



**AgEcon** SEARCH  
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

## Wildfire risk and optimal investments in watershed protection

Travis Warziniack<sup>1</sup> and Matthew Thompson<sup>2</sup>

### Introduction

Following what was then one of the most destructive fire years on record, President Bush signed into law the Healthy Forests Restoration Act of 2003. The law requires no less than fifty percent of all funds allocated for hazardous fuels reductions to occur in the wildland-urban-interface (WUI), with the aim of enhancing the protection of homes and reducing the costs of fighting wildfire. Available resources, however, have not been able to keep up with the accumulation of fuels and a rapidly expanding WUI. In 2012, wildfires burned 9 million acres in 67,000 separate fires throughout the United States. Total acreage burned was roughly equivalent in size to the states of Massachusetts and Connecticut combined and was the third largest annual acreage burned since 1975. That same year, Colorado saw its two most destructive fires on record, and Oregon saw its largest fire in more than a century. Costs for fighting these fires totaled about \$1.6 billion, in line with a twenty year trend of increasing costs of wildfire suppression (National Interagency Fire Center 2013).

In the West, these fires burn in the same forests that supply our drinking water. Language in the Healthy Forests Restoration Act relating to the importance of healthy forests for drinking water focuses on forests' role in filtering pollutants but says nothing about the risk unmanaged forests may cause to drinking water supplies. This omission is remarkable considering 80 percent of freshwater originates in forested areas in the US, 50 percent of Western freshwater originates in National Forests, and most of those watersheds are highly threatened by wildfire (Weidner and Todd, 2011).

High severity wildfires can destroy the forest canopy and vegetation that usually intercepts falling precipitation, and burned soils can acquire a water-repellent layer. These changes lead to increased overland flow and runoff composed of ash, soil, rocks, and vegetative matter during precipitation events (Parise and Cannon 2012). Streams, in turn, see changes in flow regimes, flood frequency, erosion, debris flows, and ultimately degraded water quality (Moody and Martin 2009; Shakesby et al. 2006; Neary et al. 2005; Ice et al. 2004). Such impacts to watersheds increase drinking water treatment costs, increase sedimentation of reservoirs, and damage critical infrastructure (Cannon and Gartner 2005; Meixner and Wohlgemuth 2004).

Reducing wildfire risk throughout the West has proven to be a Herculean task, requiring both public and private land owners to take action. In an effort to engage multiple stakeholders, and reduce the cost to the federal government, agencies have begun partnering with some of the country's largest water suppliers. The Western Watershed Enhancement Partnership, for example, is a collaborative effort between the US Department of Agriculture and the US Department of Interior to work with local water users to mitigate risks of wildfire to the nation's water supply and critical infrastructure, often located on federal lands. The pilot project for the initiative focuses on the watersheds of the Upper Colorado Headwaters and the Big Thompson, which are managed by a diverse group of state, federal, and private owners and supply drinking water to much of Colorado's Front Range.

---

<sup>1</sup> Research Economist, USFS Rocky Mountain Research Station, Fort Collins, CO, [twwarziniack@fs.fed.us](mailto:twwarziniack@fs.fed.us)

<sup>2</sup> Research Forester, USFS Rocky Mountain Research Station, Missoula, MT, [mpthompson02@fs.fed.us](mailto:mpthompson02@fs.fed.us)

Buy-in for these collaborations has been mixed. While water suppliers are well aware of the costs associated with protecting their watershed, measurements of the benefits are usually anecdotal. Arguments for protection often cite, for example, the effects of heavy rains in 2002 that followed the Hayman Fire and filled Denver Water's reservoirs with sediment, leading to \$28 million in removal costs (Meyer 2006). Similarly, heavy rains following the High Park Fire in 2012 forced Fort Collins Utilities to shut down its Cache la Poudre River intakes and prompted a 4 percent rate hike to fund capital improvements necessary for maintaining the river as a viable drinking water source (Fort Collins Utilities 2012). Proponents also often cite cross-sectional studies that look broadly at the benefits of investments in watersheds and costs associated with watershed degradation (Ernst 2004, Moore and McCarl 1987, Forster et al. 1987, Dearthmont et al. 1998, Holmes 1998). Holmes (1988), on the other hand, found that water utilities in the US with raw water turbidity levels over 10 Nephelometric Turbidity Units (NTUs) already use sedimentation or flotation during treatment and are not likely to see sizeable benefits from investments in green infrastructure. Anecdotal evidence is useful in understanding post-fire costs, but does not address the probability of a fire actually occurring. The cross-sectional studies are useful in valuing small changes in turbidity but are not useful in assessing the costs of extremely large and sudden increases in sediment loads associated with post-fire floods.

