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Research article

Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado

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A B S T R A C T

A small but growing number of watershed investment programs in the western United States focus on wildfire risk reduction to municipal water supplies. This paper used return on investment (ROI) analysis to quantify how the amounts and placement of fuel treatment interventions would reduce sediment loading to the Strontia Springs Reservoir in the Upper South Platte River watershed southwest of Denver, Colorado following an extreme fire event. We simulated various extents of fuel mitigation activities under two placement strategies: (a) a strategic treatment prioritization map and (b) accessibility. Potential fire behavior was modeled under each extent and scenario to determine the impact on fire severity, and this was used to estimate expected change in post-fire erosion due to treatments. We found a positive ROI after large storm events when fire mitigation treatments were placed in priority areas with diminishing marginal returns after treating >50–80% of the forested area. While our ROI results should not be used prescriptively they do show that, conditional on severe fire occurrence and precipitation, investments in the Upper South Platte could feasibly lead to positive financial returns based on the reduced costs of dredging sediment from the reservoir. While our analysis showed positive ROI focusing only on post-fire erosion mitigation, it is important to consider multiple benefits in future ROI calculations and increase monitoring and evaluation of these benefits of wildfire fuel reduction investments for different site conditions and climates.

1. Introduction

Large, severe wildfires can negatively affect forested watersheds, jeopardizing critical ecological functions and ecosystem service benefits. These impacts include post-fire erosion and flooding, increased carbon emissions, loss of timber and non-timber forest products, loss of recreation access or quality, changes in habitat and biodiversity, and changes in scenic beauty (Kline, 2004; Mason et al., 2006; Loudermilk et al., 2014; Milne et al., 2014). Each of these effects can have substantial economic and social costs in addition to the direct costs of a wildfire, which include loss of life or property, fire suppression costs, and evacuation and administrative costs (Lynch, 2004). The prevalence, severity, and intensity of wildfire is increasing in the U.S. due to a combination of changing climate (Westerling et al., 2006; Flannigan et al., 2009; Van Mantgem et al., 2013; Rocca et al., 2014) and past fire suppression policies that led to the accumulation of fuels in many forest types (Stephens and Ruth, 2005). Coupled with an increasing number of homes in and near wildfire-prone ecosystems means the costs of federal fire management are also growing, and it is projected that 67% of the U.S. Forest Service's budget will be devoted to wildfire suppression by 2025 (USFS, 2015). These increasing costs affect the ability of federal agencies

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to meet other land management responsibilities and have led to repeated calls for more rigorous evaluation of the benefits and costs of wildfire risk reduction efforts (ERI, 2013).

Payments for ecosystem services (PES) are an increasingly important approach to conservation finance where the beneficiaries of ecosystem services pay for or incentivize the production of those services from ecosystem service providers (Wunder, 2015). The U.S. has more than 40 active PES programs focused on water related ecosystem services (Huber-Stearns, 2015), and this mimics a much broader global effort to increase government and private investments in securing watershed services from green infrastructure (Bennett and Carroll, 2014). Watershed investment programs are a specific type of PES program where downstream water users and upstream landowners collaboratively develop and fund activities to safeguard water supply (Ozment et al., 2016). A small but growing number of watershed investment programs focus on wildfire risk reduction (Bennett et al., 2014); experience with past fire events is often the catalyst for the creation of such programs (Emelko et al., 2011; Thompson et al., 2013; Bladon et al., 2014; Writer et al., 2014). For many of these programs municipal water providers are the primary beneficiaries and funders, and they are interested in reducing the large and direct costs to water delivery that occur following a fire (Ozment et al., 2016). One example of these costs is the effect of the Buffalo Creek and Hayman fires on Denver Water, in Denver, Colorado. The water utility spent more than $26 million post-fire on water quality treatment, sediment and debris removal, reclamation techniques, and infrastructure projects (Denver Water, 2016).

As a result of these high costs, Denver Water is involved in several watershed investment programs focused on wildfire risk reduction. It is part of the U.S. Forest Service's Forests to Faucets project, an arrangement between water utilities and the U.S. Forest Service that finances wildfire risk mitigation practices on federal lands that produce their source drinking water. In the Forests to Faucets partnership, Denver Water has spent over $11.5 million between 2011 and 2015 to conduct fuel reduction work and reforestation in previous high severity burn areas across three national forests and five watersheds, and they plan to invest an additional $16 million between 2016 and 2020 (Denver Water/USFS, 2014). Additionally, Denver Water is a key partner in the Upper South Platte Partnership (USPP); the USPP formed in 2015 to promote fire mitigation activities on private lands in the Upper South Platte watershed that complements work being conducted on federal lands through the Forests to Faucets program (CFRI, 2016). To date this partnership has raised millions of dollars to invest in wildfire risk mitigation. Colorado is not alone in these watershed investments to reduce wildfire risk, with similar efforts occurring in California, New Mexico, and Arizona (Bennett et al., 2014).

PES programs are increasingly being asked to provide evidence of the impact of their investments on ecosystem service outcomes as opposed to reporting implementation accomplishments (Ferraro and Pattanayak, 2006; Asbjornsen et al., 2015). However, few PES programs have conducted impact assessments, especially with more traditional economic frameworks such as cost-benefit analysis or return on investment (ROI) calculations (Boyd et al., 2015). Calculating ROI from wildfire risk reduction activities could aid watershed investment programs in demonstrating to stakeholders a need for proactive fire mitigation interventions that adaptively manage where and how much they invest and help secure additional funding. Financial and practical constraints limit the extent of wildfire risk reduction interventions, thus development of a system to prioritize management activities is crucial. In this paper we used a ROI framework to identify how the quantity and placement of wildfire risk reduction interventions would affect ROI in the Upper South Platte River watershed, southwest of Denver, Colorado. The Upper South Platte River watershed is a high priority site for Denver Water, as 80% of the water used by the 1.4 million residents of the Denver metropolitan area passes through this watershed. A series of large, severe wildfires have adversely affected water quality and sediment delivery to the main reservoir in the past (e.g., Moody and Martin, 2001).

Our overarching research question was: how do the quantity and placement of wildfire mitigation activities affect ROI? To answer this question we simulated fuel reduction activities (e.g., mechanical tree thinning), allowing the extent of fuel mitigation activities to vary between 5% and 100% of forested area within the watershed using the following placement strategies: (a) a strategic prioritization map and (b) accessibility. Potential fire behavior was modeled under 97th percentile fire weather conditions for each fuel mitigation placement scenario to determine the impact of fuel reduction interventions on predicted fire severity. We then calculated the expected change in post-fire erosion with and without fuel treatments for each of these modeled fire scenarios and used this to estimate the economic benefits and costs of investing in pre-fire wildfire risk reduction activities. The modeling approach presented here can be adopted for other PES programs to inform decisions about investments in wildfire risk reduction activities aimed at enhancing the resilience of forested watersheds to wildfire.

