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JFSP Final Report

Consequences of alternative response strategies to wildland fires in the northern Rockies and Southwest in 2007 and 2008.

Project 09-1-05-2

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Abstract

This project addressed JFSP project announcement FA-FRA09-001, and the task statement "Trade-off assessments of AMR decisions". The project evaluated the consequences of alternative responses to 2007 and 2008 wildland fires in three wilderness areas. Specifically, it examined alternative initial response strategies and what could have happened if ignitions had been allowed to burn. Consequences were quantified in terms of area and type of area burned, days of fire activity, and impact on landscape scale fire risk. Situational factors were also examined for their influence on the response strategy and outcome. Simulations of three case study extended duration fires were also done to look for evidence that earlier fire and fuels treatments had influenced the outcomes, and for evidence that a critical decision early in the management of one of the examples influenced outcomes.

Background and Purpose

This purpose of this project was to gain insight about the tradeoffs surrounding Appropriate Management Responses (AMR) decisions. Federal fire management policy allows for a wide range of AMR on any incident (National Interagency Fire Center 2001). Alternative responses range from aggressive suppression to passive fire monitoring to intermediate strategies such as confine and contain approaches. During 2007 and 2008, there was an increased effort in several regions to more fully implement this policy, and an increased number of ignitions were managed as longer duration events.

To make such decisions to manage longer duration fires, managers need to anticipate the consequences of their fire management decisions. These consequences include the risks and benefits of both suppressing ignitions and allowing them to burn. Unfortunately, it is difficult to conceptualize the risks, benefits and costs of actions not taken. Quite often it's only the short term immediate outcomes that can be imagined and the longer term future consequences are ignored. In particular, it is difficult to see the potential ecological benefits that are foregone when an ignition is aggressively suppressed at initial attack.

This project used methods developed during previous efforts to quantify the foregone benefits of fire when an ignition is suppressed (Miller and Davis 2009). These methods employ the use of retrospective fire growth simulation wherein the growth and behavior of an ignition that was suppressed at some point in the past are simulated using knowledge of the weather and fuels conditions that existed at the time of the ignition. The hypothetical "what-if" outcomes from the ignition being allowed to burn are then compared to the actual observed scenario in which the ignition was suppressed at initial attack.

Study Description and Location

We focused our study on three wilderness areas where the preferred and desirable AMR for lightning-caused ignitions is passive fire monitoring. In wilderness, it is critically important that

managers fully exploit their opportunities to allow natural ignitions to burn. Data for all three wilderness areas were buffered by 5 km.

Our first study area was the Selway-Bitterroot Wilderness (SBW; 0.5 million-ha) on the border of north-central Idaho and western Montana. Elevations range from 430-3070 m. The vegetation ranges from open stands of ponderosa pine at lower elevations, to mixed conifer forests at intermediate elevations, to whitebark pine, alpine larch, and Engelmann spruce at higher elevations. The area experiences a mixed severity fire regime: many fires are nonlethal surface fires but under suitable weather and fuel conditions, lethal surface fires and even stand replacing crown fires occur. Within the wilderness boundary, unplanned ignitions are often allowed to burn, although if a threat is perceived to the wildland-urban interface outside the wilderness, fires within the wilderness are often controlled.

The second study area, the Bob Marshall Wilderness Complex (BMWC) in northwestern Montana (621,600 ha), runs for 60 miles along the Continental Divide, with elevations ranging from 1,200 m to more than 2,800 m. The area is characterized by rugged ridge tops that slope down onto alpine meadows, heavily forested hillsides, and timbered river valleys. Similar to the Selway-Bitterroot, the area experiences a mixed severity fire regime, and within the wilderness boundary, ignitions are often allowed to burn.

The third study was the Gila-Aldo Leopold Wilderness (GALW; 307,800 ha) in west-central New Mexico. The GALW ranges in elevation from 1380m to 3310m and features steep mountains, rough deep canyons, flat mesas, large river channels and flood plains. Vegetation ranges from desert scrub at the lowest elevations, through pinon-juniper woodlands and ponderosa pine and Douglas fir forests at middle elevations, to subalpine forests at the highest elevations. Fires are frequent in most of the study area and typically of low severity. Fire management objectives are to return fire to its natural role in the wilderness ecosystem to the maximum extent possible, consistent with safety of persons, property, and other resources.

The project had two parts. In part 1, we considered the initial response strategy. We evaluated the consequences of alternative responses to 2007 and 2008 wildland fires in the three study areas. We characterized the consequences of strategies that were actually implemented and contrasted those with what could have happened had alternative strategies and tactics been used. In particular, we examined what could have happened if ignitions had been allowed to burn. We quantified consequences in terms of area and type of area burned, days of fire activity, and impact on landscape scale fire risk. We also examined how situational factors (location and timing of ignition, national and regional preparedness level, fire activity in the area, and fire weather indices) influenced the response strategy and outcome. In part 2, our intent was to conduct in-depth analyses of two case study extended duration fires to compare and contrast the actual outcomes of key decisions and tactics with alternatives. For two case study fires, we looked for evidence that earlier fire and fuels treatments had influenced the outcomes from the

incident. For a third case study fire, we looked for evidence that a critical decision early in the incident management influenced outcomes.