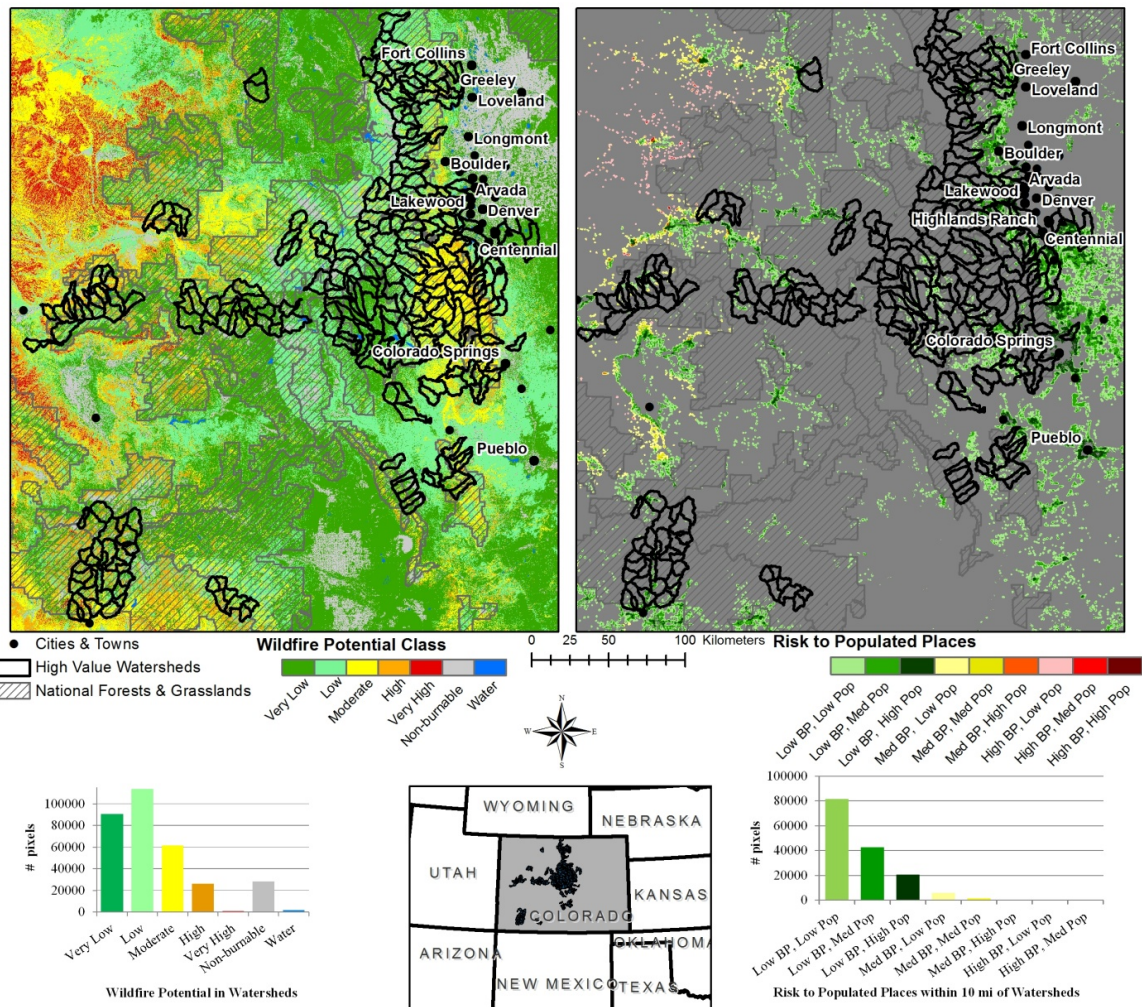
In this paper, we argue that a more thorough assessment of the benefits from green infrastructure should treat investments in watershed protection like a risky portfolio of assets. We use a familiar tool in finance, the Sharpe ratio, to model efficient wildfire loss mitigation, taking into account constrained budgets and risk of wildfire across multiple watersheds. The application of a finance tool to set priorities for wildfire protection is novel, though they have been used to prioritize investments in other areas of environmental protection (e.g., Qui et al. 1998). Decision support tools for wildfire mitigation are becoming increasingly sophisticated in terms of their ability to evaluate wildfire risk, but efforts at prioritizing mitigation activities have generally not considered investment theory or financial risk. Here, in an illustrative example for Colorado and Fort Collins, we present spatial mapping tools and data useful for assessing watershed risk, and combine these tools with our investment model to show how land managers can optimize investments in wildfire risk reduction.

