Title: Vulnerability and ecosystem services in wildfire risk assessments and fuel treatment planning

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This final progress report is being submitted to the Joint Fire Science Program to provide a summary of findings, accomplished deliverables to date, and proposed products. This information is preliminary and is subject to revision. It is being provided to meet the need for timely 'best science' information. The assessment is provided on the condition that neither the U.S. Geological Survey nor the United States Government may be held liable for any damages resulting from the authorized or unauthorized use of the preliminary information. Interpretive results will be published in refereed publications. This project was supported by funding from the Joint Fire Science Program, and the U.S. Geological Survey Land Change Science Program. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. government.

Abstract:

The cost of fighting large wildland fires in the western United States has grown dramatically over the past decade. This trend will likely continue with growth of the WUI into fire prone ecosystems, dangerous fuel conditions from decades of fire suppression, and a potentially increasing effect from prolonged drought and climate change. Fuel treatments are often considered the primary pre-fire mechanism to reduce the exposure of human life and values at risk to wildland fire, and a growing suite of fire models and tools are employed to prioritize where treatments could mitigate wildland fire damages. Assessments using the likelihood and consequence of fire are critical because funds are insufficient to reduce risk on all lands needing treatment, therefore prioritization is required to maximize the effectiveness of fuel treatment budgets.

Social and community vulnerability measures from natural hazards research attempt to map the heterogeneity of vulnerable populations to understand how mitigation actions can minimize the negative effects of hazards. We compare multiple social vulnerability indices and address methodological and scale issues that occur when these indices are created in areas with low population densities. We also introduce a measure of road criticality that assesses the importance of individual segments of a road network in connecting forest populations and critical facilities. Together, these measures will help fuel treatment plans minimize the potential negative economic effects and quality of life disruptions that can occur during a wildland fire incident.

To include ecosystem service in fuel treatment planning, we model biomass as a proxy for the climate regulating ecosystem service of carbon storage, and sediment retention as a contributing factor to water quality, in a case study on the Deschutes National Forest of Central Oregon. Our objective is to maximize the averted loss of ecosystem service benefits subject to a fuel treatment budget. We model expected fuel treatment costs across the study landscape using a modified version of the My Fuel Treatment Planner software, using stand-level tree list data, local mill prices, and GIS-measured site characteristics. Using this dataset, we introduce cost-effectiveness as a measure for the spatial prioritization of fuel treatments using the Land Treatment Designer program. We test four prioritization algorithms and measure the effectiveness of each algorithm in ecosystem service terms by comparing the differences between treatment and no treatment scenarios. We use fire simulations to generate burn probabilities, and estimate fire intensity as conditional flame length at each pixel. Two algorithms prioritize treatments based on cost-effectiveness and show small to substantial gains over those using only benefits. A larger effect of incorporating cost-effectiveness is the ability to treat up to 25% more area for the same budget. Variations in the heterogeneity of costs and benefits create opportunities for fuel treatments to maximize their expected averted loss of values. By targeting these opportunities we demonstrate how our cost-effective framework can improve the outcome of fuel treatment planning.

Background and purpose:

The increase in western wildfire in recent decades has led to firefighting expenditures by federal agencies often exceeding $1 billion annually (Whitlock 2004, Calkin et al. 2005). In an effort to reduce this expenditure and limit losses from catastrophic wildfire, large investments have been made in wildland fuels reduction (USDA and USDI, 2001; HFRA, 2003). Due to the large spatial heterogeneity in values at risk (VAR), wildfire probability, and wildfire severity, strategic fuel treatment planning could decrease expected losses from wildfire, and recent landscape risk assessments and wildfire models have made significant progress on this topic (Miller and Ager 2013). Yet considerable work remains and certain improvement within the commonly accepted wildland fire modeling and risk assessment frameworks would allow users a broader suite of values and data to consider when assigning actions.

Fuel treatment planning and wildfire risk analyses in or near the wildland urban interface (WUI) are, at their core, most fundamentally designed around structures at risk as a proxy for minimizing loss of life and property. Structures at risk are one element in understanding exposure to wildfire hazards, however this actuarial approach ignores other significant aspects of societal vulnerability, such as socioeconomic status, demographic sensitivity, evacuation potential, and community adaptive capacity (Turner et al. 2003, Wisner 2004, Polsky et al. 2007, Wood et al. 2010).

Community-level impacts are similarly ignored when structures guide fuel treatment prioritization. Maintaining important economic and social services are critical during an extreme event and its aftermath. For example, the loss of road networks and connectivity can be life threatening for evacuees before and during a wildfire, increase time to containment, and cause business interruptions and reduce social services after the fire is extinguished. The economic wealth and social services of a community, county, or region, are often dependent on access, yet few tools or applications are available to assess road networks and their criticality to community services.

In addition to social vulnerability and community-level impacts, another example of a potential policy tradeoff in fuels reduction is between WUI values and ecosystem services – the economic and nonmarket benefits that society receives from ecosystems (Assessment 2005). There are certain monetary and human well-being benefits to minimizing risk within the WUI (Schoennagel et al. 2009). Similarly, the services provided by natural ecosystems are critical, but harder to quantify and typically less visible until they need to be restored or replaced (Daily 2000). This is particularly true in forests, where wildfire can flip carbon sinks to sources and dramatically increase erosion rates, among other effects. And while a growing number of studies have assessed ecological values at risk and restoration objectives that involve wildland fire, examples of multiple ecosystem services or other ecological criteria used in planning are only beginning to influence the fuel treatment prioritization process (Ager et al. 2007a, Ager et al. 2007b, Thompson et al. 2011a, Thompson et al. 2011b).

In an effort to address multiple issues in fuel treatment planning and wildfire risk analyses, we have combined methods from multiple disciplines to provide new applications for policy relevant wildland fire and natural resource management issues. Our overall objective of this research was to improve landscape level fuel treatment planning and decision support capability by including aspects of vulnerability, economics, and ecosystem services. In doing, we have made several key findings and developed new methods to aid fuel treatment planning and wildland fire risk assessments. These have tremendous bearing on wildland fire management, particularly in WUI communities.

We have key findings for five specific tasks that we addressed in this project. These include:

1. *Social vulnerability*: how to incorporate/quantify aspects of social vulnerability for fire hazards?
2. *Community vulnerability*: how to incorporate/quantify aspects of community vulnerability for fire hazards?
3. *Ecosystem services*: how to model ecosystem services for prioritization in fuel treatment planning to minimize the expected loss of services?
4. *Modeling costs*: how to model the potential revenue and costs of fuel treatment activities at the stand level for an entire landscape?
5. *Cost-effective fuel treatment planning*: how to prioritize fuel treatments cost-effectively to maximize the effectiveness of fuel treatment budgets?