2. Background

Quantifying the impact of wildfire risk mitigation efforts on the probability of large, severe wildfires and their associated post-fire costs is a complex and challenging endeavor (ERI, 2013; Kalies and Kent, 2016). In the case of mitigating post-fire water quality impacts, the benefits from wildfire risk reduction depend on their ability to: (a) reduce the severity and/or probability of wildfire; (b) mitigate post-fire water quality outcomes such as erosion, debris flows, and increased chemical levels; and (c) reduce the costs to water utilities or other beneficiaries resulting from degraded water quality, loss of reservoir storage capacity, sediment removal from water intake facilities, and damage to infrastructure (Fig. 1). The estimated human benefits are highly dependent on the presence of wildfires and the magnitude of the precipitation after a fire. The type, quantity and placement of fuel reduction interventions within the watershed can influence the likelihood that any one of these outcomes will occur (Kalies and Kent, 2016; Sidman et al., 2016).

The decision of how much and where to invest can be informed by understanding the ecological, hydrological, and socioeconomic conditions of the watershed as well as the interactions among these. For example, a watershed investment program is likely to yield the most watershed service benefits in areas with potential for high severity wildfire resulting in complete overstory tree mortality and minimal ground cover, biophysical conditions that favor erosion and high sediment delivery (e.g., steep slopes, erodible soils, frequency and severity of rainfall, etc.), and where existing water infrastructure is susceptible to post-fire watershed impacts. Related to the latter point, each water utility or other beneficiary has different vulnerabilities to wildfire impacts due to both geographical characteristics such as spatial location of reservoirs and infrastructure and the type of gray, or built, infrastructure already in place to deal with these post-fire events. Therefore, spatial prioritization is critical for assessing the areas at highest risk and the associated placement of wildfire risk reduction efforts (Thompson et al., 2013).

Predicting the outcomes of wildfire risk reduction efforts requires linking potential fire behavior to runoff and erosion models to calculate the impact on watershed services that would occur with and without these efforts. Very few studies have tried to show

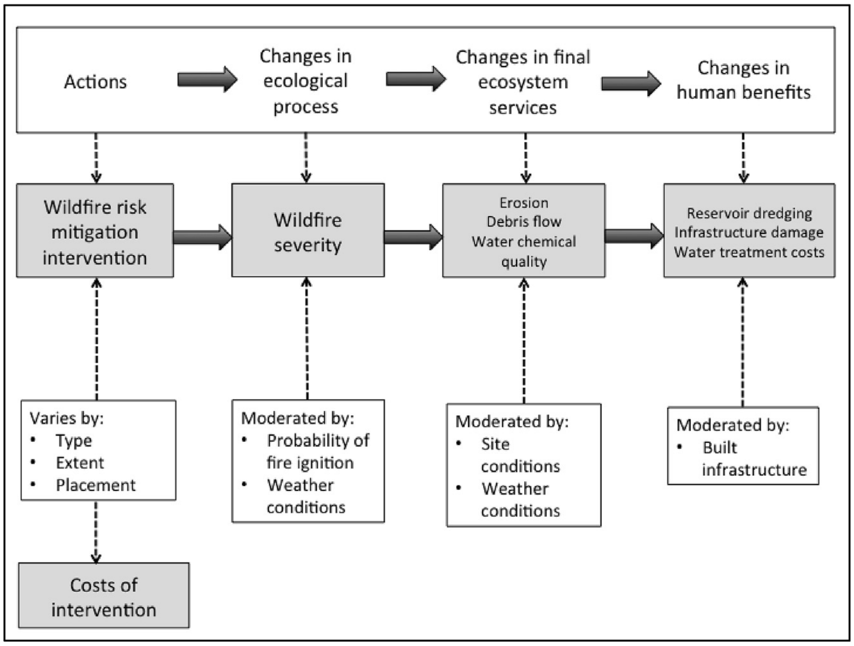

Fig. 1. Conceptual model of the economic benefits and costs from changes in watershed services due to wildfire risk reduction.

whether wildfire risk mitigation will lead to changes in water quality outcomes (Buckley et al., 2014; Kalies and Kent, 2016; Sidman et al., 2016). Once changes in hydrological outcomes from fuel treatments are predicted, the potential benefits to water utilities or other beneficiaries can be converted to monetary units using economic valuation methods. For example, the economic benefits of avoiding loss of reservoir storage can be measured as the avoided costs of dredging (Buckley et al., 2014); changes in chemical water quality can be reflected in savings to water treatment costs (Adildtrup et al., 2013); and the avoided loss of infrastructure can be assessed using the replacement cost of these items.

The benefits of investing in fuel reduction should be balanced against the financial costs (Boyd et al., 2015). Similar to the heterogeneity of ecosystem service benefits on the landscape, most natural resource management expenditures vary by landscape characteristics, and accounting for these costs often increases the efficiency of investments (Naidoo et al., 2006). While the largest cost in the case of wildfire risk reduction will be direct expenditures on implementing the wildfire reduction practice (Fig. 1), money will also have to be allocated for monitoring and re-treatment, as necessary. Additionally, staff time is required to negotiate and contract with other organizations to carry out the wildfire reduction interventions. These latter transaction costs are rarely estimated as part of the true costs of watershed investment programs.

Watershed investment programs focused on wildfire risk reduction may have other goals and objectives besides reducing post-fire impacts on watershed services. For example, additional benefits to investing in source water protection listed by Denver Water included reduced staff time negotiating and implementing post-fire responses (C. Burri, Denver Water Environmental Scientist, Personal Communication, 2016). These savings in employee time would have to be compared to time spent contracting for proactive fuel treatments in order to definitively say whether there is a net gain. However, mental health aspects, such as level of employee stress, are likely much lower when wildfire impacts are mitigated. PES programs also might emphasize the enhancement of other ecosystem service benefits such as recreation, carbon sequestration, scenic beauty, and habitat. Finally, some programs will include the benefits of decreased suppression costs, avoided loss of life or property, and reduced evacuation and fire administrative costs as part of their objectives.