### **Wildfire threats to water supplies and mitigation opportunities**

During a wildfire, incident managers must consider fire behavior and spread with respect to the location and susceptibility of water supply systems and other highly valued resources and assets (HVRAs), for which the decision support functionality is embedded within the Wildland Fire Decision Support System (Calkin et al. 2011). In a post-fire environment, efforts are typically aimed at assessing severity and associated water quality impacts in order to prioritize watershed stabilization and rehabilitation efforts (Robichaud and Ashmun 2013, Cannon et al. 2010, and Calkin et al. 2008). In a pre-fire environment, however, wildfire activity is uncertain, necessitating projections of potential wildfire-watershed interactions and their consequences. Increasingly, spatial wildfire risk assessments are used to support such pre-fire assessment and mitigation planning (Miller and Ager 2012). A general framework for wildfire risk assessment considers three main factors: fire likelihood, fire intensity, and resource or asset susceptibility (Scott et al. 2013). The use of stochastic wildfire simulation modeling can capture spatial variability in ignition patterns, weather patterns, topography, and fuel conditions, providing a key probabilistic foundation for risk modeling (Thompson and Calkin 2011). Overlaying fire modeling outputs with maps of HVRAs can quantify HVRA exposure to wildfire in terms of burn probability, fire intensity, and HVRA area burned (Thompson et al. 2013a; Scott et al. 2012). Further, the characterization of potential wildfire impacts to HVRAs, based in part off of linkages between fire intensity and fire severity (Heward et al. 2013; Keeley 2009), can allow for the

quantification of wildfire risk in terms of expected loss (Thompson et al. 2013b; Thompson et al. 2013c).

As an illustration of exposure analysis, we overlaid fire modeling outputs with maps of high value watersheds (Figure 1, left panel) and populated areas (Figure 2, right panel) for the state of Colorado. Maps of high value watersheds come from the US Forest Service’s Forests to Faucets project, and maps of residentially developed populated areas come from a new risk-based WUI layer (Haas et al. 2013). Both panels rely on spatially-resolved fire modeling outputs from the FSim fire modeling system (Finney et al. 2011). In the left panel, we use a derived product called Wildland Fire Potential (WFP), which is produced by the US Forest Service’s Fire Modeling Institute and which integrates burn probability and fire intensity outputs. Areas with higher WFP values have a higher probability of having fires with torching, crowning and other forms of extreme fire behavior, which could lead to increased difficulty of control and to increased damages. In the right panel, by contrast, raw burn probabilities are used and intersected with population density to categorically depict risk to populated places. Areas with the highest likelihood of burning and the highest population densities pose the greatest risk.



**Figure 1:** Wildfire exposure analysis for high value watersheds (left panel) and populated places (right panel), for the state of Colorado.

As the figure shows, areas of northwestern Colorado exhibit the greatest wildfire potential (left panel) and commensurately some of the highest risk to populated places (right panel). However, the absence of highly valued watersheds in these areas means there is little risk to water supplies in this region of the state. This result highlights a key point for risk mitigation planning – the need to account for spatial variation in HVRA location with respect to spatial variation in wildfire potential (Ager et al. 2013).