This project used a combination of data, modeling platforms, and analyses to compare the results of a fire management decision made to the potential results if a different decision had been made. The project relied most heavily on two fire modeling platforms. The first, FARSITE (Finney 2004), was used to retrospectively simulate the growth and behavior of suppressed ignitions if they had been allowed to burn (part 1). FARSITE was also used to simulate the growth and behavior of three case study fires (part 2). We followed previously developed methods for these retrospective simulations (Davis et al. 2010). The output from these simulations was used to compare the actual outcomes that did occur with the potential outcomes that might have occurred, for example, if these suppressed ignitions had been allowed to burn (i.e. "what-if?" fires in part 1). Outcomes were summarized in terms of fire duration, fire size, area burned by resource type (e.g., wilderness vs. non-wilderness, sensitive species habitat, etc.) and severity of burn. The second platform, FSim (Finney et al. 2011), was used to evaluate the potential outcomes of these "what-if?" fires in terms of future fire risk. Because the potential—or the perceived potential—for a wilderness fire to spread beyond the wilderness boundary is something that currently constrains a wilderness manager's decision space (Black et al. 2008), we used FSim to generate maps depicting the likelihood of wilderness fire escapes.

Key Findings:

1. If additional ignitions had been allowed to burn in 2007 and 2008, substantially more area could have seen wildfire in all three study areas.

All ignitions from 2007 and 2008 that occurred within the three study areas (wilderness buffered by 5-km) were mapped and described. Successfully suppressed ignitions at initial attack were identified and selected for the FARSITE simulations. Ignitions included those that started inside wilderness as well as those that started in the 5-km non-wilderness buffer. We quantified the amount of area that these simulated fires would have added to the observed fire activity.

In the SBW, it was found that four times as much area could have burned in this study area. For 2007, we simulated the outcomes of 40 fires which would have added 315,879 acres of burned area to the 105,081 acres that actually did burn, and for 2008 we simulated 14 fires which would have added 43,134 acres to the 9,494 acres that actually did burn. In the BMWC, 25 simulated fires in 2007 would have added 266,747 acres to the 188,069 that actually did burn; and 12 simulated fires in 2008 would have added 30,807 acres to the 587 acres that actually did burn. In the GALW, we simulated the outcomes of 32 fires in 2007 and 26 fires in 2008. Simulations suggest that a *lot* more could have burned, adding over 223,736 acres to the 19,972 acres that did burn in 2007 and over 675,000 acres to the 1,431 acres that burned in 2008.

2. Allowing more naturally occurring wilderness fires to burn in 2007 and 2008 would have made measurable progress toward restoring wilderness fire regimes.

Several of the simulated fires were wilderness ignitions that would have escaped onto adjacent lands and a few were human caused ignitions. Although written fire management policy technically supports the use of human-caused ignitions for resource benefits, they are rarely, if ever, considered as candidates for fire use. Similarly, although fire management plans and policy guidance are increasingly permissive of managing for resource benefits on non-wilderness lands, the reality is that if a fire is likely to escape the wilderness, it is usually not viewed as a candidate for fire use. Managers cannot know for sure which ignitions will stay within wilderness and which will escape, but the retrospective simulations provided the benefit of hindsight. The analysis focused on the outcomes that resulted from the simulations of lightning-caused ignitions that started inside wilderness and did not escape the wilderness. These were thought of as unexploited or missed opportunities to use natural wilderness fire and were referred to as additional candidate ignitions for fire use.

In the SBW, simulations suggested that these additional candidate ignitions would have added about 20% to the area that did burn in wilderness in 2007 (17,591 acres added to the 96,499 acres that did burn). In 2008, fire use candidates would have added 3,628 to 364 that actually did burn. If these opportunities had been exploited, the fire rotation for the wilderness would have been reduced from 81 years to 77 years (based on a 27 year period 1984-2010). This reduction would have made marginal progress toward pre-settlement fire rotation estimates of around 44 years. In the BMWC, candidate fire use ignitions could have doubled the wilderness area burned in 2007 (adding 139,723 acres to the 140,576 acres that did burn) and in 2008, such fires would have increased the area burned in wilderness ten-fold (adding 5,078 acres to 578 acres). As a result, the fire rotation would have decreased from 196 to 162 years. In the BMWC, restoration targets of 100,000 to 200,000 acres burned per decade have been estimated. A 162-year fire rotation corresponds roughly to the lower target, suggesting that these additional candidate ignitions would have essentially restored a natural rate of burning. In the GALW, candidate ignitions would have tripled the wilderness area burned in 2007 (adding 42,128 acres to 17,049 acres that actually burned), and increased the wilderness area burned in 2008 by one hundred-fold (adding 41,355 acres to 411 acres that actually burned). This additional area burned would have marginally reduced the fire rotation from 38.6 to 33.4 years.