Our task one objective uses analyses of social vulnerability from other hazards and applies them to wildland fire – though a wholesale appropriation of established methods is problematic for wildland fire. In task two we address vulnerabilities to community infrastructure and facilities, to understand the critical elements of connectivity for our study communities. Task three introduces a way to assess natural capital for a community – ecosystem services – and how these values can be used to prioritize fuel treatments to minimize their expected loss. In task four we describe a landscape level fuel treatment cost modeling approach to create stand-level estimates of fuel treatment costs for use in planning. Task five introduces cost-effectiveness as a metric in fuel treatment planning and illustrates the potential gains in a case study integrating multiple aspects of this project.

Study description and location:

Study Areas

Our Deschutes study region of central Oregon encompasses the entire Deschutes National Forest, parts of the Willamette, Umpqua, Winema, Fremont, and Ochoco National Forests, the Crooked River NGL, BLM lands, and contains just less than 750,000 total acres. The landscape is located on the eastern side of the Cascade mountain range and vegetation varies greatly due to climatic and elevation gradients that become increasingly drier and lower to the east of the study area. Mountain hemlock and mixed conifer forests with wet meadows shift to lodgepole and ponderosa forests, and finally transition to sagebrush shrubland and steppe ecosystems at the drier end of the landscape. Significant habitat exists for RTE species including the Northern Spotted Owl and Middle Columbia ESU Steelhead, as well as diverse habitats for game and nongame species and plants. Forests store and sequester significant amounts of carbon and feed water supply and hydropower reservoirs (Nelson et al. 2008, Polasky et al. 2008, Nelson et al. 2009).

Fire is a regular occurrence within the study area, and several recent large fires have affected the Deschutes. These include the Pole Creek (2012), Rooster (2010), Cascade Crest (2006), B&B complex (2003) and Davis (2003) fires. Collectively these burned over 160,000 acres and often at high burn severities. Fires are largely started by lightning and have increased area burned four-fold from the 1990s to the 2000s (Ager et al. 2013a). These fires were largely contained to interior forest locations, but the Pole Creek fire threatened the community of Sisters, and other fires have disrupted travel and community services.

The study area contains the city of Bend, numerous small communities (e.g., Redmond, La Pine, and Sisters), destination resorts, and recreational areas catering to thousands of tourists drawn to natural amenities. In addition, the study area contains significant regional transportation corridors (e.g., Highways 20, 97, and 126). As the city of Bend expands, a growing WUI stresses fire containment resources and complicates fire management options similar to many western regions (Radeloff et al. 2005, Byrd et al. 2009, Schoennagel et al. 2009). The risk to these communities is influenced by recent housing growth, decades of fire suppression (Agee 1996) a fire regime characterized by frequent fires but departed from natural conditions (Agee 1996), and climate change (Westerling et al. 2006). Thus, it is similar to many communities in the west affected by wildland fire threats.

Vulnerability methods

Research into the social and community vulnerability to natural hazards affords a more nuanced view of populations exposed to risks. Instead of considering all people or locations similarly, methods incorporating vulnerability address factors affecting the resilience and adaptive capacity of individuals and communities. Important measures that are often considered include social, economic, and demographic characteristics of populations, the geographic distribution of population density, and the community services and infrastructure provided by, and linking, critical facilities. Many vulnerability assessment techniques were developed for sudden onset hazards, such as tsunamis or volcanoes, where vulnerability is partially a function of evacuation capability. Wildland fire can be considered a sudden onset hazard in more extreme cases, but is potentially exacerbated by chronic fuel accumulation that could be mitigated. An often cited method for quantifying vulnerability is the Social Vulnerability Index (SoVI)(Cutter et al. 2006). However, this index may be sensitive to several geographic and analytic issues that may pose challenges to its use at finer scales or areas with a more distributed population. Thus, assessing vulnerability to wildland fire is not as simple as applying methods developed for other hazards. This project seeks to address this issue by developing methods to measure residential and employee population distributions, distributions of critical facilities, social vulnerability, and road network criticality for wildfire risk analysis models.

Fuels Data

For fire simulation we use surface and canopy fuel data from the national LANDFIRE (2010 refresh dataset) to create a landscape file (LCP file) for use in our fire modeling approach. Individual data layers include canopy height, canopy base height, canopy bulk density, fuel model (Scott and Burgan), canopy cover, slope, aspect, and elevation. We resampled all data to 90m resolution grids with nearest neighbor methods to facilitate the computationally intensive fire modeling process, according to standard practice. LANDFIRE data are commonly used in research and management for planning fuel treatments and risk analyses, and often at the scale of the district and at 90m resolution (Ager et al. 2014). We used these data to reflect current pre-treatment conditions, and alter them to reflect post fuel treatment scenarios using routines from ArcFuels (Vaillant et al. 2012).

Ecosystem services

We model two ecosystem services commonly affected by high intensity wildland fires for use in our fuel treatment planning: carbon storage and sediment retention. Natural resource management is increasingly moving in the direction of incorporating ecosystem services into decision making, and our intent is to demonstrate ways of quantifying these services for decision support and explicit inclusion in fuel treatment planning. Many other reasons to conduct fuel treatments exist, and a growing literature documents fuel treatment planning for single species targets, forest restoration, and structure or community protection. Our work builds on this research, and has a primary objective of using nationally available datasets and common modeling procedures to facilitate the use of these methods for other areas.

We modeled standing carbon using FCCS biomass values crosswalked to LANDFIRE data (refresh 2010). We created a flame length to biomass consumption response function to translate a conditional flame length (CFL) to the consumption percent for six aboveground biomass pools (canopy, shrubs, woody debris, lichen litter moss, non-woody debris, and ground), based on a flame length relationship from Agee (1996) and Rothermel (1983), and used in the CONSUME model. We use a pre and post-fire biomass difference surface to determine where stands would lose the greatest amount of stored carbon if they encountered a fire, according to any given pixel's CFL and burn probability (BP). Therefore the benefit is calculated as the expected averted loss of standing carbon based on both the probability of an event occurring, and the consequence of the most likely fire severity at that stand.

We modeled a surface of avoided sedimentation with the InVEST Sediment Retention Model (Kareiva et al. 2011). This model is based on the common Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith 1978), which uses geospatial information on land-use/land-cover (LULC) patterns, soil properties, elevation, rainfall, and climate data to determine sediment loads to a hydrological network. To determine the expected increase in sediment mobilization occurring after a fire, we adjusted the vegetation parameters of the InVEST model in the post-fire scenario to reflect the subsequent loss of vegetation filtration and sediment retention. Using the pre and post-fire difference surface allowed us to calculate the expected averted loss of sediment retention across the landscape for inclusion in the fuel treatment prioritization.