### **Optimal investments in fuel treatments**

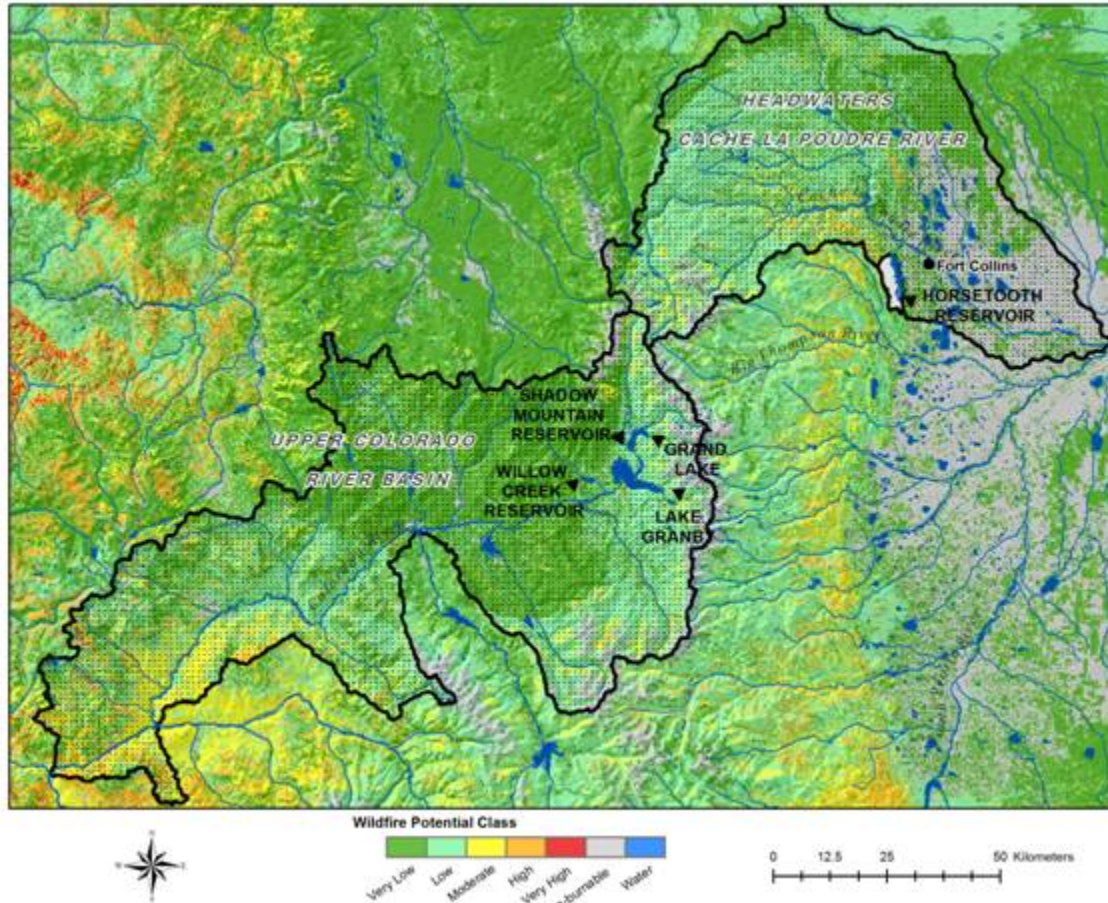
Whereas in some cases it may be possible to design treatments to simultaneously protect multiple HVRAs (e.g., Ager et al. 2010), in other cases there are likely to be tradeoffs associated with treatment location and opportunities for HVRA protection. While a formalized or widely used framework for assessing these tradeoffs has yet to emerge for wildfire, it is a rather old finance problem, one of maximizing the Sharpe ratio, given by

$$Max S = \frac{\sum_n w_n R_n}{\sigma}$$

where, as modified to capture watershed benefits,  $R_n$  is the expected return of fuel treatments in watershed  $n$  (excess returns above the status quo management scenario),  $w_n$  is the percent of the budget spent on treatments in watershed  $n$ , and  $\sigma$  is the standard deviation of benefits in the portfolio. The Sharpe ratio measures the expected return per unit of risk. In this case, returns can be quantified in terms of avoided water treatment costs or via proxy by reduced post-fire sediment volumes. Volatility in returns stems from stochasticity in ignition processes and fire weather, and their spatial patterns with respect to treatment and watershed locations.