3. The majority of opportunities to use natural wilderness fires were exploited by managers of these study areas during these two years.

All three study areas have a history and experience with allowing naturally ignited wilderness fires to burn. The SBW and the GALW are especially well known for their wilderness fire programs and are considered national, if not international, leaders in this practice. Outcomes of the FARSITE simulations and the knowledge gained from this hindsight were used to assess how fully opportunities to use natural fire in wilderness were exploited in these three study areas. The number of lightning-caused wilderness ignitions that were suppressed but that might have been allowed to burn without escaping the wilderness boundary was examined.

In keeping with its reputation, the SBW managed far more wilderness ignitions as WFU than as wildfires during 2007 and 2008. In 2007, although 13 wilderness ignitions were suppressed, there were 49 ignitions managed as WFU. These 49 WFUs were managed as two complexes. Of the 13 wilderness ignitions that were suppressed, 2 of these escaped initial attack but ultimately burned mostly without intervention and in fact were managed along with the two large WFU complexes. Another of the 13 suppressed wilderness ignitions was determined to be a "non-starter", and we did not simulate it because the subsequent weather conditions would have precluded it from spreading. Of the remaining 10 wilderness ignitions that were suppressed, simulations suggest that 7 of these would have escaped the wilderness boundary. This would have left only 3 wilderness ignitions that would have stayed within the wilderness boundary and therefore may have been missed opportunities to use natural fire within the wilderness. These three ignitions represent less than 5% of the wilderness ignitions in 2007. In 2008, seven wilderness ignitions were suppressed and 18 were managed as WFU. Two of the suppressed ignitions were determined to be "non-starters" and one escaped initial attack to burn 2500 acres. Simulations of the remaining four suggest that none of them would have escaped the wilderness boundary. One of these was human-caused, leaving three missed opportunities to use natural fire in the wilderness. These three represent 12% of the wilderness ignitions in 2008.

Overall, the BMWC had fewer opportunities for WFU compared with the SBW. In 2007, 19 wilderness ignitions were suppressed while 5 were managed as WFU. One of the WFUs was later converted to suppression status and ultimately grew to 60,000 acres. Of the 19 wilderness ignitions that were suppressed, 7 escaped initial attack and one was determined to be a "non-starter." Simulations of the remaining 11 suggest that eight would have stayed within the wilderness boundary. One of these was human-caused, and another one was in a zone identified in the fire management plan as a fire exclusion zone, leaving six missed opportunities to use natural wilderness fire. These six represent 25% of the wilderness ignitions in 2007. It should be noted that two of these missed opportunities occurred when a large high complexity suppression fire was being actively suppressed; under the circumstances, it would have been difficult to allow these wilderness ignitions to burn. In 2008, there were only a total of eight wilderness ignitions and five of these were managed as WFU. Simulations of the three that were suppressed suggest that two of them would have stayed within the wilderness. One of these, however, was human-caused and in the fire exclusion zone, leaving one missed opportunity to use natural fire in wilderness. This single ignition represents 13% of the wilderness ignitions in 2008.

The GALW had many opportunities to use natural wilderness ignitions. In 2007 there were 30 wilderness ignitions were suppressed and 18 were managed as WFU. Twelve of the suppressed ignitions were "non-starters." Simulations of the remaining 18 suppressed wilderness ignitions suggest that 5 would have escaped the wilderness boundary, leaving 13 missed opportunities to use natural wilderness fire. These 13 ignitions represent 27% of the wilderness ignitions in 2007. In 2008, 17 wilderness ignitions were suppressed and 8 were managed as WFU. Simulations suggest that 6 of the suppressed ignitions would have escaped the wilderness boundary. Of the

remaining 11 ignitions, one was human-caused, leaving ten missed opportunities to use natural wilderness fire. These ten represent 40% of the wilderness ignitions in 2008.

4. The most important situational factor influencing the initial response strategy was ignition location.

Multiple situational factors were examined for their influence on the initial response strategy decision: location, timing in the fire season, national preparedness level (PL), regional PL, the number of active fires in the study area, and the Energy Release Component (ERC) at the time of the ignition. The initial response strategy for wilderness ignitions depended most strongly on the ignition's distance from the wilderness boundary; the more interior an ignition, the more likely it was allowed to burned. This was consistently true across all study areas. This influence was strongest in the SBW, which has the most populated and geographically expansive WUI of the three study areas.