3. Materials and methods

3.1. Study area

The two study watersheds were the Lowest North Fork (LNF; 12,100 ha) and the South Platte Canyon (SPC; 9700 ha). Both of these are hydrological unit code (HUC)-12 watersheds that drain to Denver Water's approximately 8.6 million m^3 Strontia Springs Reservoir (Fig. 2). They are located within the larger HUC-8 Upper South Platte River watershed (479,100 ha). The boundaries of the LNF and SPC watersheds together contain approximately 19,300 ha of forested land (89% of total; Rollins, 2009). Forests in the focal watersheds are composed primarily of mixed conifer forests (approximately 75%) dominated by *Pinus ponderosa* and *Psuedotsuga menziesii* along with a notable component of *Pinus ponderosa* woodlands (approximately 13%; Rollins, 2009). The soils of the Upper South Platte watershed are generally formed from decomposed granite, which is highly erodible (Graham, 2003; Moody and Martin, 2001). Accessibility is limited in the vicinity of the reservoir; for example, within the surrounding 2 km, more than 70% of the slopes are steep (>35% slope), and only one road is present.

3.2. Return on investment analysis

ROI analysis is a comparison of an investment's benefits and costs (Boyd et al., 2015). The benefits in a ROI analysis are the change in a desired outcome attributable to the investment. While a ROI analysis could consider all benefits and costs of a PES program, gathering information on each benefit and cost is challenging and time consuming. After past fires, Denver Water incurred large costs from dredging reservoirs and much smaller costs associated with changes in water treatment costs or damage to infrastructure (C. Burri, Denver Water Environmental Scientist, Personal

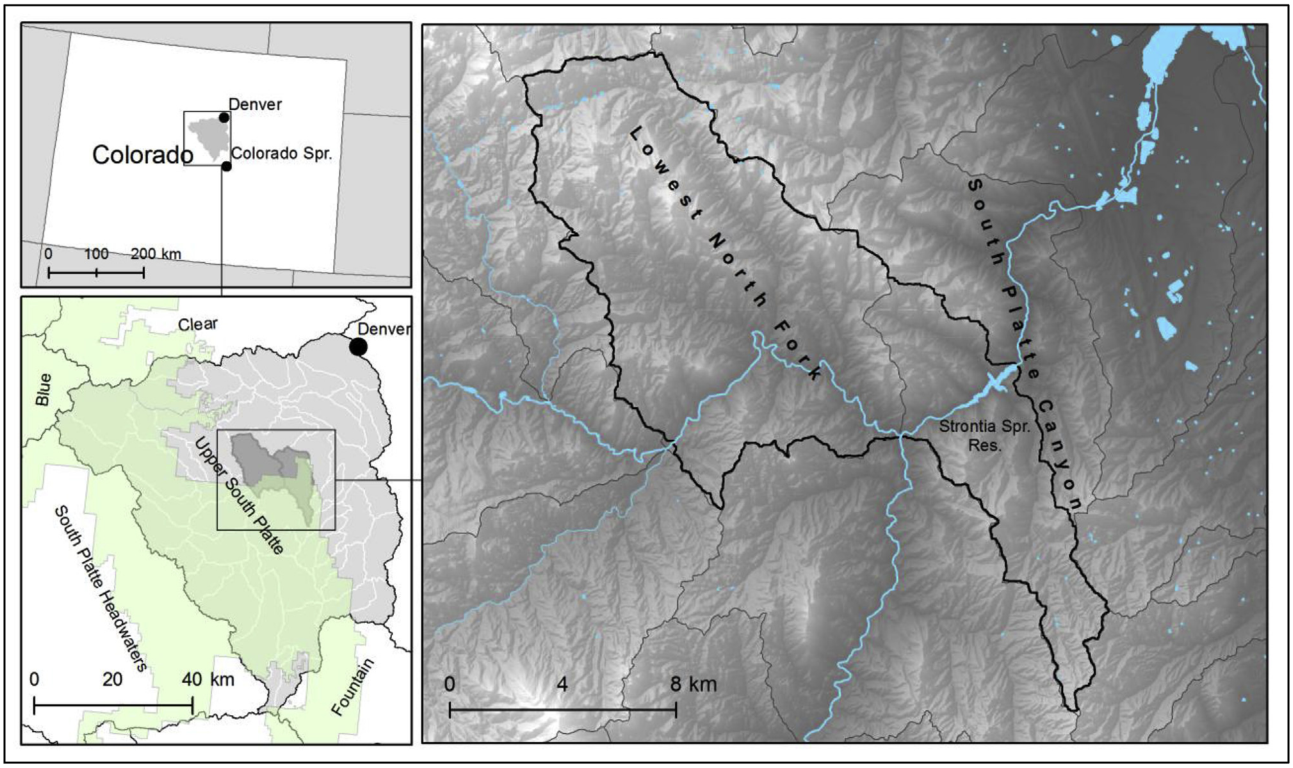

Fig. 2. Insets show the Lowest North Fork (LNF) and South Platte Canyon (SPC) sub-basins within the larger Upper South Platte watershed southwest of Denver and how much of these watersheds are in the Pike-San Isabel National Forest (shown in green). The larger map shows the portions of the LNF and SPC watersheds that contribute to Strontia Springs Reservoir. Main stream channels are in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Communication, 2016). For this reason, we focused on expected changes to sediment input into Strontia Springs Reservoir as a measure of expected ROI from PES investments in wildfire risk reduction. We used the avoided costs method to estimate these economic benefits. Investment costs were measured as expected expenditures on implementing fuel treatments under different extents and locations. Information on the calculations that go into the ROI analysis follows.

3.2.1. Fuel treatment and fire severity modeling

To simulate potential wildfire risk mitigation areas, we generated a hexagonal fishnet using 16.2 ha (40 acre) fuel treatment units distributed across forested portions of the two HUC-12s that contribute to Strontia Springs Reservoir (Fig. 3). Because sediment delivery usually decreases with distance from source (Walling, 1983; Wagenbrenner and Robichaud, 2014), we also analyzed ROI when wildfire mitigation activities were placed only in the SPC watershed, which contains Strontia Springs Reservoir. Fuel mitigation treatments were simulated in a factorial design that varied fuel treatment placement and extent, which is defined as the percent of the forested area of a watershed that is treated. We used two fuel treatment placement scenarios—an accessibility-based fuel treatment and a priority-based fuel treatment. Treatment extents within these two scenarios were varied from 5% to 100%. We only considered fuel mitigation treatment by mechanical and manual woody biomass removal since the use of prescribed fire remains very challenging and is partially restricted in Colorado (Hickenlooper, Executive Orders D 2012-006 and D 2015-002).