Wise investors know that diversifying a portfolio can reduce risk by investing in assets that are negatively correlated with each other. Positively correlated investments, on the other hand, increase risk. Negative correlations for wildfire risk between watersheds are probably not possible, but near zero correlations are possible by investing in geographically disjoint watersheds. The risk-return tradeoffs associated with these types of decisions are clear. Investing heavily to protect a single high value watershed could yield significant returns, but could leave multiple other watersheds unprotected. By contrast, spatially distributing fuel treatments across multiple watersheds could diversify risk since not all watersheds are likely to burn in the same fire event or the same fire season, but could lead to dampened treatment effectiveness in any given watershed.

Expected returns will be a function of both the probability of a watershed experiencing high severity fire as well as the magnitude of watershed response given the fire does occur. The benefits from fuel treatments will tend to be highest in watersheds where probability and/or consequences are high. The degree of correlation between investing in different watersheds will depend largely on the degree of spatial connectivity, from a fire growth perspective, between watersheds.



**Figure 2:** Fort Collins, Colorado water supplies.

Consider the source watersheds for Fort Collins, Colorado, shown in Figure 2. Fort Collins draws water from the Cache la Poudre River and Horsetooth Reservoir, which gets its water from the Western Slope as part of the Colorado-Big Thompson Project. That the two watersheds are physically separated by the Continental Divide is more an artifact of growing water needs along the Front Range than a strategic decision related to wildfire risk. Nonetheless, enough topography and geography separate the watersheds to make it unlikely that the same fire will affect both. Separate fires did occur, however, in both watersheds in 2012. The High Park Fire burned in the Cache la Poudre watershed in June of 2012, and the Fern Lake Fire burned in the Big Thompson watershed in October of 2012 (InciWeb 2012a, InciWeb 2012b). Further damages were caused by the Galena Fire near the banks of Horsetooth Reservoir in March 2013 (Gabbert 2013), and massive flooding in September 2013 that destroyed some of the Colorado-Big Thompson Project's delivery infrastructure (Scrongin 2013). Of these, only the High Park Fire caused serious problems for water treatment, leading to the closing of the Cache la Poudre River intakes and sole reliance on Horsetooth Reservoir (Oropeza and Heath, 2013). During the 2013 flood, sediment clogged the canals that deliver water to Horsetooth reservoir, but those are expected to be cleared relatively quickly (Scrongin 2013).

We can apply the Sharpe ratio framework to Fort Collins' watershed management decisions – between investments in sediment reduction in the High Park burn area, fuels treatments to

reduce burn probability and potential severity in the Colorado-Big Thompson watershed, and maintenance of Horsetooth Reservoir.<sup>3</sup> Expected returns in the numerator are given by

$$ER = w_{Poudre} \times \text{Benefits of sediment reduction post High Park} \\ + w_{Horsetooth} \times \text{Benefits of maintaining Horsetooth reservoir} \\ + w_{C-BT} \times \text{Benefits of fuels reductions in CO} \\ - \text{Big Thompson}$$

The standard deviation of the portfolio is

$$\sigma = \sqrt{w_{Poudre}^2 \times \sigma_{Poudre}^2 + w_{Horsetooth}^2 \times \sigma_{Horsetooth}^2 + w_{C-BT}^2 \times \sigma_{C-BT}^2 \\ + 2w_{Horsetooth}w_{C-BT}Cov(Horsetooth, C - BT)}$$

For simplicity we assume the covariance between returns on investments in the Poudre and elsewhere are zero, though we do consider the covariance between returns on investments in Horsetooth Reservoir and the Colorado-Big Thompson.

The cost of sediment in the Poudre has already shown itself to be high, thus benefits for sediment reduction are also high. In comparison, maintaining Horsetooth Reservoir beyond the status quo is not likely to yield significant benefits. The reservoir is not threatened by erosion, and the surrounding vegetation cannot sustain a high intensity fire. Benefits from reducing fuels in the Colorado-Big Thompson watershed come from reducing the probability of a high severity fire. The project delivers water to a large population, which is why it was chosen as the pilot project for the Western Watershed Enhancement Partnership. Treatments that can successfully reduce wildfire risk in the Colorado-Big Thompson watershed will have large benefits.