Fuel Treatment Costs

To generate a landscape scale fuel treatment cost surface we developed a semi-automated process using the My Fuel Treatment Planner software (MyFTP) (Biesecker and Fight 2006). MyFTP is a spreadsheet based calculator that takes Forest Vegetation Simulator (FVS) tree lists as input and requires many other variables for estimating fuel treatment costs. Required data include user supplied project and site variables (slope, aspect, elevation), species and size-class specific local market prices, travel distances, mastication options, surface treatment options including prescribed fire, and transportation variables affecting costs. The major benefit of our process is a fuel treatment surface that accounts for variable costs and revenues generated from fuel treatments based on spatially explicit stand level data, but for an entire landscape. We created a set of R scripts and GIS calculations to streamline the process of generating a cut list and other input variables, and then ran hundreds of planning units through MyFTP to generate a heterogeneous surface of fuel treatment costs (Figure XX). We modeled one treatment type that was designed to reduce fire intensity through the removal of small trees, ladder, and surface fuels, following guidance from similar studies of ponderosa pine dominated western dry forests and local input (Agee 1996, Agee and Skinner 2005, Ager et al. 2007a, Ager et al. 2013b). In practice, multiple types of treatments could be modeled and included within an analysis to determine where and what types of fuel treatment should occur on the landscape.

We used a FVS-ready gradient nearest neighbor (GNN) dataset (Ohmann and Gregory 2002) from the local district to generate the FVS cut list for each stand within a planning unit. Using this tree list derived data enabled a more accurate view of the expense and potential revenue derived from each treated stand. Planning units had sufficient resolution to capture homogenous stand conditions and cost factors, but large enough to cover the XX ha study area (ave of acres or ha). We generated a per acre cost estimate per planning unit, that represented the average per acre cost of treatments occurring at the stand level. However we used stands in the treatment prioritization routine as described in the following sections.

Cost-effectiveness

In environmental economics and conservation planning, cost-effectiveness is a common objective when allocating limited resources toward program goals. In the spatial prioritization of actions, i.e. payments for management action or land purchases, cost-effectiveness is often achieved through "benefit-cost" targeting, and typically defined as the ratio of an action's expected benefits divided by the cost of the action (Babcock et al. 1997, Wu et al. 2001, Newburn et al. 2005). "Benefit-cost" targeting is often described as trying to maximize the benefits per dollar of program expenditure, thereby seeking to achieve the "best bang for the buck". A rich literature explores the nuances of incorporating costs, cost-effectiveness, targeting, and real world applications of agri-environmental and conservation programs (Bode et al. 2008, Claassen et al. 2008), and has repeatedly demonstrated superior outcomes when costs are included(Ando et al. 1998, Newburn et al. 2005, Naidoo et al. 2006, Stoms et al. 2011). In some cases, the heterogeneity of costs may even be more important in driving outcomes compared to the benefits (Stoms et al. 2011).

When formulated as a resource constrained maximization problem, fuel treatment planning is quite similar to those programs described above, and shares a theoretical foundation. Adding to benefits and costs, the economic concept of additionality, doing something that wouldn't occur otherwise, can be included in cost-effective targeting by estimating the expected averted loss of benefits through prescribed actions. This "benefit-loss-cost" targeting (Davis et al. 2003, Newburn et al. 2005, Davis et al. 2006) ensures actions are additional. Fortunately, the concept of additionality or prioritizing based on the averted loss of values is easily represented through burn probability and fire effects modeling, and fits seamlessly into the expected net value change risk framework of Finney (2005). Without estimating potential loss, prioritized actions may be cost-effective but located where no potential loss of values would occur.

Prioritizing treatments

We prioritize fuel treatments according to our objective of maximizing the expected averted loss of ecosystem services, subject to a characteristic fuel treatment budget. We compare four algorithms: two that use the Land Treatment Designer (LTD) (Ager et al. 2012), a spatial decision support program designed to explore fuel treatment prioritization scenarios, and two simpler algorithms implementing "benefit-loss", or "benefit-loss-cost" approaches outside of the LTD. Our process using LTD follows the user manual (Ager et al. 2012)and the general methods of Ager et al. (2013b) with a few additions to include cost-effectiveness. The base planning method prioritizes stands to maximize the averted loss of benefits, derived from the difference between treatment and no treatment alternative scenarios for biomass and sediment retention benefits. We refer to this treatment prioritization algorithm as BL (benefits-loss). We also test this method using an option in the LTD that spatially aggregates stands into treatment areas of user defined size (BL-LTD). This option simulates the logistical constrains more reflective of a real-world fuel treatment scenario. Our cost-effective algorithms are identical to BL and

BL-LTD, but use fuel treatment cost data to consider cost-effectiveness. With these algorithms, the data used to select stands is a cost-effectiveness ratio of the averted loss of benefits divided by the expected fuel treatment costs. We refer to these planning techniques as BLC and the spatially aggregated version BLC-LTD. These cost-effective techniques are analogous to the benefit-loss and benefit-loss-cost targeting of Newburn et al. (2005) and Stoms et al. (2011).

Fire modeling and ArcFuels

We use fire simulation modeling to test treatment scenarios by comparing the results of a prioritization to a scenario with no treatments. We modify scenarios receiving treatments with ArcFuels (). The Landfire derived LCP file is modified by treatment adjustment factors to represent a post-treatment landscape. Treatment adjustments could be changing a fuel model, or raising canopy base height, for example. We simulate fire with Randig, a command line version of FlamMap that allows for more complex weather scenarios, and uses the MTT algorithm (Finney 2002). We model burn probability through >10,000 random ignitions and a fire weather scenario representative of local problem fire conditions (Ager et al. 2007a, Ager et al. 2013b). We calculate CFL with ArcFuels, and use CFL to model the expected loss according to biomass and sedimentation specific loss functions.

KEY PRELIMINARY FINDINGS:

1. *Social vulnerability*: how to incorporate/quantify aspects of social vulnerability for fire hazards?

We address two critical methodological issues in the construction of composite vulnerability indices in this analysis. These issues deal with potential problems that may limit the reliability of the resulting indices constructed using the Social Vulnerability Index (SoVI) methods. First, because the SoVI relies on a Principal Component Analysis (PCA) for its generation, it is potentially impacted by the number of study units sampled, and changes in the scale of analysis. It may therefore be problematic to apply the SoVI in WUI communities or similar areas such as the Deschutes, due to the limited number of census units for which all data is available, and to maintain a constant scale of analysis. The originators of the SoVI suggest that this issue may be addressed by using organic growth regions, or expanded study areas, that are sufficiently large to produce stable PCA results. To address these issues, we created a series of social vulnerability indices to see how these proposed changes affected the performance of the SoVI: one based on the traditional SoVI algorithm at the Census tract level using a standard organic growth approach to address the number of study units; one at the Census tract level using an organic growth approach that was constrained to include only geographic areas similar to the study area; and one at the Census block level using a mixture of variables available at the block level and those available at the tract level. Results from these analyses indicated that while the tract level indices created using both organic growth models were fairly similar for this study area, the constrained organic growth approach did produce slightly more stable results, and could also lead to more substantial differences in other geographic contexts. The comparison of the block and tract level analyses revealed large changes in the correlation matrix and differences in vulnerability rankings.