For the accessibility-based scenario, we classified all fuel treatment units as either accessible or inaccessible, where an accessible unit was defined as having >70% of the unit with slope <35% and within 2 km of a road or trail (30 m slope data, LANDFIRE; Roads and Trails, US Geological Survey, US Forest Service); we assumed all roads and trails were accessible to logging machinery. Using this accessibility criterion limited treatment extent to no more than 40% of the total study area. The priority-based treatment scenario was based on a map collaboratively developed by the USPP (http://uppersouthplattepartnership.org). The USPP prioritization ranked areas within these watersheds on a scale of one to six, based on identification of local areas where high wildfire hazard, high burn probability, and high potential for soil loss all coincide (CFRI, 2016). It is important to note that the larger scale process of sediment transport and delivery along streams to water infrastructure was not considered in this initial prioritization map. In the priority-based scenarios we simulated fuel treatments in all units in order of ranked priority with increasing extent from 5% to 100%. When we simulated fuel treatments for the SPC watershed only, extent ranged from 17-34% for accessibility-based scenario and from 17-86% for priority-based scenario.

For each fuel treatment scenario described above, we used LANDFIRE fuel and canopy layers to represent post-treatment forest conditions; LANDFIRE provides national spatial databases describing vegetation, fuel, and fire regimes (Rollins, 2009). For each treated unit, we simulated fuel treatments by reducing canopy cover by 30% (Fulé et al., 2012) and reducing canopy bulk density by 40%, although this may be a conservative reduction (Keane et al., 2005). Mechanical thinning typically removes small trees, thus treatment simulations increased mean canopy height and mean canopy base height by 20% (Ziegler, 2014). Post-treatment surface fuel models were reclassified as moderate-load conifer litter (model 183, Scott and Burgan, 2005), a surface fire behavior model characterized by low spread rate and flame length (approximately 1.7 m min^{-1} and 0.5 m, respectively under 97th percentile weather conditions).

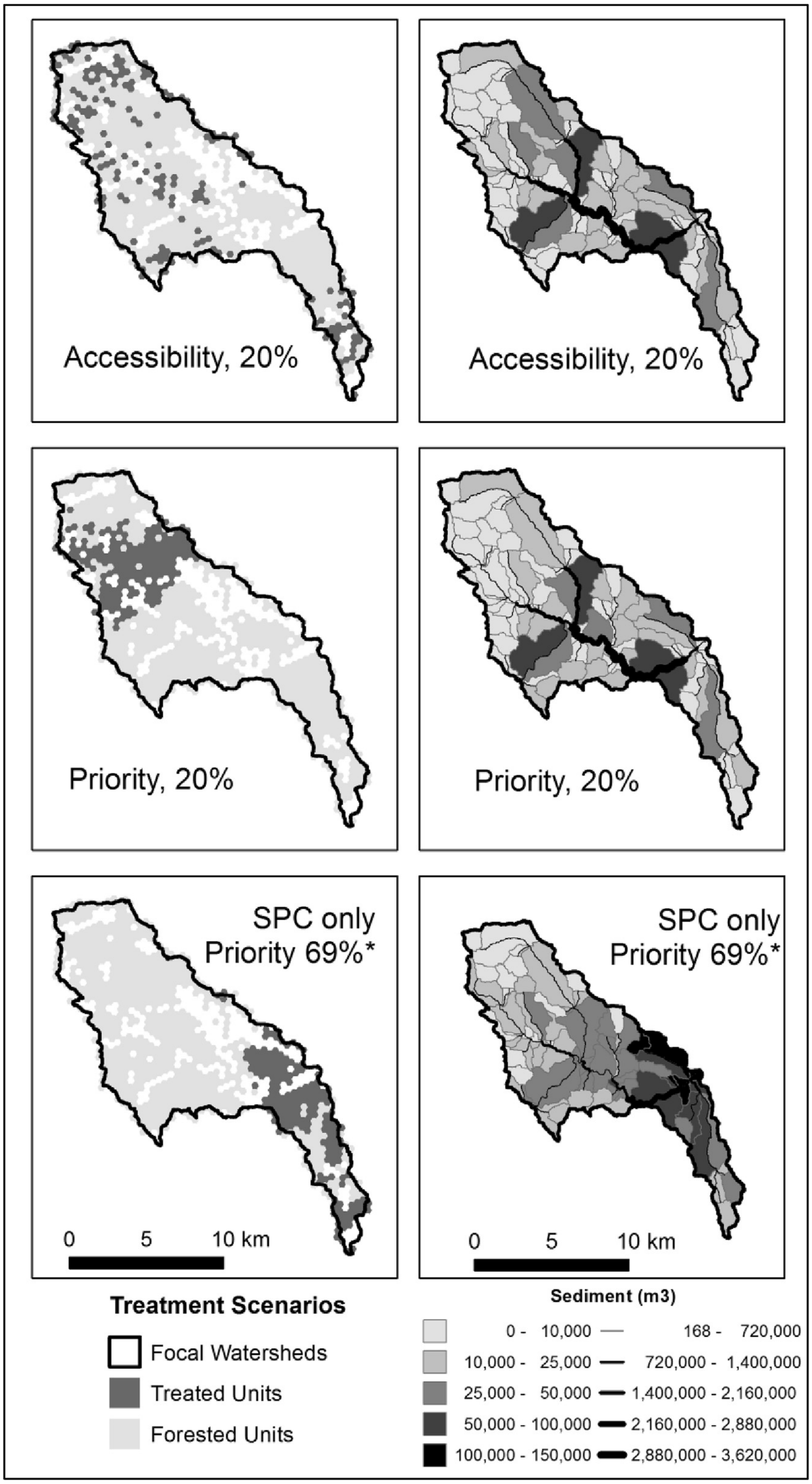

Fig. 3. Examples of simulated treatment location (left panel) and hillslope sediment production for the 100-year storm event (right panel). Panels show from top to bottom: 20% extent under accessibility scenario for both watersheds; 20% extent under priority scenario for both watersheds; 69% extent under priority scenario for SPC watershed. *69% SPC only is equivalent in area (hectares) to 20% extent of both watersheds.

Effects of simulated fuel treatments on potential fire behavior were simulated with FlamMap version 5. FlamMap calculates fire behavior characteristics such as spread rate and flame length for heterogeneous landscapes within a GIS framework (Finney, 2006). Inputs to FlamMap included a spatially-explicit landscape file with topography and fuel structure information (Scott and Reinhardt, 2001), and severe weather data (97th percentile fuel conditions from three weather stations <10 km from the watersheds of interest; Zachariassen et al., 2003). A wind speed of 48 km hr^{-1} (30 mi hr^{-1}) was used to represent conditions from spread periods of recent Colorado wildfires (Graham, 2003; Graham et al., 2012). A static wind direction of 225° was modeled in all fire simulations based on the modal direction of winds >16 km hr^{-1} (10 mi hr^{-1}) during the fire season (April 1 - October 31). The crown fire activity output was classified as surface fire (i.e., no crown fire), passive crown fire (i.e., torching), and active crown fire. These classes were used as a proxy for low, medium, and high burn severity, respectively (e.g., Tillery and Haas, 2016). Potential fire behavior was simulated in FlamMap for the entire study area and is representative of extreme fire behavior.