Measuring the variance of the portfolio is a difficult task. A best-guess ranking of variances would place investments in the Colorado-Big Thompson as the most risky; they depend on the probability of a wildfire ignition, the probability of an ignition leading to a large severe fire, and the probability of a severe fire leading to excess sediment. The Wildland Fire Potential map can speak to the probabilities for the first two components, but additional information on topography, soil type, precipitation patterns, etc., would need to be considered to assess the likelihood of excess sedimentation. Due to the nested probabilities that vary across space, even with well-located fuel treatments the variance of benefits to Fort Collins is likely to be high. Direct investments in Horsetooth Reservoir are less risky; the science behind reservoir management is well-developed. Most of the risk associated with investments in Horsetooth comes through its covariance with benefits in the Colorado-Big Thompson watershed, as seen during the September 2013 flooding. Post-fire investments in sediment reduction in the Cache la Poudre watershed are of medium risk compared to investments in Horsetooth Reservoir and the Colorado-Big Thompson. We have already seen periods of high rainfall and high sediment runoff. These areas are being targeted for stabilization; it is mainly the effectiveness of that stabilization that is in question.

<sup>3</sup> The City of Fort Collins does not operate the Colorado-Big Thompson Project, and does not routinely make investments in its watershed. This is not to say, however, that such agreements could not be put into place.

It is a straightforward exercise to expand this investment framework to consider the perspective of the Forest Service or other public land management agencies. The basic investment framework remains the same, but the composition of the investment portfolio changes. The portfolio of options may now include fuel treatments for WUI protection in addition to watershed protection. As with comparison across treatments to protect watersheds, how returns co-vary will depend on spatial relationships and connectivity between municipal watersheds and the WUI.

## **Discussion**

The investment framework introduced here provides a pathway forward for analysis and design of economically efficient fuel treatment strategies. We illustrated how the model can be used to identify optimal combinations of fuel treatments to protect municipal water supplies, as well as potential extensions to consider other treatment objectives such as WUI protection. The model can also highlight tradeoffs across objectives, and could identify conditions under which watershed-oriented treatments may be more or less efficient relative to WUI protection. In future applications it could also be possible to expand the portfolio of options to consider not just fuel treatments but also investments in capacity building for suppression response and post-fire rehabilitation.

As an example we focused on the state of Colorado, where recent fire seasons have resulted in highly devastating consequences to human life, homes, and water supply infrastructure, and where multiple stakeholders are currently partnering to fund fuel treatments to protect municipal water supplies. The issue of protecting water supply in this region will likely remain if not grow in the future, due in part to population growth and climate change forecasts signaling increases in temperatures, warmer springs, earlier runoff, and longer fire seasons (Litschert et al. 2012). We illustrated alternative approaches for characterizing HVRA exposure and identified potential geographic disparities in where fuel treatments would be implemented for watershed protection. Although we focused on Colorado, the general framework and the tension between alternative fuel treatment investment portfolios can be applied across the western United States.

The investment framework also shows us the type of information that we need to gather. What do we readily have? Where do we need to focus our data efforts so we can make better investment choices? At root, the basic pieces we need are expected excess benefits and standard deviation of the total investment portfolio. Although we have a limited empirical basis of wildfire-treatment interactions, recent and ongoing work may enable us to mine historical data and quantify these relationships directly. Alternatively, from a modeling perspective it would be possible to generate this information, and in fact the use of wildfire simulation is increasingly being applied to quantify how treatments affect the distribution of possible fire outcomes (e.g., Thompson et al. 2013d, e).

An important question moving forward is how to identify the “excess returns” from the perspective of the Forest Service. Any proposed action, such as a fuel treatment, requires an assessment of potential environmental impacts, but the alternative of doing nothing is not a risk free option given the inevitable occurrence of wildfire (Fairbrother and Turnley 2005). One possibility is to consider the expected HVRA impacts, be it degradation of water quality or home destruction in the WUI, under a no-treatment scenario and assuming some default suppression response. This in effect becomes a cost-benefit analysis of treatments, while accounting for the volatility of treatment returns. Ongoing and future research describing the return on investment for fuel treatments and other pre-fire risk mitigation activities will be critical for successful implementation of this investment analysis framework.