In the SBW, additional factors that were significant were timing in the fire season, regional PL, national PL, and the number of active fires in the study area at the time of the ignition. Fires were more likely to be allowed to burn if they occurred later in the season, occurred when PLs were higher, and when current fire activity was higher. The influence of timing in the fire season intuitive: with fewer days remaining in the fire season, fires that are allowed to burn pose less of a risk of escape. The influence of higher PLs and fire activity may seem counterintuitive because allowing a new fire to burn would be a decision to add to the workload and complexity in a time of limited resources. In this case, however, this relationship was mostly a function of two large complexes of multiple WFU fires that were being managed in 2007, a very active fire season. This could indicate that opportunities for using natural wilderness fire are being exploited even in the height of the season. In the BMWC, additional factors that were significant were regional PL, national PL and to a lesser degree, number of active of fires in the study area at the time of ignition. The relationship was opposite to the relationship in the SBW; in the BMWC, fires were more likely to be allowed to burn if they occurred when PLs and current fire activity were lower. The start date of the ignition was not a significant factor in the BMWC. In the GALWC, no factors other than distance to boundary were significant.

5. The highest risk wilderness ignitions paradoxically have the greatest potential to reduce future risk of escaped fires.

The BMWC was used as a case study area to explore the role of wildfires on mitigating future risk. Specifically, the effect that the "what-if" simulated fires would have had on reducing the likelihood of future wilderness fire escapes was quantified. Escape probability was computed from ignitions and wildfire perimeters simulated by FSim. This probability was computed for the observed landscapes after 2007 and 2008 and for alternative landscapes that reflected the effects of each of the "what-if" simulated fires on fuels and vegetation. The most dramatic differences in average escape probabilities were created by the "what-if" fires that ignited closest to the

wilderness boundary (Figure 1). Although these ignitions near the boundary may be at higher risk to escape, they also have the potential to create fuel breaks for future fires.

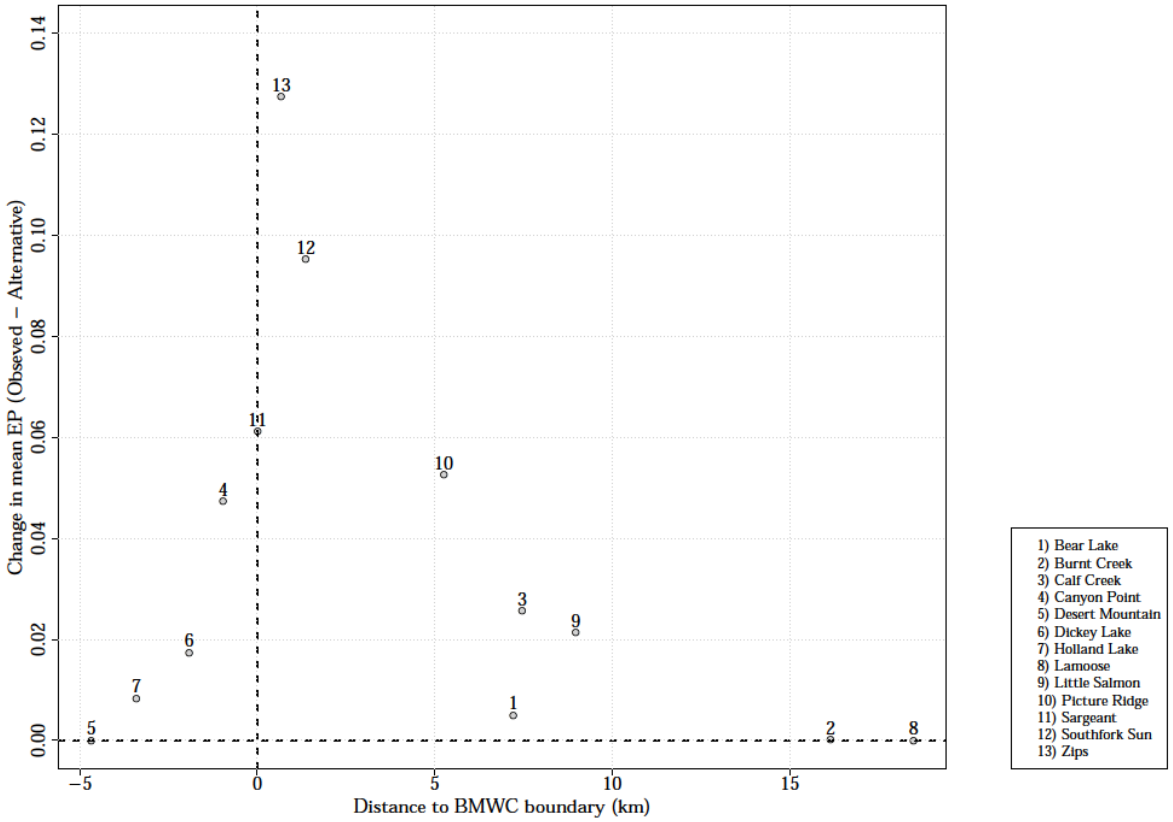


Figure 1. Change in average EP within the treatment fire perimeters plotted against the distance from the treatment fire's ignition point to the BMWC boundary. Negative distance values indicate locations outside the BMWC boundary.

We also computed the size of the area within the wilderness that had very low escape probabilities (<0.01). Ignitions starting in this zone would have very low likelihood of escaping the wilderness, and therefore represent the greatest opportunities for being allowed to burn. However, the size of this low risk zone was most influenced by the largest simulated fires which could be the most difficult and riskiest fires to manage (Figure 2).