3.2.2. Erosion modeling

We used the crown fire activity outputs to estimate post-fire sediment delivery to Strontia Springs Reservoir during rain storms using the Automated Geospatial Watershed Assessment Tool and Kinematic Runoff and Erosion model (AGWA-KINEROS2). KINEROS2 is an open-source physically-based model that simulates interception, infiltration, surface runoff, erosion, channel flow, and channel sediment transport (www.tucson.ars.ag.gov/kineros). These processes are simulated for a network of hillslope elements and channels within the watershed. All hydrological processes are described by differential equations and solved by finite difference techniques to produce total sediment production for each hillslope element (Semmens et al., 2008) and total sediment delivery to each channel segment.

We prepared the inputs required for KINEROS2 using AGWA, which is available as an add-in tool for ArcGIS software (Miller et al., 2007). Using a 30 m digital elevation model (DEM; http://earthexplore.usgs.gov) AGWA discretizes the hillslope and channel network, with the user selecting the contributing source area (CSA) for hillslope elements as a percentage of total watershed area. We tested CSA values from 0.01% to 10% since erosion prediction is a scale-dependent process in the KINEROS2 model (Canfield and Goodrich, 2006). We selected a CSA of 1% for our final outputs; this produced 108 planes ranging in size from 1-606 ha (avg. of 150 ha) and 43 stream segments. Topographic parameters (slope, flow length, and area) were derived from the 30 m DEM; hydraulic properties were extracted from the STATSGO soil survey dataset (http://websoilsurvey.nrcs.usda.gov) (Levick et al., 2004); land use and land cover came from the National Land Cover Data (NLCD) dataset (http://viewer.nationalmap.gov; Homer et al., 2004). We used AGWA's built-in look-up tables to modify land cover and hydrologic soil class for the first year post-fire based on each burn severity scenario (Goodrich et al., 2005; Canfield et al., 2005). KINEROS2 is an event-based model, and it is suitable for representing post-fire erosion in the study area, where erosion is generated almost entirely by convective summer thunderstorms (Benavides-Solorio and MacDonald, 2005). For the simulations, we used 6-h storms with return periods of 1-, 10-, and 100-years and assumed that these storms occurred during the first year post-fire before vegetation regrowth. The storms were applied uniformly over the watersheds.

KINEROS2 outputs include total sediment production (kg) and sediment yield (kg ha^{-1}) from each hillslope element and channel segment for each fuel treatment and storm scenario. For channel segments, the sediment production and yield values were simulated based on the upstream hillslope inputs and sediment routing through the channel network. We summed sediment mass across the hillslope and channel elements that connect to Strontia Springs Reservoir to determine the total potential sediment load entering the reservoir (kg). Finally, we converted the mass of sediment to a volume using an average bulk density of 1.6 (t m^{-3}) (Avnimelech et al., 2001; Verstraeten and Poesen, 2001).

3.2.3. Economic analysis of costs and benefits

The change in predicted sediment input volumes to Strontia Springs Reservoir were calculated for no fuel treatment plus wildfire and each fuel treatment scenario plus wildfire. This gave us the expected change in sediment input that could be attributable to each fuel treatment scenario. To convert this into a monetary value we used the U.S. dollars m^{-3} spent by Denver Water in dredging Strontia Springs Reservoir following the Buffalo Creek and Hayman fires; adjusting for inflation this is approximately $100 m^{-3}.

To estimate the costs of fuel reduction treatments we first summed the area treated under each fuel scenario by accessible and inaccessible using the definition given in section 3.2.1. For accessible areas we used a fuel treatment cost estimate of $3700 per ha ($1500 per acre), and for inaccessible areas we used a fuel treatment cost of $6100 per ha ($2500 per acre). The costs of fuel treatment were estimated based on a combination of recent fuel treatment projects in the Upper South Platte River watershed, published literature, and expertise on our team. In general, fuel treatment costs vary by slope and accessibility of the unit, and estimates in the literature range between about $2500 and $6000 per ha (Skog and Barbour, 2006; Hartsough et al., 2008; Buckley et al., 2014). We assumed no project revenue from biomass or merchantable timber following fuel treatments since projected revenue from these sources is minimal in the Upper South Platte; this was determined from reviewing recent fuel treatment projects in the area. We did not discount monetary expenditures on fuel treatments but assumed that they were incurred over the course of one year. This was done to match the one-year calculation of post-fire sediment delivery (section 3.2.2).

4. Results

We found little difference between the accessibility- and priority-treatment scenarios in terms of the reduced extent of high-to-medium severity wildfires (Table 1). The greatest reduction in these wildfires was due to increasing the area treated, although this was limited to a maximum of 40% of forested area under the accessibility-based criterion. Hence, accessibility-based treatments reduced canopy cover from 46% to 41% and reduced high-to-medium severity fire extent from 87% with no treatment to 60% when 40% of the area was treated (Table 1). For priority-based treatments canopy cover was reduced from 46% to 32%, and the associated reduction in high-to-medium severity fire extent was from 87% with no treatment to 16% when 100% of the area was treated.

Similar outcomes were found when fuel treatments were constrained to occur only in the SPC watershed. As accessibility-based treatments increased from 17% to 34% of the forested area, high-to-medium severity fire extent decreased from 85% to 61% (Table 1). Since we were able to treat more area in the priority-based scenarios, high-to-medium severity fire extent was reduced from 85% with no treatment to 17% when 86% of the area was treated.

The simulated volume of sediment delivered to Strontia Springs Reservoir (sediment load, m^3) had a similar pattern between the three storm events but with different magnitudes (Table 1). The sediment loads reported in Table 1 have a higher degree of precision than is justified by the absolute accuracy of the erosion model, but the absolute values illustrate the relative differences between scenarios. Accessibility-based treatment scenarios had no effect on sediment load given the limited extent of treatment, whereas priority treatment scenarios had no effect on sediment load when 30% or less of the watersheds were treated. When >40% of treatment units were treated under the priority-based scenario, sediment load for the 1-year storm event was less than 1000 m^3 of sediment (Table 1), but this value increased to 10,000 m^3 when <40% of the

Table 1
Fire and erosion simulation summaries across treatment scenarios and storm events from both watersheds and the SPC watershed. Sediment load columns sum the total volume of sediment delivered to Strontia Springs Reservoir across all hillslopes.