## **Works Cited**

- Ager, A. A., Vaillant, N. M., & McMahan, A. (2013). Restoration of fire in managed forests: a model to prioritize landscapes and analyze tradeoffs. *Ecosphere*, 4(2), art29.
- Ager, A. A., Vaillant, N. M., & Finney, M. A. (2010). A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management*, 259(8), 1556-1570.
- Calkin, D. E., Thompson, M. P., Finney, M. A., & Hyde, K. D. (2011). A real-time risk assessment tool supporting wildland fire decisionmaking. *Journal of Forestry*, 109(5), 274-280.
- Calkin, D., Jones, G., & Hyde, K. (2008). Nonmarket resource valuation in the postfire environment. *Journal of Forestry*, 106(6), 305-310.
- Cannon, S.H., & Gartner, S.H. (2005). Runoff and erosion generated debris flows from recently burned basins. *Geological Society of America Abstracts*, 37 (7), 35.
- Cannon, S. H., Gartner, J. E., Rupert, M. G., Michael, J. A., Rea, A. H., & Parrett, C. (2010). Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geological Society of America Bulletin*, 122(1-2), 127-144.
- Dearmont, D., McCarl, B. A., & Tolman, D. A. (1998). Costs of water treatment due to diminished water quality: a case study in Texas. *Water Resources Research*, 34(4), 849-853.
- Ernst, C. (2004). *Protecting the Source: Land conservation and the future of America's drinking water*. The Trust for Public Land, San Francisco, California, and the American Water Works Association, Denver, Colorado.
- Fairbrother, A., & Turnley, J. G. (2005). Predicting risks of uncharacteristic wildfires: application of the risk assessment process. *Forest Ecology and Management*, 211(1), 28-35.
- Finney, M. A., McHugh, C. W., Grenfell, I. C., Riley, K. L., & Short, K. C. (2011). A simulation of probabilistic wildfire risk components for the continental United States. *Stochastic Environmental Research and Risk Assessment*, 25(7), 973-1000.
- Forster, D. L., Bardos, C. P., & Southgate, D. D. (1987). Soil erosion and water treatment costs. *Journal of Soil and Water Conservation*, 42(5), 349-352.
- Fort Collins Utilities. (2013). City of Fort Collins Economic E-Newsletter, Fort Collins, Colorado, December, <http://www.fcgov.com/business/archive/201212-newsletter.php?cmd=6>, accessed December 30, 2013.
- Gabbert, Bill. (2013). Update on the Galena Fire near Fort Collins, March 18, 2013, *Wildfire Today*, <http://wildfiretoday.com/tag/galena-fire/> accessed December 30, 2013.
- Haas, J. R., Calkin, D. E., & Thompson, M. P. (2013). A national approach for integrating wildfire simulation modeling into Wildland Urban Interface risk assessments within the United States. *Landscape and Urban Planning*, 119, 44-53.
- Heward, H., Smith, A. M., Roy, D. P., Tinkham, W. T., Hoffman, C. M., Morgan, P., & Lannom, K. O. (2013). Is burn severity related to fire intensity? Observations from landscape scale remote sensing. *International Journal of Wildland Fire*, 22(7), 910-918.
- Holmes, T. P. (1988). The offsite impact of soil erosion on the water treatment industry. *Land Economics*, 64.