The second methodological issue we considered also dealt with limits on the PCA-based approach described above. Other researchers (Tate 2012) have found that inductive index construction approaches do not produce as accurate results as those based on hierarchical methods. Hierarchical methods are beneficial because they do not suffer from the study area size or scale limitations of the inductive approaches. To explore the benefits of such an approach, we created a hierarchical index at the block level using Analytical Hierarchy Process (AHP) methods. We compared vulnerability scores from this approach to the block level SoVI-based index, and while the broad patterns were fairly similar, the AHP-based hierarchical results are preferred because of the lack of inherent limitations found in the inductive, SoVI-style approaches.

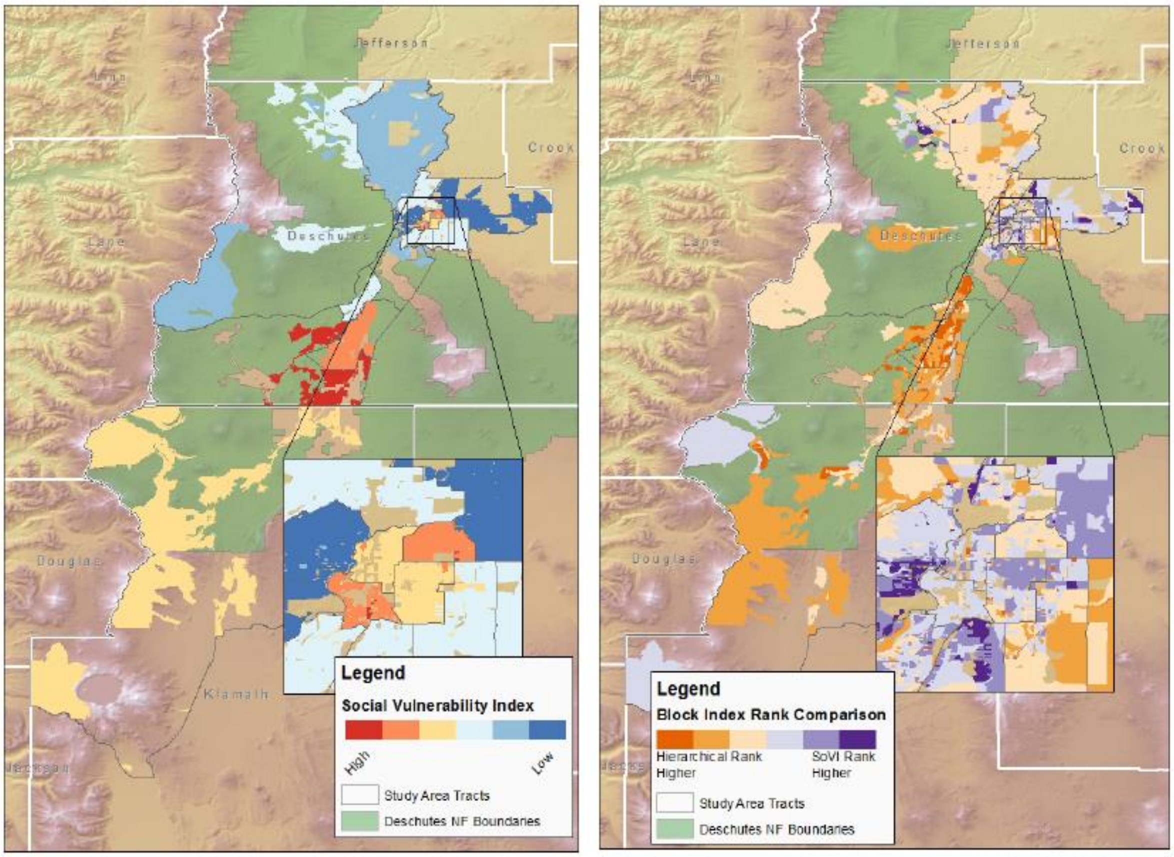

Figure 1: Indices of social vulnerability. Left panel shows the SOVI index and the right panel shows a comparison of the SOVI index to the Hierarchical Index.

2. *Community vulnerability*: how to incorporate/quantify aspects of community vulnerability for fire hazards?

We address an important aspect of community vulnerability by quantifying the impact of the loss of transportation infrastructure connecting essential facilities and people. Lack of connectivity to critical facilities during a fire event could be a disruption or economic loss, at the least, to life threatening on a worst case scenario. To determine the importance of each road segment in and around the Deschutes National Forest, we identified the locations of populations within the forest (represented by populated Census block centroids), as well as the locations of all essential facilities located within the broader study area (hospitals, fire stations, gas stations, grocery stores, police stations, banks, and post offices). We then ran a pairwise series of closest facility operations for each category of essential services and population centers. We then iteratively removed each road segment in the network to simulate a fire related closure. With 21,308 road segments in the forest, the closes facility operation was run 21,308 times for each category of essential facility, and in each run, a separate road segment was removed from the analysis. For all unique iterations of road segments and facilities, we calculated the total number of residents who lost access, as well as the total population weighted distance from the population points to the essential facilities. We calculated the average population losing access and the population weighted distance to facilities across the different types to determine how important a given road segment was in providing resident access to essential facilities. In most cases, the network of roads in the forest is redundant enough that residents would only loose access to essential facilities in the case of a fire in their neighborhood. The average population weighted distances to essential facilities would increase if a number of critical road segments were disrupted in a larger event.

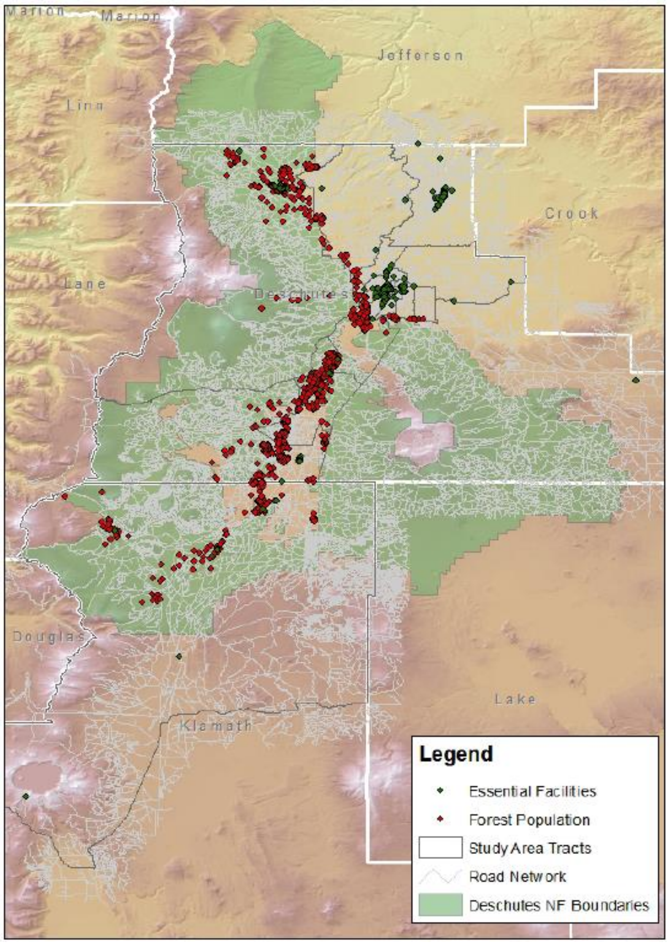

Figure 2: Distribution of essential facilities, population centroids, and roads through the study area.