Treatment Scenario	Area treated (ha)	High–Medium Severity Fire Extent (% watershed)	Mean Canopy Cover (%)	Sediment Load 1-year Storm Event (thousands m^3)	Sediment Load 10-year Storm Event (thousands m^3)	Sediment Load 100-year Storm Event (thousands m^3)
Both SPC and LNC watersheds						
No Treatment 0%	0	87	46	10	680	2500
Accessibility 5%	712	83	45	10	680	2500
Accessibility 10%	1408	80	44	10	680	2500
Accessibility 20%	2817	73	43	10	680	2500
Accessibility 30%	4225	67	42	10	680	2500
Accessibility 40%	5633	60	41	10	680	2500
Priority 5%	712	83	45	10	680	2500
Priority 10%	1408	80	44	10	680	2500
Priority 20%	2817	72	43	10	680	2500
Priority 30%	4225	66	41	10	680	2500
Priority 40%	5633	59	40	3	640	2400
Priority 60%	8450	45	37	1	340	2000
Priority 80%	11,266	30	34	1	230	1700
Priority 100%	14,083	16	32	1	230	1700
SPC watershed						
No Treatment 0%	0	85	53	10	660	2400
Accessibility 17%	712	73	51	10	650	2400
Accessibility 34%	1408	61	48	10	650	2400
Priority 17%	712	72	50	2	580	2300
Priority 34%	1408	59	47	1	430	2100
Priority 52%	2121	45	45	1	230	1600
Priority 69%	2817	30	42	1	230	1600
Priority 86%	3529	17	39	1	230	1600

area was treated. Far higher sediment loads resulted from the 10-year and 100-year storms for scenarios with <40% treated (680,000 and 2,500,000 m^3 respectively). Sediment loads declined steeply for these storms following 40%–80% fuel treatment extent and stabilized at >80% treatment (230,000 and 1,700,000 m^3 for 10-year and 100-year storms, respectively).

Because the SPC watershed is closest to Strontia Springs Reservoir, simulated treatments that focused only on this watershed were more effective at reducing sediment load (Table 1; Fig. 3). For example, in the scenario with 2817 ha of treatment spread across both SPC and LNF (Priority 20%), declines in sediment loads for all storms were negligible relative to the no treatment scenario. Concentrating the same total treatment area in SPC (2817 ha; Priority 69%) produced 36–90% reductions in sediment load relative to the no treatment scenarios, with the largest percent reduction in the 1-year storm and largest absolute reduction in the 100-year storm. Sediment load to the reservoir following priority-based treatments in the SPC dropped off considerably across all storm events when ~50% extent was treated and stabilized just above 50% treated.

The economic benefits followed similar patterns to the predicted sediment load to Strontia Springs Reservoir, with larger benefit when >40% extent was treated using the priority-based scenario (Table 2). However, the increasing fuel treatment costs with extent treated created diminishing returns (Figs. 4 and 5). When both watersheds were treated, priority-based treatments only resulted in a positive ROI in the case of a 100-year storm event and when at least 50% of the watershed was treated (Fig. 4). Financial returns began to decline after 80% of the area was treated.

For the SPC watershed the priority-based treatment scenario resulted in positive ROI for both 10- and 100-year storm events for all treatment extents (Fig. 5). A positive ROI was found when treatment extent was as low as 17%, and the maximum ROI occurred when about 50% of the forested area was treated. There was no positive ROI for the 1-year storm event as this generated less than 2% of the sediment load compared to the 10- and 100-year storm events.

5. Discussion

5.1. Management implications

Denver Water and other beneficiaries of fuel treatments in the Upper South Platte River watershed could potentially achieve positive ROI conditional on severe fire under extreme conditions and storm occurrence following fuel reduction investments. Across both watersheds positive ROI could be achieved after about 50% extent treated (~7000 ha; about $40 million in fuel treatment costs) and as little as 17% extent treated in the SPC watershed (~1000 ha; about $2.6 million in fuel treatment costs). These areas and budgets are in the range of current and future expected efforts in the Upper South Platte (e.g., Forests to Faucets and the USPP). For example, under the first five years of the Forests to Faucets program about 16,000 ha were treated across five watersheds with about 5500 ha treated in the Upper South Platte River watershed (across entire HUC-8: total area, 479,100 ha). The program expects to treat another 18,000 ha in its priority zones between 2016 and 2020 (Denver Water/USFS, 2014). We reached the 5500 ha mark after

Table 2
Economic benefits and costs across fuel treatment scenarios and storm events from both watersheds and the SPC watershed.

Treatment Scenario	Fuel Treatment Costs (thousands $)	Economic Benefits with 1-year Storm Event (thousands $)	Economic Benefits with 10-year Storm Event (thousands $)	Economic Benefits with 100-year Storm Event (thousands $)
Both SPC and LNC watersheds				
No Treatment 0%	0	N/A	N/A	N/A
Accessibility 5%	2800	0	100	230
Accessibility 10%	5500	0	130	440
Accessibility 20%	11,000	0	310	960
Accessibility 30%	16,400	0.2	490	1560
Accessibility 40%	21,900	0.4	620	1990
Priority 5%	3300	0	100	230
Priority 10%	6600	0	100	440
Priority 20%	13,200	0	160	800
Priority 30%	19,700	0.3	280	1230
Priority 40%	26,500	700	4400	11,340
Priority 60%	40,700	900	34,100	53,890
Priority 80%	54,600	900	44,700	84,190
Priority 100%	66,900	900	45,000	84,870
SPC watershed				
No Treatment 0%	0	N/A	N/A	N/A
Accessibility 17%	2600	0	150	330
Accessibility 34%	5300	0.4	350	850
Priority 17%	2600	700	7900	15,100
Priority 34%	5200	800	22,430	33,000
Priority 52%	7900	900	42,400	80,380
Priority 69%	10,400	900	42,540	80,730
Priority 86%	13,100	900	42,740	81,150

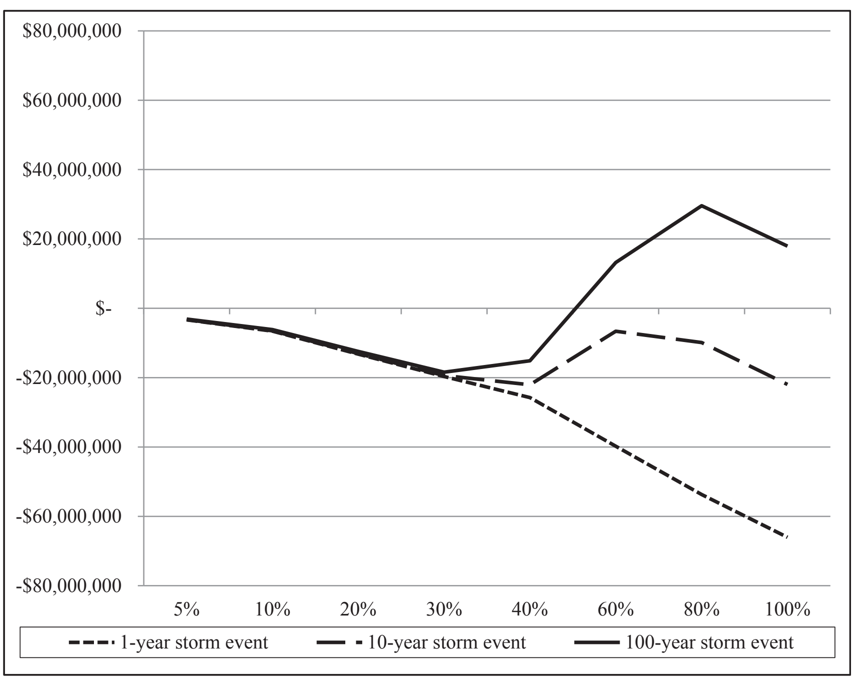

Fig. 4. Return on investment by treatment extent and storm recurrence interval (1-, 10-, and 100-years) for both watersheds (SPC and LNC) under the priority-based treatment scenarios. Y-axis is return on investment and X-axis is extent of fuel treatment simulation (not the absolute percent of the watershed that was treated).

treating 40% of both watersheds, and 5500 ha represented >86% extent treated in the SPC watershed. In our modeling simulations, ROI would be maximized after treating about 11,000 ha across both watersheds and 2000 ha in the SPC watershed.

Our simulated modeling results provide insight on how the extent of area treated and the prioritization of fuel treatments affect a PES program's expected financial returns. For example, our analysis shows that spatial placement of fuel treatments within the watershed affects ROI. Basing fuel treatments on accessibility alone did not yield positive ROI under any extent treated. The USPP's previously created prioritization map for our two watersheds resulted in positive financial returns, but our findings suggested higher prioritization should be given to the SPC watershed, whereas the former prioritization map emphasized the LNF watershed. This discrepancy is likely to arise because of the different scales and objectives used for the prioritization map

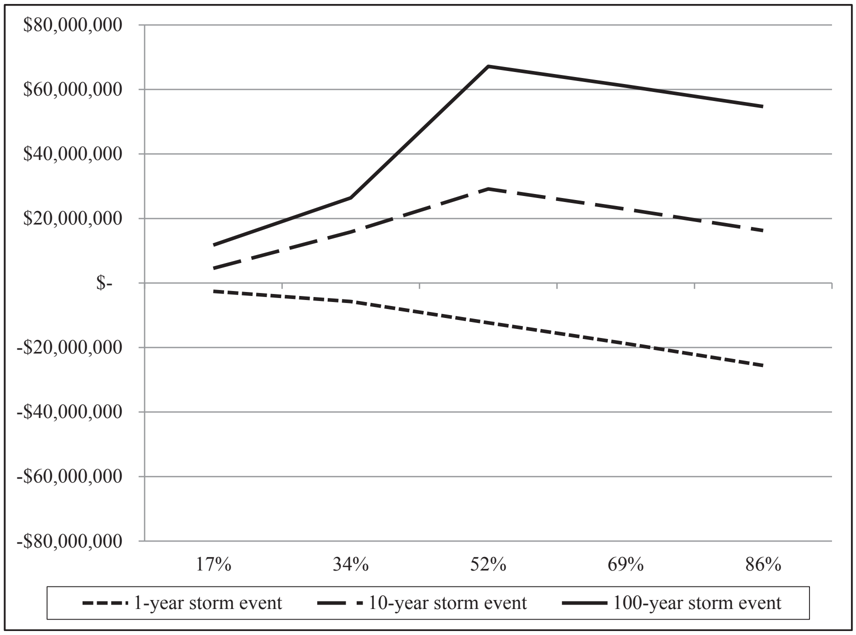

Fig. 5. Return on investment by treatment extent and storm recurrence interval (1-, 10-, and 100-years) for SPC watershed under the priority-based treatment scenarios. Y-axis is return on investment and X-axis is extent of fuel treatment simulation (not the absolute percent of the watershed that was treated).

produced by the USPP versus our analysis (section 3.2.1). The prioritization map was developed with the goal of preventing soil loss and does not explicitly model sediment transport and delivery to reservoirs following erosion. However, in our analysis the focus was on sediment transport and delivery to Strontia Springs Reservoir. Hence, our approach shifted fuel treatment emphasis toward investments in forests that directly drain into reservoirs as compared to fuel treatments aimed solely at mitigating post-fire erosion (e.g., Fig. 3). This discrepancy highlights the importance of considering landscape-scale transport processes when conducting landscape-level prioritizations for reducing erosion.

For the two watersheds and SPC-only scenarios, treating 50% of forested area was optimal in terms of maximizing ROI. However, the total area needed for maximizing ROI varied considerably from 2000 ha in the SPC watershed to 11,000 ha across both watersheds. Our analysis in the SPC watershed highlights that smaller forested areas that are proximal to water infrastructure can have a disproportionately higher contribution to sediment delivery than may be expected based solely on erosion risk assessments that do not consider sediment transport along stream networks. These differences can have significant impacts to watershed services and ROI for water utilities.

In addition to placement and extent of fuel treatments, the financial returns to PES investments will also be affected by the post-fire costs to beneficiaries. The monetary cost of dredging Strontia Springs is significantly higher than many other reservoirs due to the difficulty in accessing the reservoir and the soil type within the watershed. For example, in the Mokelumne watershed in CA, a dredging cost of \$26 m^{-3} was used to calculate ROI; this figure comes from a published study of dredging costs in the Klamath Basin (Buckley et al., 2014). Even within Denver Water's system, the cost of dredging Strontia Springs is significantly higher than what they have spent dredging other reservoirs; for example, they spent \$24 m^{-3} to dredge Cheesman Reservoir after the Hayman fire. If dredging costs were \$25 m^{-3} for Strontia Springs, our ROI calculations would have only been positive for the SPC only treatments following a 100-year storm event in the first year after burning. In this case the ROI would have been closer to \$6 million instead of >\$60 million.