- Ice, G. G., Neary, D. G., & Adams, P. W. (2004). Effects of wildfire on soils and watershed processes. *Journal of Forestry*, 102(6), 16-20.
- InciWeb. (2012a). High Park Fire, InciWeb incident 2904, <http://inciweb.nwcg.gov/incident/2904/>, accessed December 30, 2013.
- InciWeb. (2012b). Fern Lake Fire, InciWeb incident 3294, <http://inciweb.nwcg.gov/incident/3294/>, accessed December 30, 2013.
- Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire*, 18(1), 116-126.
- Litschert, S. E., Brown, T. C., & Theobald, D. M. (2012). Historic and future extent of wildfires in the Southern Rockies Ecoregion, USA. *Forest Ecology and Management*, 269, 124-133.
- Meixner, T., & Wohlgemuth, P. (2004). Wildfire impacts on water quality. *Journal of Wildland Fire*, 13(1), 27-35.
- Meyer, Jeremy P. (2006). Hayman Fire still mucking up water. *The Denver Post*, November 24, 2006.
- Miller, C., & Ager, A. A. (2013). A review of recent advances in risk analysis for wildfire management. *International Journal of Wildland Fire*, 22(1), 1-14
- Moody, J. A., & Martin, D. A. (2009). Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. *International Journal of Wildland Fire*, 18(1), 96-115.
- Moore, W. B., & McCarl, B. A. (1987). Off-site costs of soil erosion: a case study in the Willamette Valley. *Western Journal of Agricultural Economics*, 12(1), 42-49.
- National Interagency Fire Center. 2013. Statistics website, [http://www.nifc.gov/fireInfo/fireInfo\\_statistics.html](http://www.nifc.gov/fireInfo/fireInfo_statistics.html), accessed December 27, 2013.
- Neary, D. G., Ryan, K. C., & DeBano, L. F. (2005). Wildland fire in ecosystems: effects of fire on soils and water. *US Forest Service Gen. Tech. Rep. RMRS-GTR-42-vol, 4*, 250.
- Oropeza, Jill and Jared Health. 2013. Effects of the 2012 Hewlett and High Park Wildfires on Water Quality of the Poudre River and Seaman Reservoir, City of Fort Collins Utilities, Fort Collins, Colorado.
- Parise, M., & Cannon, S. H. (2012). Wildfire impacts on the processes that generate debris flows in burned watersheds. *Natural Hazards*, 61(1), 217-227.
- Qiu, Zeyuan, Tony Pareto, and Michael Kaylen. (1998). Water Shed Economic and Environmental Trade-Offs Incorporating Risks: A Target MOTAD Approach, *Agricultural and Resource Economics Review*, 27, 231-240.
- Robichaud, P. R., & Ashmun, L. E. (2013). Tools to aid post-wildfire assessment and erosion-mitigation treatment decisions. *International Journal of Wildland Fire*, 22(1), 95-105.
- Scott, J. H., Thompson, M. P., & Calkin, D. E. (2013). A wildfire risk assessment framework for land and resource management. *Gen. Tech. Rep. RMRS-GTR-315*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Scott, J., Helmbrecht, D., Thompson, M. P., Calkin, D. E., & Marcille, K. (2012). Probabilistic assessment of wildfire hazard and municipal watershed exposure. *Natural Hazards*, 64(1), 707-728.

- Scrongin, Dana (editor). 2013. Northern Water WaterNews, Northern Colorado Water Conservancy District, Berthoud, Colorado.
- Shakesby, R. A., & Doerr, S. H. (2006). Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews*, 74(3), 269-307.
- Thompson, M. P., and Calkin, D. E. (2011). Uncertainty and risk in wildland fire management: A review. *Journal of Environmental Management*, 92(8), 1895-1909
- Thompson, M. P., Scott, J., Kaiden, J. D., & Gilbertson-Day, J. W. (2013a). A polygon-based modeling approach to assess exposure of resources and assets to wildfire. *Natural Hazards*, 67(2), 627-644.
- Thompson, M. P., Scott, J., Langowski, P. G., Gilbertson-Day, J. W., Haas, J. R., & Bowne, E. M. (2013b). Assessing watershed-wildfire risks on National Forest System lands in the Rocky Mountain Region of the United States. *Water*, 5(3), 945-971.
- Thompson, M. P., Vaillant, N. M., Haas, J. R., Gebert, K. M., & Stockmann, K. D. (2013c). Quantifying the potential impacts of fuel treatments on wildfire suppression costs. *Journal of Forestry*, 111(1), 49-58.
- Thompson, M. P., Vaillant, N. M., Haas, J. R., Gebert, K. M., & Stockmann, K. D. (2013d). Quantifying the potential impacts of fuel treatments on wildfire suppression costs. *Journal of Forestry*, 111(1), 49-58.
- Thompson, M. P., Hand, M. S., Gilbertson-Day, J. W., Vaillant, N. M., & Nalle, D. J. 2013e. Hazardous fuel treatments, suppression cost impacts, and risk mitigation. In: González-Cabán, Armando, tech. coord. Proceedings of the fourth international symposium on fire economics, planning, and policy: climate change and wildfires. Gen. Tech. Rep. PSW-GTR-245. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station, 66-80.
- Weidner, Emily and Al Todd. 2011. From the Forests to the Faucet: Drinking Water and Forests in the US, USDA Forest Service  
[http://www.fs.fed.us/ecosystemservices/FS\\_Efforts/forests2faucets.shtml](http://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml).