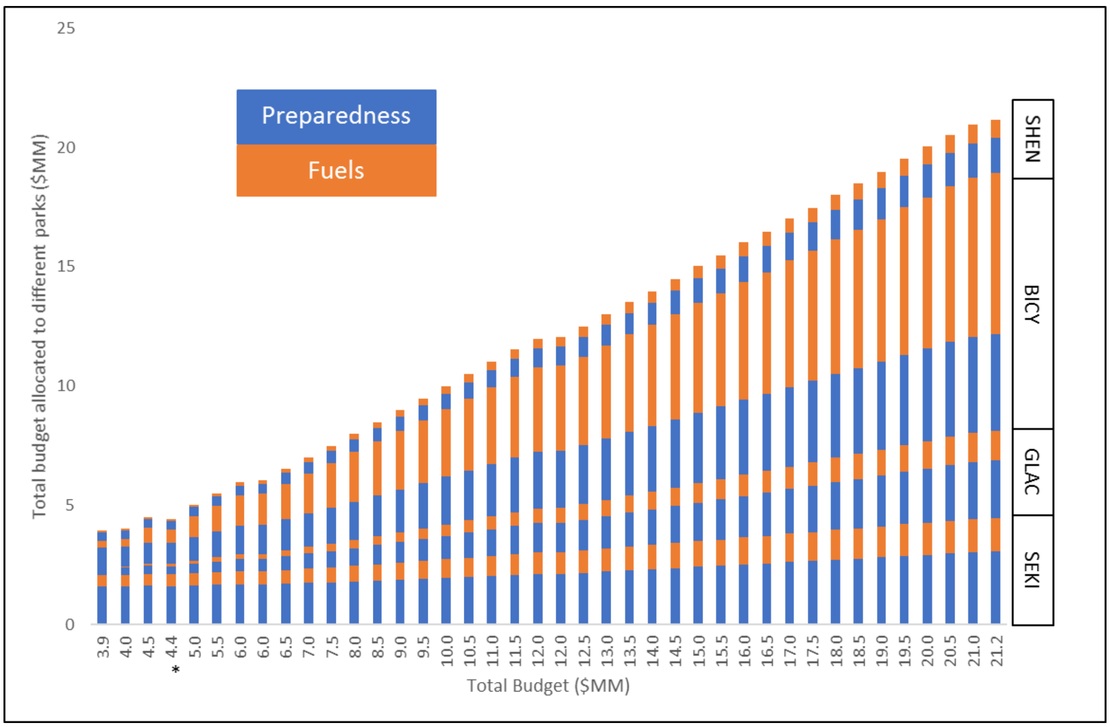

Figure 15. Wildland fire program budget allocations for Sequoia and Kings Canyon National Parks, Glacier National Park, Big Cypress National Preserve, and Shenandoah National Park across different budget levels, with the current national budget being marked by the asterisk.

The current allocation of fuels budgets is $532,746, $7,839, $346,048, and $58,400 and the current allocation of preparedness budgets are $1,777,292, $349,145, $8,93,195, and $389921 for SEKI, GLAC, BICY, and SHEN respectively. For our four-park national demonstration, this reflects a national budget of about $4.4 million.

Based on our analysis, the current budget of $4.4 million should be allocated differently to yield the greatest value added. Instead of the current allocation, the budget would be reallocated with fuels budgets being $490748, $85094, $562907, and $72254 and preparedness budgets being $1610552, $345938, $873805, and $362046 for SEKI, GLAC, BICY, and SHEN respectively.

We scaled the values back by 10% to cover a budget decrease while still running the path through the current budget and beyond. After scaling the current budgets back to start the gradients, we increased the budgets by an increment of about $2000. Our process seeks out the combination of program budgets that lead to the greatest value added. The national budget allocations derived from this research differ from current allocations as expected. Current budgets did not have the advantage of this information.

4 Discussion

This represents the first approach to the science of fire program budgeting and allocation that we know of. As such all of the methods and results are new. We found that by carefully establishing the programmatic analysis of the fuels and preparedness programs at the planning unit level, our extension to a national analysis was both straightforward and pragmatic. The ability to generate the unit level point data and then fit a valued production function to it is key as it the novel application of the gradient method for identifying budget allocations that promote the comprehensive performance measure of ROI. A highly significant finding is that the application of the gradient method has the important property of both promoting ROI and promoting stable programs within the agency at all levels. This process also has high potential for technology transfer as demonstrated through our webinar through the Southern Rockies Science Exchange Network, through several refereed journal articles and professional presentations. The USDOI currently has plans to extend and apply the process to portions of the National Park Service and to the Bureau of Land Management.

The National Strategy (2012) provides general guidance for managing vegetation and fuels. The goals include prioritizing fuel treatments to reduce risk near communities and homes, manage resources for ecological purposes to achieve fire-resilient landscapes and where economically feasible to expand fuel treatments use.