3. *Ecosystem services*: how to model ecosystem services for prioritization in fuel treatment planning to minimize the expected loss of services?

There are a wide variety of reasons fuel treatments are used in forest management, though they are primarily a means of changing expected fire behavior to promote certain fire regimes or to reduce the likelihood and negative effects of fire on values at risk. Values at risk can range from homes to endangered species home ranges. We focus on two ecosystem services to illustrate how natural capital can be explicitly considered as values in prioritizing the location of fuel treatments. Our objective is to maximize the expected averted loss of standing biomass and sediment retention subject to a fuel treatment budget. We use Biomass as a proxy for the climate regulating ecosystem service of carbon storage, and sediment retention as a contributing factor to water quality, particularly with respect to fire effects and downstream hydropower reservoir siltation. Other ecosystem services that were not modeled but could easily be incorporated into this framework, and forest management in general, include carbon sequestration, water yield, nutrient retention, scenic quality, recreation, and timber production.

For our case study of the Sisters Ranger District, we show the location and expected effect of a fuel treatment plan on two ecosystem services (figure 3). We used the LTD program to prescribe treatments and create project areas sequentially until the hypothetical budget constraint is met. To determine the expected benefits of the treatment plan we assess the expected averted loss by comparing the fire effects for treatment and no-treat scenarios (figure 3).

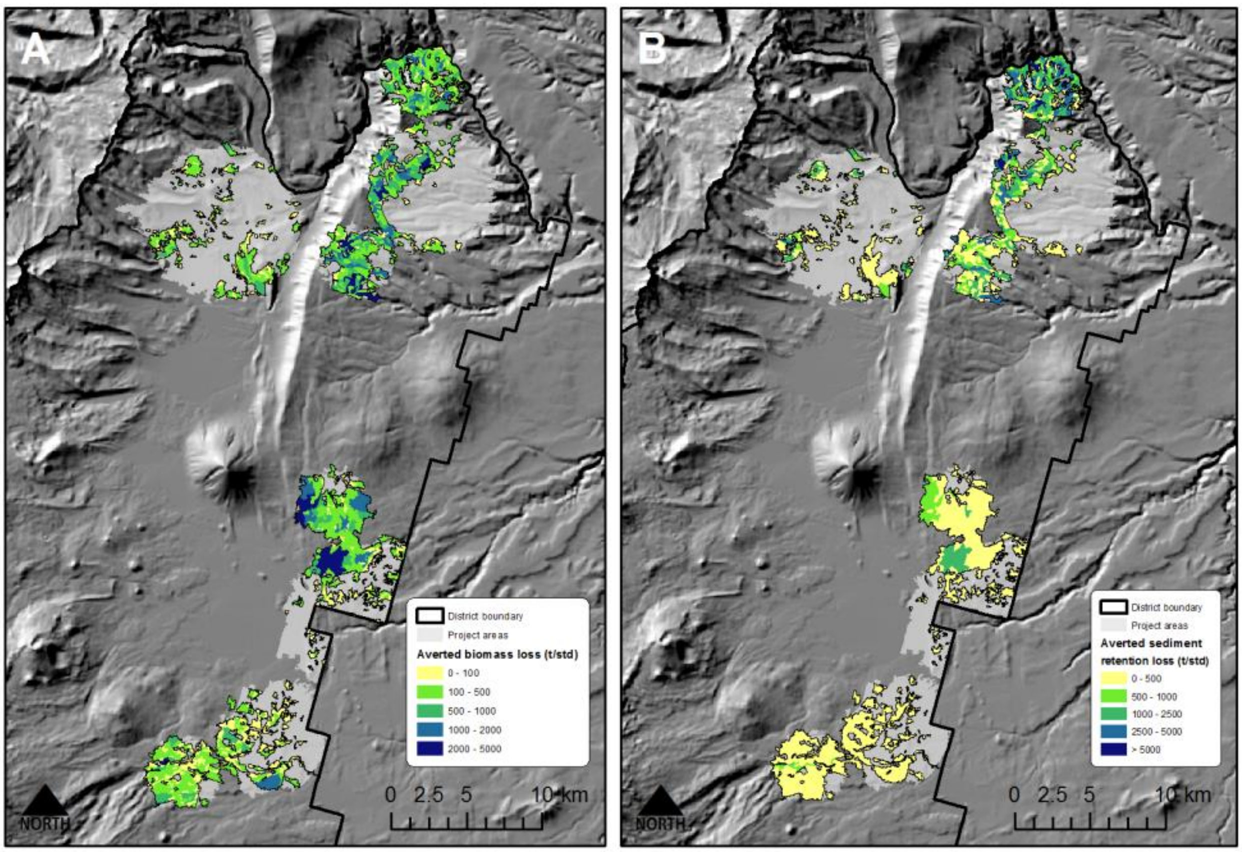

Figure 3: Maps of the expected averted loss from fire of two ecosystem services following a fuel treatment. Panel A shows the expected averted loss of biomass, a proxy for standing carbon, and panel B shows the expected averted sediment retention loss. These two services are shown in averted loss benefit terms as the potential outcome from the BLC-LTD $60 million fuel treatment scenario, also seen in figure 5. Model output is available across the entire study area, but shown for a given fuel treatment to illustrate the framework.

4. *Modeling costs*: how to model the potential revenue and costs of fuel treatment activities at the stand level for an entire landscape?

Our method of estimating fuel treatment costs using MyFTP was a compromise between accuracy and efficiency. By estimating revenue and expenditures at the stand level using geospatially derived input data we assume our derived values are more accurate than the rough estimates used to budget fuel treatments. Another benefit of working at the scale of actual forest management practices is that the resultant data are in a format that can be readily ingested into the Forest Vegetation Simulator, ArcFuels, or the Land Treatment Designer, among other forest management software tools. Our workflow required some manual processing, but this could be easily streamlined in an update to MyFTP or the creation of a new landscape scale cost estimating tool.

Per acre fuel treatment cost estimates varied from less than $1000/ha to over $5000/ha (~$400/ac to over $2,000/ac). Factors influencing these expected costs came from the distances travelled by equipment and logs to a mill, type and density of logs and non-utilized fuels, potential revenue, and physical features such as slope and accessibility. Though the per hectare costs are generalized to a larger planning unit, the cost estimates are similar in magnitude to values used in the Deschutes Skyline CFLRP, though likely more realistic as they account for heterogeneity in the factors affecting costs and revenue. Future improvements to our workflow would further automate the process and retain all detail from tree list input data.