Thus, future analyses of ROI from watershed investment programs would benefit from considering the full suite of outcomes that PES programs investing in wildfire risk reduction aim to impact. In the case of Denver Water, the savings to staff time and resources was considered a major benefit to being proactive versus reactive to large fires, but this staff time would have to be balanced against their time spent contracting for wildfire risk mitigation activities. A more complete ROI might account for: other ecosystem service benefits from reducing the probability of large, severe wildfires (e.g., recreation, aesthetics, timber); reduced suppression costs following a less-severe wildfire event; and the impact of the watershed partnership on community or social capital. Current evidence on the ecological and socioeconomic impacts of fuel treatments is limited (ERI, 2013; Kalies and Kent, 2016). More complete information on the full suite of benefits from wildfire risk reduction will take time to materialize, and watershed investment programs can help facilitate these efforts by implementing and maintaining monitoring protocols around each program objective. An ideal monitoring protocol would include collecting data before interventions occur and collecting data on control, or untreated, sites. PES programs can partner with academic institutions and research centers to develop monitoring protocols and conduct evaluations.

5.2. Modeling caveats and research needs

The goal of our study was to estimate the potential ROI of fuel reduction treatments in avoided sediment removal costs following an extreme fire event in the Upper South Platte. The values of ROI we presented depend on several assumptions about extreme weather and timing of fire and precipitation events. For example, our results do not consider fuel treatment longevity and assume that a fire immediately follows treatment and that extreme storms then cause erosion on the burned area during the first year post-fire. These findings are based on hypothetical scenarios and represent a worst-case situation. We also caution that these results should not be transferred one-for-one to other watersheds because each location has a unique combination of factors that affect wildfire risk, post-fire erosion and sediment transport, and financial impacts on downstream users. Other PES programs should consider how their investments would be impacted by the unique biophysical and socioeconomic conditions present in their own watersheds (e.g., Fig. 1).

Inputs into our modeling framework directly influenced ROI results. A complete simulation of wind directions, weather parameters, burn probabilities, and ignition probabilities was beyond the scope of our analysis and therefore we created a simplified burn scenario to increase tractability (Miller and Ager, 2013). The weather parameters simulated here were dry (97th percentile fuel moisture conditions) with high wind speeds (48 km hr^{-1}; 30 mi hr^{-1}) but were comparable to conditions modeled in other landscape-scale assessments of fuel treatment effectiveness (e.g., Moghaddas et al., 2010). To simplify analyses, we used the crown fire activity output from FlamMap to approximate fire severity in extreme conditions, and we assumed that the entire focal watersheds of interest were burned. Although we assumed all ~21,000 ha of our two watersheds burned, fires of this size are not unprecedented in the study area (e.g., 56,000 ha Hayman fire in 2002 [Graham, 2003]; 5000 ha Buffalo Creek fire in 1996 [Moody and Martin, 2001]; and approximately 4000 ha Hi Meadows fire in 2000 [Wagenbrenner et al., 2006]).

Our study did not explicitly model fire growth and spread, so the effect of fuel treatments acting as fuel breaks was not incorporated (Green, 1977). Other fire models have incorporated the effect of fuel treatment arrangements on wildfire spread (e.g., Spies et al., 2017), and previous studies have found that completing forest fire mitigation over just 20–40% of a landscape in a prioritized fashion can be optimal to reduce potential fire spread (Finney et al., 2011). We did not explicitly analyze optimal arrangement of fuel treatments for reducing fuel spread, and our finding that ~50% area should be treated to maximize ROI relates to the area needed to reduce erosion and sediment delivery. Our model did not incorporate forest dynamics such as fuel treatment longevity (Rhodes and Baker, 2008) or post-fire recovery since we did not explicitly incorporate a time dimension. Future models estimating ROI would benefit from adding in a decline in fuel treatment effectiveness over time. Most PES programs invest in fuel treatments over a number of years, and changes in effectiveness over time would affect the expected benefits and costs from wildfire risk mitigation for any given year. Additional future research directions include investigating the effects of prescribed fire in combination with mechanical thinning to maintain the longevity of fuel treatments (Kalies and Kent, 2016), and incorporating predicted erosion from treatment activities such as logging roads or biomass removal into post-treatment erosion scenarios.

The complex overland flow, erosion, and channel processes we simulated represent hypothetical reservoir sedimentation under specified storm conditions; similar to findings in other studies, these types of scenarios help estimate relative reductions in sediment production from different fuel treatment extents and locations (Buckley et al., 2014; Sidman et al., 2016). Our simulated sediment loads appear reasonable compared to post-fire sediment inputs to Denver Water's reservoirs after recent fires (~760,000 m^3 from Hayman and Buffalo Creek fires; Bladon et al., 2014). The simulations each represent single storm sediment loads rather than accumulated sediment over time, and actual post-fire erosion will depend on the magnitude and timing of rainstorms falling on areas of varying burn severity. The hypothetical erosion simulations are affected by uncertainties in burn simulations; methods for relating fire model output to burn severity, ground cover, and soil hydraulic properties; and assumptions about model parameter values. For this application, we used potential crown fire as a proxy for burn severity, but more research is needed to test methods for relating fire model output to vegetation and soil parameters in erosion models. Future research could expand on the AGWA approach for relating burn severity to changes in erosion model parameters; verifying changes with data from a wide range of fires would help improve confidence in the relationships between fire model outputs and erosion model inputs. Tests of erosion model sensitivity also show that the simulated sediment loads are affected by the size of the hillslope elements, indicating that further research is needed to define the appropriate scale for applying this model.

A major step forward in fire-erosion-economic integrated modeling would be to place future analyses into a probabilistic risk management framework. This type of analysis could evaluate fire and erosion risks more comprehensively by considering the time range of fuel treatments, probability of fire during a sequence of years after treatment, and probability of storms during a sequence of years after the fire. We found that extreme, low probability storms (10- and 100-year events) cause much more erosion than higher probability storms (1-year event). Managers will likely need to be prepared for the most extreme fire and erosion scenarios, but a more comprehensive risk assessment could combine burn and storm probabilities to determine the joint likelihood that an extreme storm would follow an extreme wildfire. Incorporating these temporal and probabilistic dimensions would permit a more accurate assessment of ROI for watershed investors, allowing incorporation of uncertainty and discounting of economic costs and benefits into the ROI calculations.

6. Conclusions

With growing emphasis on evidence-based natural resources management, PES programs and government agencies are increasingly required to provide information on the effectiveness of their expenditures. Our results provide preliminary evidence that wildfire risk reduction practices can have a positive financial return under assumptions of extreme fire events in terms of avoided impacts on downstream watershed services. If the full suite of potential outcomes from reducing severe wildfires were accounted for, the economic and social benefits from investing in watershed health and fire resilience would likely be much higher for the Upper South Platte. Our research question and integrated modeling effort illustrate the evolution towards a more intensive analytical approach to estimating ROI for PES programs by linking biophysical and economic information. While integrated modeling is a credible method to estimate the impact of wildfire risk reduction investments on erosion and sediment delivery, these models are still at an early development stage. Future advances and validation of these models will greatly benefit PES programs and other organizations interested in wildfire fuel reduction investments.

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