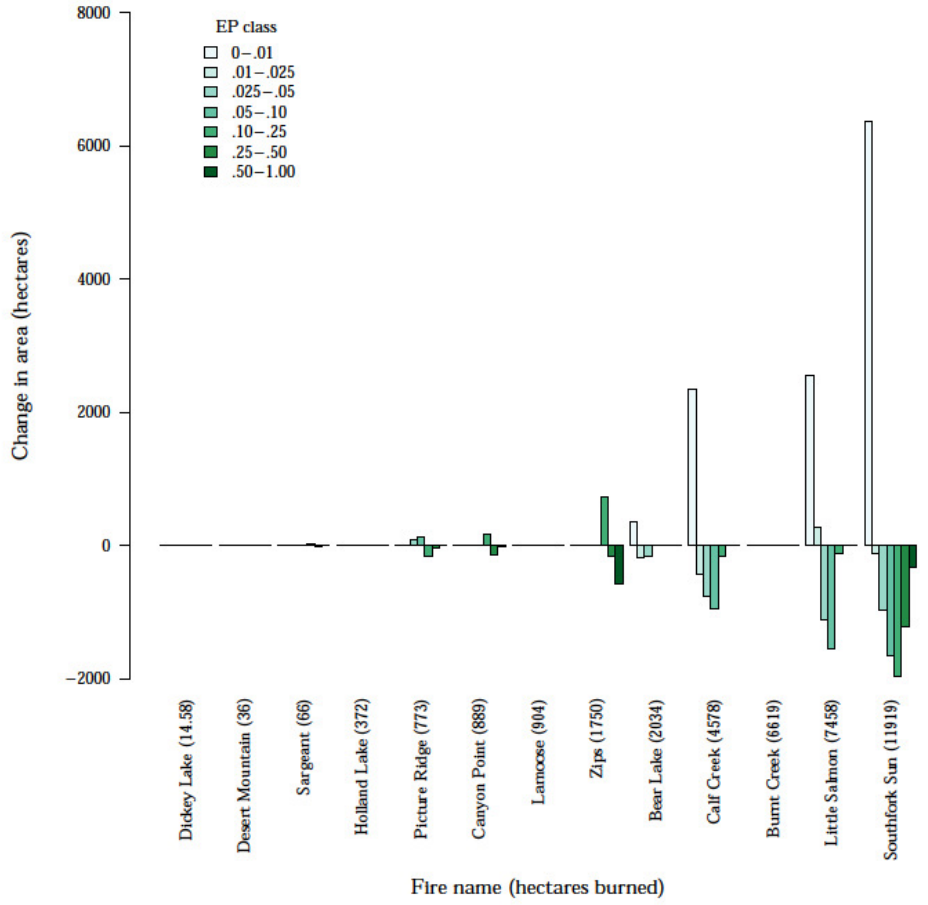


Figure 2. Change in area for each EP class within treated areas between the observed and individual-alternative scenarios. Positive values indicate more area in the alternative scenario relative to the observed scenario, while negative values represent less area in the alternative scenario; bars for a single fire sum to zero because gains in one EP class are offset by losses in another. The treatment fires are ordered along the x-axis by area burned inside the BMWC boundary; size of each treatment fire is provided in parentheses.

6. If additional ignitions had been allowed to burn in 2007 and 2008, estimates of future annualized area burned and suppression costs would have been reduced.

The role of wildfires as fuel treatments that would reduce future suppression expenditures was examined for the BMWC. Using FSim, wildfires for 25,000 artificial fire seasons were simulated for the observed landscapes after 2007 and 2008 and for alternative landscapes that reflected the effects of the "what-if" simulated fires on fuels and vegetation. A suppression cost model was then linked to the wildfire perimeters generated by FSim and annualized suppression costs were computed at the landscape scale. The "what-if" fires from 2007 would have reduced annualized mean area burned in a subsequent fire season by 17% and would have reduced mean suppression costs in a subsequent fire season by 20%. The "what-if" fires from 2008 affected much less area

than those from 2007 and these would have reduced the mean area burned by only 3% and costs by only 2%.

7. Insufficient data on costs and tactics significantly hinders our ability to learn from past decisions and their outcomes.

One of the project goals was to evaluate the economic effectiveness of wildfire management decisions, which requires the pairing of relatively fine scale spatial data about where specific suppression actions were taken with daily information on quantity and cost of resources used. Specific incident documents (e.g. Situation Reports) provide broad descriptions of where different suppression resources are allocated within broad geographic areas, but there were no reliable spatially explicit data to describe actual management decisions at a given location. This data gap hinders the ability to evaluate the effectiveness of suppression resources in terms of altering fire spread, intensity, and improving the likelihood of containment (Holmes and Calkin 2012; Finney et al. 2009), and therefore hinders the ability to learn from previous incidents. Though substantial energy was devoted to acquiring daily incident cost data by resource type for all our fires from I-Suite, we were only marginally successful with this. While we were able to obtain daily management costs for our three extended duration case study fires, we were unable to obtain data for the other fires in the study areas which limited our ability to extrapolate beyond these case study fires. Yet even with the daily management cost data, it was difficult to discern why suppression costs vary throughout the duration of a fire without spatial data. Furthermore, costs were not broken down by resource type and quantity which limited our ability to evaluate differences between tactical approaches on these fires.