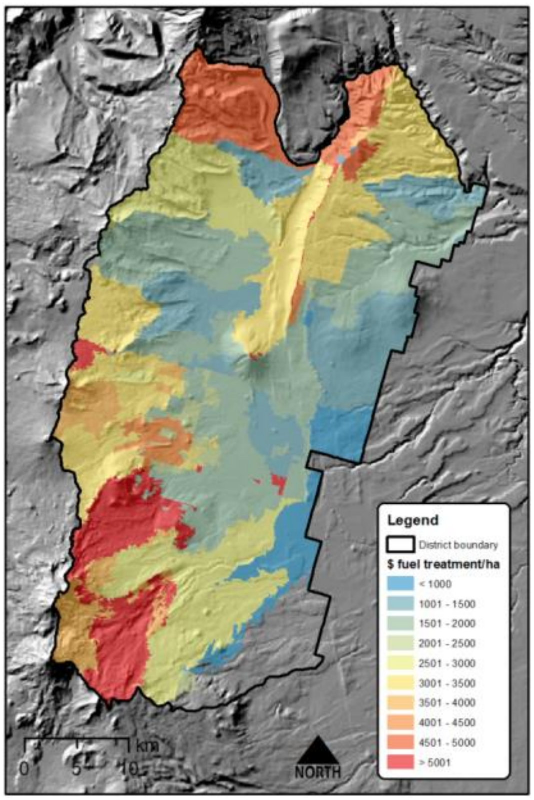

Figure 4: Estimated fuel treatment costs on the Sisters Ranger District for a characteristic fuel reduction treatment in dollars per hectare.

5. *Cost-effective fuel treatment planning*: how to prioritize fuel treatments cost-effectively to maximize the effectiveness of fuel treatment budgets?

Much of the research on wildland fire risk assessments and fuel treatment planning has focused on the data, models, and frameworks to accurately simulate fire and fire effects. Less research has focused on the costs associated with wildland fire, and little has addressed cost-effectiveness in fire management. Cost-effectiveness, doing the most good per dollar, would seem to be an important fuel treatment metric, yet studies or plans that prioritize fuel treatments using costs or cost-effectiveness measures are absent from the literature.

To test the effect of using costs within an established fuel treatment planning software package (LTD) we compare four prioritization algorithms designed to reduce risk in a case study examining fuel treatments on the Sisters Ranger District of central Oregon. For benefits we use our modeled sediment retention and standing biomass (task 3), and measure the effectiveness of each algorithm by comparing the differences between treatment and no treatment alternative scenarios. Our objective is to maximize the averted loss of net benefits subject to a representative fuel treatment budget. We use our modeled fuel treatment costs (task 4) as the denominator in our cost-effectiveness calculation. Two prioritization algorithms target treatments based on cost-effectiveness and show moderate to large improvements over similar algorithms that use only benefits (figure X).

Area treated was not an explicit criterion within the benefit surfaces used for prioritization, but it is an objective or measure often used in fuel treatment planning. In both comparisons, the cost-effective scenarios treated more area than their counterpart scenarios, by up to ~25% (figure X). We calculated benefits using a function that integrates both the burn probability and the conditional flame length at a given pixel. With enough area treated, the average burn probability across the landscape will decline for areas treated but also adjacent areas not treated. At some level this neighborhood effect will translate into greater averted losses. Thus the slopes of the ecosystem service curves illustrated in figure X may actually increase with respect to increasing cumulative costs, rather than the common diminishing returns observed elsewhere in similar environmental and natural resource management applications. This ‘tipping point’ could be reached at lower cost using our cost-effective prioritization techniques.

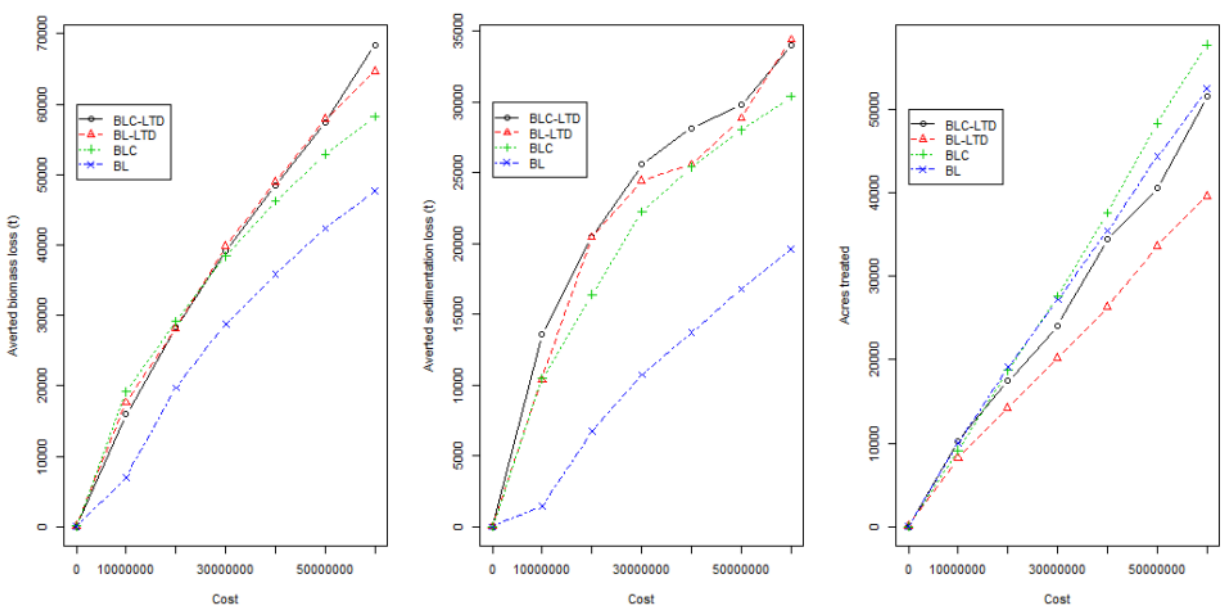

Figure 5: Comparison of fuel treatment planning algorithms using our cost-effectiveness framework with and without the LTD program. Treatment scenarios are described by their use of B – benefits, L – expected loss, C- costs, and using the LTD program to create spatially adjacent treatment areas. Ecosystem services are in units of tons (averted loss of sediment or biomass if a fire occurred). Total acres treated represent the size of cumulative treatments by each scenario up to the cumulative $60 million fuels reduction budget.