4.1 Deliverables cross walk

Table 4: Project deliverables

Deliverable Type	*Description*	*Date*
Refereed Publication	Science-based budgeting for national fire programs (WIT Transactions on Ecology and the Environment)	June, 2017
Refereed Publication	STARFire: Strategic budgeting and planning for wildland fire management, Park Science. Vol. 33 No. 1	Winter 2016-2017
Refereed Publication	Rideout, DB, Wei Y, Kirsch A, Kernohan N (2016) Strategic Planning and Budgeting of Wildland Fire Preparedness Programs for Risk Management. Int J. of Safety and Security Eng. 6(2) 246-253	2016
Demonstration of Landscape Analysis Results: professional conference presentation. Proceedings paper.	Fifth International Fire Behavior and Fuels Conference. Portland, OR. Introduction to STARFire: wildland fire spatial planning and budgeting. "Strategic planning and budgeting of wildland fire preparedness programs for risk management", Risk Analysis 2016, Rideout, D. B., Wei, Y., Kirsh, A., Kernohan, N.	April 12, 2016
JFSP Knowledge Exchange Consortium Presentation	Southern Rockies Fire Science Webinar 'The Science of Budgeting Fire Programs'	September 22, 2017
Datasets	A collection of spatial outputs	October, 2017
Conference Presentation and Publication.	International Conference on Risk Analysis, Greece. "Strategic planning and budgeting of wildland fire preparedness programs for risk management", Risk Analysis 2016, Rideout, D. B., Wei, Y., Kirsh, A., Kernohan, N.	April 2016.

5 Key Findings, Implications for Management and Future Research

The expected benefits of this report include: 1) the ability for managers to plan and budget for site restoration and protection, 2) maintain investments in previous treatment areas, 3) identify fuel treatment locations generating the most value added (V)[4] to the landscape, 4) quantify the relationship between fuel treatments and preparedness by planning alternative, 5) assess the

[4] Value added (VA), refers to the amount of benefit or value added from fire management effort. V differs from ROI in that ROI includes a comparison of the value added with the cost of its generation.

impact of budget increase/decreases across fire programs and 6) construct cost effective national budget allocations to landscapes while ensuring that national fuel treatment priorities are being addressed while maintaining the programmatic context that includes preparedness budgeting.

Summary of Key Findings. This research developed the scientific concepts and techniques for economically sound and socially stable budget formation and allocation from the planning unit to the national level. Landscape or planning unit level analysis was performed in a spatially explicit way at the cellular level for fuels programs. The fuels analysis was combined with preparedness analysis at the program level to form a programmatic foundation to support national budget formation and analysis. This represents a key finding and technique that is pragmatically valuable. The technique relied on two other key findings: generation of a valued production function for fuels and preparedness and the generation of a funding gradient to guide funding and budget decisions along the surface. Once the programmatic analysis was performed, we extended the technology to perform budget analysis at the national level. Key findings are:

1. The program level technology was pragmatically and soundly extended to the nation.
2. The analysis demonstrated sound and stable budget formation and allocations.
3. The use of a common and performance metric throughout of “return on investment” was both viable and reflected DOI policy. (Return on investment is consistent with promoting cost-effective decisions.)
4. Using ROI to guide performance could be pragmatically accomplished in a way that would not seek to keep budget allocations stable to promote stability in programs, workforce and capital formation.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products:

1. Book Chapters

i) Economics of Ecosystem Restoration: Using derived demand to promote sustainable ecosystems, WIT Transactions on Ecology and The Environment (accepted for publication)

ii) Science-based Budgeting for National Fire Programs, WIT Transactions on Ecology and the Environment (accepted for publication)

2. Journal Articles

i) STARFire: Strategic budgeting and planning for wildland fire management, Park Science (accepted for publication)

ii) Comparing Alternative Budget Allocation Models To Support Strategic Wildland Fire Program Analysis Across US National Parks, International Journal of Safety and Security Engineering (accepted for publication)

Appendix C: Metadata

As proposed in the Data Management Plan, the data is being archived in the Forest Service Data Archive. Metadata will be found at the https://www.fs.usda.gov/rds/archive/products site.

Appendix D: FlamMap Parameters

Table 4. FlamMap Wind and Fuel Moisture parameters for each study site.

			Fuel Moistures				
Study Site	**Wind Speed (mph)**	**Wind Direction (degrees)**	**1hr**	**10hr**	**100hr**	**Live Herbaceous**	**Live Woody**
BICY	14	55	6	8	16	93	125
GLAC	11	225	4	5	9	38	84
SEKI	11	225	3	4	6	26	24
SHEN	10	225	6	7	14	52	101