8. The evaluation of the economic efficiency of fire management decisions remains an intractable problem.

Currently, there are no formal economic evaluation frameworks for fire and fuels management. Instead, decision-making in wildfire and fuels management has embraced a quantitative risk-assessment framework, predicated on the principles of actuarial sciences, whereby wildfire risk is formulated by integrating the likelihood, intensity, and positive and negative effects of wildfire on market and non-market resources, and is calculated in terms of 'net value change' (Finney, 2005). Wildfire risk can be broken down into its two main subcomponents: the "exposure analysis" and "effects analysis". Exposure analyses examine the spatial relationship between wildfire likelihood, intensity, and resources at risk, without incorporating how a given resource at risk might be affected by wildfire at different intensity levels. Effects analyses extend exposure analyses by including information about the likely response of resources to fire at different intensity levels. Resource responses can be both positive and negative in attempt to capture the fact that wildfire can be both beneficial and destructive to a given resource depending on fire intensity (e.g. critical habitat).

Conceptually, the quantitative risk assessment framework can be used along with suppression cost models to evaluate the economic efficiency of alternative wildfire management strategies. Attempts were made to incorporate monetary estimates for market and non-market resources into the risk assessment framework to calculate a dollar value of expected resources at risk. By comparing these estimates with expected suppression expenditures, the objective was to flag certain "what-if" fires as being more or less economically efficient. Unfortunately, there are several significant limitations to such an approach that hindered the ability to economically evaluate alternative wildfire management strategies.

One set of limitations surrounds the development of appropriate response functions which serve as the foundation in effects analyses. These response functions represent the 'value change' for a given resource as a function of fire intensity level. Putting a value on changes in market and nonmarket resources due to wildfire is challenging and as a result value change has often been quantified in terms of percentage change (Venn and Calkin 2011). However, it is unclear exactly what percentage change means in the context of non-market resources at risk. Is it the change in physical amount of the resource, or the change in how society views that resource after it is affected? Value change has also been represented as an area based metric (Thompson et al. 2011), yet such a metric may not appropriately represent risk to the provision of market and non-market resources. Rather than using an area based metric to quantify value change, it is theoretically feasible to assign a value to each resource in the risk analysis, and using the response function approach, estimate the expected value change measured in terms of dollars for a given landscape. While theoretically appealing, there are drawbacks to incorporating non-market estimates derived from non-market valuation studies into the wildfire risk framework in order to economically evaluate wildfire and fuels management. Transferring estimates from non-market valuation studies into wildfire risk analyses assumes that the interpretation of the non-market value is compatible with the use of response functions to characterize changes in the level of that resource. An example of this is with valuing changes to critical habitat. Most of the geospatial data related to critical habitat represents areas on the landscape where critical habitat exists. However, most non-market valuation studies do not elicit information on societal values towards enhancing or avoiding loss of critical habitat; generally, such studies capture society's willingness to prevent the extinction of the species that occupies the critical habitat. Transferring an estimate of the value of protecting the extinction of an animal onto geospatial data representing critical habitat is not appropriate because they do not represent the same thing. The same can be said for estimating the value change due to wildfire for biodiversity, smoke management, and fisheries. The interpretation of the non-market resource value rarely aligns with the spatial data used to represent the spatial distribution of the resource.

Another fundamental limitation to evaluating the economic efficiency of fire management decisions is lack of data and knowledge about the costs of managing a wildfire with less aggressive strategies. Recent attempts to disentangle differences in management strategies on suppression costs have been hindered by a lack of and inconsistencies in reported data on

suppression costs for fires that were not aggressively suppressed (Gebert and Black 2012). Additionally, such data are often confounded because information derived from decision documents about management strategy does not always reflect how the wildfire was actually managed on the ground.

As a result of the intractability associated with valuation, response functions, and effects analysis, efforts focused instead on the use of exposure analysis to evaluate efficiency of the "what-if" fires. The effect of these fires on altering the likelihood that subsequent wilderness ignitions would escape the wilderness boundary was evaluated (see Finding #5). Information from the exposure analysis was also linked with a suppression cost model to evaluate their effect on expenditures at the landscape scale (see Finding #6).

9. Retrospective fire behavior modeling was unsuccessful for evaluating management decisions in the context of the extended response strategy.

The original aim of part 2 of the project was to use retrospective fire behavior simulation to evaluate outcomes that might have resulted from alternative decisions on extended duration case study incidents. This aim proved to be unrealistic given the information we were able to collect, the expertise we had for the fire behavior modeling, and the particulars of the weather and terrain of the case study fires. In general, we were only marginally successfully in calibrating the FARSITE parameters to observed fire progression data. Detailed information on the actual suppression actions taken were lacking, as was information on the effectiveness of these actions. For two case study fires (Ahorn and Fool Creek, both in 2007), we looked for evidence that earlier fire and fuels treatments had influenced the outcomes from the incident. Unfortunately, tor these two fires, weather data, specifically wind data, appeared to be unrepresentative of actual conditions. These same two case study fires grew substantially under extreme weather conditions with reported plume dominated fire behavior and long distance spotting. Long distance spotting seemed to be particularly important to the growth of one of these fires, as it spread through an area with numerous large natural barriers. Unfortunately, FARSITE simulations were unable to replicate this kind of fire behavior. Although adjustments were made to the FARSITE parameters to more closely calibrate the simulations with observations, we did not have high confidence in our results. For the third case study fire (Lane 2, 2008), we looked for evidence that a critical decision early in the incident management influenced outcomes and examined the first 24 hours after this decision. No substantial difference in the outcomes was apparent.

<u>Management Implications</u>

The risk averse decision to suppress is more likely for ignitions close to the wilderness boundary. And yet the decision to suppress is a decision to delay or put off that fire to a later date. Conversely, the decision to allow fire to burn is more likely if the fire is expected to stay small and more likely when the ignition is far from the wilderness boundary (and the built environment with its associated values at risk). The three study areas we looked at are large and have a

reputation for natural wilderness fire management for good reason. Ignitions can be allowed to burn because they are remote. The size of the wilderness area confers a large decision space. These study areas also have a legacy from a history of decisions and that legacy takes the form of a fuel mosaic and lower landscape fire risk. It appears that all three of these study areas are exploiting the opportunities they have for natural wilderness fires more often than not, and this is the case even in extreme record setting weather conditions and high fire activity. Even so, the restoration of natural fire regimes is not complete and missed opportunities were identified in 2007 and 2008. These missed opportunities were relatively close to the boundary. Paradoxically, these may be the most important opportunities because of their ability to alter landscape fire risk. The highest risk ignitions may be the most important risks to take in the long term.

Relationship to recent findings

Recently published studies relate to at least three aspects of this project: retrospective fire modeling, use of wildfire probabilities for supporting fire management decisions, and cost modeling in counterfactual scenarios.

Cochrane et al. (2012) used FARSITE in a retrospective mode to create fire spread maps for 14 large wildfires that interacted with previously implemented fuels treatments. Their purpose was to assess the effectiveness of these fuel treatments in reducing the size of the wildfires. Similar to our approach with the three case study fires, they used information about the weather that existed at the time of the fire. After calibrating the simulation parameters to observed progression data, they then ran a counterfactual scenario in which the previous fuel treatments were omitted. This required data manipulations similar to those done in this project. Their methods differed notably in their use of the stochastic spotting feature in FARSITE. Our simulations did not use this feature; spots were manually introduced when needed to reproduce perimeters. In Cochrane et al., multiple simulations were run to account for stochastic spotting, thereby allowing wildfire perimeters, and the effectiveness of the fuel treatments, to be presented in terms of probabilities. This is a valuable improvement over the methods used here.

Scott et al. (2012) used FSim to compute the probability that wilderness fires would reach a wildland urban interface. They demonstrated that this risk could be mitigated by selectively suppressing ignitions, and made these selections based on time in the season and tabulated results by month. Their approach employed a probabilistic metric very similar to the escape probability generated in this project. The approaches differ in two important ways. First, the escape probability represents an entire fire season and does not capture the within-season influences that the Scott et al. (2012) did. Second, Scott et al. (2012) presented their results aspatially, whereas maps of escape probability show this information spatially. A straightforward improvement to escape probability would be to stratify the ignitions in FSim by date so that escape probability reflects temporal dynamics within a fire season.

Houtman et al. (2013) estimated expected reduction in future suppression costs from allowing wildfire to burn, and discounted this value into the future. They looked at 50 different futures for wildfire treatments. In each future, they modeled fire probabilities, fire duration, suppression effectiveness rates, and used a state and transition model of vegetation change. A suppression cost model was then used to estimate the suppression costs throughout these futures. This was compared to a future without the initial wildfire treatment. Treatments tended to reduce future costs and these results were sensitive to the size of the initial fire of interest because it treated more area. This is consistent with our findings that larger treatment fires tended to reduce escape probability. It is also consistent with findings that annualized suppression costs decrease with increasing amount of area treated. We did not attempt to project discounted future effects but the state and transition model approach could be incorporated into escape probability analysis to enable future discounting of treatments effects. Thompson et al. (2013) also quantified the effects of fuel treatments on suppression costs. Very similar to what was done in this project, they used FSIM to produce fire size distributions on a treated and untreated landscape and then used a regression cost model to compare the suppression costs with similar results to what we found.