Management implications:

1. *Social Vulnerability:*

   It would be convenient to simply apply social vulnerability analyses from other hazards disciplines to wildland fire. Our initial research began in that direction, however, the findings form this study indicate that care must be given in constructing social vulnerability indicators to choose methods that are appropriate to the analytical context of a study area. Some widely used approaches, such as the SoVI, rely on statistical methods that may not be suitable for study areas with small numbers of Census units typically used for calculating vulnerability. This is often the case in more sparsely populated rural areas, or low population density zones adjacent to wildlands or national forests. Heirarchical approaches may be more appropriate in these contexts, but are not void of their own limitations; the performance of these models is strongly influenced by model weights (Tate 2012), so care should be given to choose these appropriately. In this example, the use of the analytical hierarchy process (AHP) provides an example of how consensus weights can be derived from expert opinion. Eliciting this expert opinion from regional and local stakeholders, emergency managers, and forest and land managers will further aid in creating a more complete understanding of the heterogeneity of social vulnerability for a region.

2. *Community Vulnerability*:

   Economic and quality of life disruptions are common during large wildland fires, though emergency management procedures often minimize these impacts. Still, pre-fire mitigation and fuel treatment planning have the potential to further limit these disruptions by reducing the likelihood and effect of fire on areas of critical transportation infrastructure required for safety and commerce. Our road network criticality analysis can be useful in identifying those road segments that are most critical in providing area residents with access to essential facilities or to maintain economic activity. Such quantification and population weighted calculations allow fuel treatment prioritization to include areas where a disruption to the transportation network would cause more serious impediment to the well-being of communities and area residents.

3. *Ecosystem Services*:

   The consideration of ecosystem services in natural resource management decision making is a topic of growing interest and increased attention by scientific, management, and policy audiences. On the policy side, a prime example is the Forest Service's new Planning Rule Revision (2012) that now requires "…land management plans providing for ecosystem services and multiple uses." It is still too early to tell how ecosystem services will be included in plans, and what this rule change will mean for forest managers. Yet examples from this project illustrate how sub-stand level analyses could provide quantitative estimates of the spatial heterogeneity of ecosystem services. Moreover, these analyses introduce methods to calculate the expected net benefits in terms of risk reduction due to forest management actions. The methods developed use tools accepted or created by the forest service, and uses ecosystem service models that are derived from physical process-based models with a long history and utility.

   From a management perspective, the incorporation of ecosystem services into planning could be considered an extension of the multiple use mandate. A primary difference will be a broader integration of social factors into decision making regarding ecological capital. Similar to the more holistic inclusion of social factors, planning and decisions would benefit from a larger landscape scale perspective and a consideration of a forest or land management unit's embedded socio-ecological context. It is possible that such planning would shift the assessment of forest priorities and tradeoffs if a broader set ecosystem service values were considered.

4. *Fuel Treatment Costs*:

Failure to consider costs when planning fuel treatment activities will most likely lead to suboptimal outcomes. Explicitly considering costs can also allow for a more transparent assessment of alternative scenarios and tradeoffs among competing values or treatment priorities. In this study, an added benefit of using costs in the prioritization routine was the ability to treat more acres, and thus reduce the risk on a larger portion of the forest, for the same treatment budget. Treating more acres with the same overall cost, while simultaneously reducing a greater amount of risk, should be a compelling argument for the inclusion of costs in planning activities.

To generalize the cost modeling in the study area, areas on flatter ground and closer to roads and mill infrastructure will cost less to treat, while stands at higher elevation, further into the forest, and on steeper and more rugged slopes had the highest cost. This shouldn't be a surprise; however, by modeling the expected cost of treatments using our methods, the heterogeneity of costs across the landscape can be explicitly incorporated and used to more effectively plan project locations and stands to treat. This study primarily used two ecosystem services as criteria for fuel treatment prioritization, and with more common forest management objectives such as dry forest restoration, endangered species habitat protection, or wildland urban interface risk reduction, the inclusion of costs would likely yield similar results.

5. *Cost effectiveness*:

In our paper we explain the underlying theory justifying cost-effectiveness, present evidence from a modeling experiment, and discuss the potential policy implications. In light of this, serious attention should be paid to the incorporation of cost-effectiveness in fuel treatment planning. The framework we present makes small adjustments to the existing LTD software that could be easily implemented into future fuel treatment planning software and decision support systems.

If the incorporation of costs into decision making occurred across USDI and USDA bureaus, the inclusion of cost-effectiveness and the data required to calculate expected costs would be a high priority for development and applied use. These tasks would align USDI and USDA bureaus with Government Accountability Office recommendations for improving methods of allocating fuel reduction funds and selecting projects by incorporating cost-effectiveness (GAO 2007).

Furthermore, incorporating cost-effectiveness may allow for an additional means of assessing tradeoffs among potentially competing fuel treatment priorities. Clear cost differences among stands may demonstrate, for example, that treating more acres for the same cost in one area could lead to a greater averted loss of resources compared to treating fewer acres in a less accessible location. By incorporating cost-effectiveness it may become apparent that even with equally weighted values guiding treatment priorities, it may be more efficient and effective to treat areas with the higher ratio of benefits/costs regardless of any individual stand's importance.

Relationship to other recent findings:

This project has drawn from several areas of disparate research to address timely questions for wildland fire management. Improving methods to map social and community vulnerability will aid in understanding the variation of heterogeneous populations and the potential effects of wildland fires. Methods to incorporate ecosystem services into fuel treatment planning and risk assessments will be helpful when the Forest Service and other agencies begin to include quantitative estimates and maps of ecosystem service supply in fuel treatment planning, risk assessments, and forest management decision making. Integrating costs and cost-effectiveness into fuel treatment planning has tremendous potential to improve the efficiency and effectiveness of fuels management and hazard mitigation activities. While these are original contributions to the wildland fire arena, there are other recent complementary efforts that this work builds upon and extends.

Vulnerability to natural hazards is commonly described as a function of the exposure and impact of a hazard on individuals or communities. In hazards research, vulnerability to a hazard is often reported to be influenced by social characteristics (Cutter et al. 2006, Nelson et al. 2007). In some of the few wildland fire vulnerability studies, correlations between mapped vulnerability indices and wildland fire risk and mitigation program participation show positive correlations (Gaither et al. 2011, Poudyal et al. 2012), indicating more vulnerable populations may be at more risk and less able to properly mitigate wildland fire hazards. This work is similar, in that vulnerable areas are highlighted for risk assessment and fuel treatment prioritization purposes, but it also addresses methodological and scale issues (Tate 2012) important for the creation of vulnerability indices.

In the ecosystem service realm, similar recent research has investigated the effect of fuel treatments on carbon pools, and to prioritize treatments for reducing risk sedimentation to key watersheds. Results from studies looking at the effect of treatments on carbon accounting are largely mixed showing a net carbon gain (Hurteau and North 2008, Hurteau et al. 2008), or a carbon loss due to a more complete accounting of carbon pools and fuel treatment effects (Ager et al. 2010). Research into post-fire sedimentation modeling from fire effects ranges from empirical validation of model outputs (Robichaud et al. 2014) to a watershed-based risk assessment to help choose priority watersheds for treatment (Thompson et al. 2013, Warziniack and Thompson 2013).

In this work our objective was not to assess any singular ecosystem service to determine if forest management actions were a net gain or loss in ecosystem service terms, but rather to prioritize stand level treatments at a fine scale for multiple services based on expected losses and cost-effectiveness. The resolution and scale of our methods are compatible with implemented fuel treatment plans, rather than broad scale regional studies, or policy frameworks explaining the concept and potential application of ecosystem services for forest management (Smith et al. 2011). Furthermore, our work is based on the assumption that fuel treatments will continue to be a primary forest management activity, and therefore the prioritization of treatments would be optimized by maximizing the averted loss of values at risk in a cost-effective manner.

The costs and economics of fuel treatments have been a topic of considerable interest to the wildland fire community, with several important reviews or large studies (Barbour et al. 2008, Skog et al. 2008). Research and tools to estimate expected costs of fuel treatments at the stand and region levels are available (Biesecker and Fight 2006, Prestemon et al. 2008), and used in this work, but still lacking is an ability to address forest-wide costs at a resolution fine enough for landscape scale fuel treatment planning. Our modification of the MyFTP program was born out of this necessity. Most of this research on fuel treatment assesses, directly or indirectly, the effect of removing marketable timber or forest products from fuel treatments on their cost. Our research also quantifies a decrease in net treatment cost due to revenue from merchantable wood products.

Cost-effectiveness has received very little attention for wildland fire management and is largely absent from the literature, though in other fields it has proved to be very important in decision making. In this study we have addressed the most fundamental cost-effectiveness analysis by assessing the expected benefits of fuel treatments divided by the required costs to realize those benefits. This is most similar to acquisition costs used in conservation planning (Newburn et al. 2005, Naidoo et al. 2006). Several other economic assessment techniques that use cost-effectiveness are applicable to wildland fire and are often used in conservation planning, including maximizing the return on investment (Murdoch et al. 2007, Kovacs et al. 2013), scheduling actions through a time horizon to account for temporal dynamics (Wilson et al. 2006, Wilson et al. 2007), and assessing the expected benefits of multiple types of potential actions at any given location (and through time) to maximize the expected benefits of program expenditures (Wilson et al. 2007, Wilson et al. 2009). These conservation planning applications are largely derived from financial and economic theory, and likely have direct utility to a number of wildland fire management problems.

Future work needed:

The most pressing area of future research and development highlighted by this project is the need for an improved fuel treatment cost model. A landscape level cost model would benefit both applied use and allow further research on fuel treatment economics. Our cost estimates were derived from custom code written for this project using the MyFTP program. While our solution was effective, it still required manual entry for each zone or sub-watershed needing cost estimates. This led to a labor intensive task to create a landscape scale view of potential treatment costs. The manual input also required a simplification of the planning unit geometry, and resulted in a moderately coarse scale of output data. With further automation, the input parameters, rules, and equations from MyFTP could be used in conjunction with batch input functionality for additional GIS derived input data, to effectively load an entire landscape of potential stands for cost estimation. Having a true stand-level estimate of potential costs would likely result in greater accuracy and highlight additional opportunities for efficiency gains. Operating at this scale would also match the level of detail generated by stand surveys and integrate with the commonly used Forest Vegetation Simulator (FVS).

With additional landscape level fuel treatment cost modeling capability, numerous critical fuel treatment and wildland fire economics questions could be more easily addressed. Issues like the expected return on investment (ROI) of fuel treatments in terms of avoided loss values by treatment dollar, longevity or lifespan of fuel treatments compared to costs, or a comparison of costs of wildland fire use to a treatment counterfactual would all provide valuable insight into maximizing the value of wildland fire expenditures.

Landscape level fuel treatment cost estimates would also greatly assist the spatial prioritization of fuel treatments, as illustrated in this project. Many additional questions could be addressed, including issues of scale, scheduling, priority, and type of treatment to prescribe, and would all be aided by cost estimates. The field of conservation planning has undergone a similar transition in the past decade, where current practices now acknowledged that certain fundamental aspects of land markets and economics are required for efficient and effective use of scarce resources for biodiversity conservation; tasks from fuel treatment prioritization and wildland fire management are likely similar.

A greater ability to assess tradeoffs of fuel treatment locations and find 'win-win' solutions would also likely result from improved cost estimates and incorporating cost-effectiveness. In our cost-effective framework for prioritizing treatments based on their benefits, expected losses, and costs, the heterogeneity of elements can be used to explain the optimality in treatment locations. It is the variation of each element, and their combined covariation, that create opportunities for cost-effective fuel treatment prioritization. Similar work in conservation has shown that costs can plan a more important role than benefits when deciding where to allocation funds (Stoms et al. 2011). A wildland fire management example where this might occur is a tradeoff of treating areas along a distance gradient from just outside the WUI to deep in the forest interior. If we consider both locations have equal values and face similar risk, in our framework the overriding factor deciding where to treat would be the cost of treatments. Based on the increasing cost of treatments with increasing distance from infrastructure or mills/markets, it may be possible to treat more area and therefore avert a greater amount of loss by focusing on areas with lesser expected treatment costs. This makes intuitive sense and is likely used by fuel treatment planners, but has yet to be included in an operational program for planning fuel treatments or discussed in the literature.

The inclusion of ecosystem services is another large area of potential future research. Our work modeling the expected averted loss of biomass and sediment retention from fuel treatments draws on existing process based models. To be most effective, all other valued and affected services would be included in wildland fire management decisions. This would require tremendous work to accurately document, model, and map ecosystem services affected by wildland fire and/or forest management activities. This is particularly true for the social and cultural aspects of ecosystem services, while the biophysical elements are better represented. Verifying ecosystem service models with empirical data from areas affected by wildland fire will be another important research area, particularly with a widespread adoption of an ecosystem service based planning framework.

The deliverables crosswalk table

Deliverable type	Title/topic	Status
Final report*, USGS SIR*	Vulnerability and ecosystem services in wildfire risk assessments and cost-effective fuel treatment planning	Delivered & In prep
Publication	Cost-effective fuel treatment planning (for IJWF)	Draft
Publication*	Vulnerability to wildland fire, (forest policy and economics, natural hazards, applied geography journals)	In prep
Publication*	Ecosystem services in fuel treatment planning (IJWF, Ecosphere, Frontiers, Forest ecology and mgmt., PLoS ONE)	In prep
Publication	Modeling fuel treatment costs for landscape level planning (forest policy and economics)	In prep
Code/data*	Generating estimates of fuel treatment costs through customs code and MyFTP over an entire landscape or forest	delivered
Presentations*	Beginning with Boise IAWF (4/2014) & Portland IALE (7/2015)	scheduled

*Original deliverable

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