Future work needed

The use of FSim to derive escape probability could lead to several fruitful research and applications. The escape probability map can be classified into zones that might be used in fire management plan guidance. Exploring how the different zones defined by the classes of escape probability change throughout a fire season may help identify windows of opportunity to allow wilderness fires to burn when the escape risk is acceptably low (Scott et al., 2012). Being able to examine these temporal dynamics would be especially valuable for smaller wilderness areas. The three study areas in this project are large and have opportunities for managing natural wilderness fire every year. A small wilderness area may only see viable opportunities late in the season, or only in certain years. Ignitions could be stratified by time in the fire season, or even by annualized climate variables, before generating maps of escape probability. The result could identify those windows, albeit narrow ones, in which natural wilderness fire is a viable option. It may also be possible to disentangle the apparent complex interactions between terrain, fuels, ignitions, and weather on escape probability within and adjacent to wildfire treatment areas through the use of a simulation experiment. In such an experiment, thousands of artificial wildfire treatments could be generated, wherein treatment size, location, shape, and orientation are systematically varied. Similar simulation approaches have been used to isolate the relative importance of different landscape variables on burn probability (e.g. Parisien et al., 2010). As in Scott et al. (2012) it should be noted that the approach can be applied to non-wilderness boundary or point of interest. Escape probability could also provide a useful framework for future research into the optimal placement of mechanical or prescribed fire treatments. Rather than thinking of fuels treatments simply as a way to reduce the likelihood and/or intensity of wildfire, the spatio-temporal placement of fuels treatments could be designed in such a way that

opportunities to allow natural fire within wilderness are expanded (Reinhardt et al., 2008). As such, escape probability could be used to help integrate the goals of hazardous fuels management with wildfire management.

There is a critical need to determine how much fires cost to manage over the long duration, especially when they are being managed for resource benefit objectives. Unfortunately, as already mentioned, data on costs that are tied to the actual actions taken on an incident are lacking. However, data being collected in WFDSS should be able to help disentangle differences in management strategies on management costs.

Deliverables Crosswalk

Deliverable Type (See Format Overview, Section VIII)	**Description**	**Status**
Conference/symposia/workshop	Meet with staff at each of 3 study areas and both of the regional offices to present methods, results, and implications • Lewis and Clark NF fire staff, Great Falls, MT, 6/2011 • Rocky Mountain Ranger District resource staff, Choteau, MT, 6/2011 • West Fork Ranger District resource staff, Darby, MT, 8/2013 • Prescott NF fire and resource staff, Prescott, AZ, 1/2011	Completed.
Dataset	Spatial data layers of model inputs and outputs delivered to each of the study area management units in electronic form	To be posted for download when new website renovation launches in Spring 2014.
Non-refereed publication	In-depth case study reports for extended response strategy analysis	Forthcoming
Non-refereed publication	Fire Management Today article on initial response strategy analysis	Forthcoming
Non-refereed publication	Research in a Nutshell two-page summary produced by the Aldo Leopold Wilderness Research Institute.	Forthcoming
Refereed article	Barnett, K.M.; Venn, T.J.; Miller, C.; Parks, S.A. A use of risk analysis to support wilderness fire decisions.	In review. Submitted to Forest Ecology and Management, November 2013.
Refereed article	Barnett, K.M. et al. Predicting changes in wildfire suppression expenditures due to alternative wilderness management strategies.	In prep. Forthcoming.

Website	Project webpage on Aldo Leopold Wilderness Research Institute website	Forthcoming when new website renovation launches in Spring 2014.
Conference/symposia/workshop	Oral presentation at professional society conference; AFE or IAWF • Barnett, K. Economic evaluation of alternative wildfire management strategies. Oral presentation presented at 5th International Fire ecology and Management Congress, Dec 3-7, 2012, Portland, OR. Also: • Barnett, K.M. Application of an ecosystem services modeling framework: evaluating the economic efficiency of wilderness wildfire management. Oral presentation at Valuing Ecosystem Services Workshop, November 15, 2011, Lubrecht Experimental Forest, MT.	Completed
Poster	Professional association conferences, 2010, 2011, 2012 One poster and three oral presentations instead of three posters: • Miller, C., and Davis, B.H. Retrospective fire modeling to quantify the hidden consequences of fire suppression. Oral presentation and poster presented at Third Fire Behavior and Fuel Conference, October 25-29, 2010, Spokane, WA. • Miller, C. Assessing fire management trade-offs: a Monday-morning quarterback approach. Oral presentation to be made at George Wright Society Biennial Conference, March 2011, New Orleans, LA. • Miller, C. Fire management tradeoffs: three wilderness case studies. Oral presentation presented at 5th International Fire ecology and Management Congress, Dec 3-7, 2012,	Completed

	Portland, OR.	
Master's thesis	Barnett, K.M. A use of risk analysis to support wilderness fire decisions. Thesis, University of Montana.	To be defended 12/2013.
	Annual progress reports, final report	Completed.

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