

A thin vertical line is positioned on the left side of the page, extending from the top of the title area to the bottom of the authors' names.

A DEFENSIBILITY HEURISTIC FOR ECONOMIC DECISION MAKING FOR WILDFIRE FUEL TREATMENTS

February 2020

Hugh Scolah, Harry Nelson, Lori Daniels

Table of Contents

Acknowledgements	2
Executive Summary	3
Introduction	5
CBA and Decision Making for Wildfire Fuel Treatments	5
Difficulties with Cost-Benefit Analysis	6
The Shape of Wildfire Cost Data	7
Existing Literature	12
A Framework for BC	16
Methods for Estimating the Defensibility Value of A Fuel Treatment	21
Insurance, not an Investment	23
A Framework for Assessing Protection Adequacy of a Fuel Treatment	23
Limitations and Shortcoming of the Method	29
Including Other Values	30
Case Studies	32
A Description of the Fuel Treatment Data	33
Greata Ranch	35
Glenrosa	37
150 Mile House	40
South Lakeside - Williams Lake	42
An Example with Perpetual Maintenance	43
Conclusions	45
On the 'Business Case' for Fuel Treatments	46
Cited Works	49

Acknowledgements

Supported by Natural Resources Canada's Climate Change Adaptation Program, the BC Wildfire Service and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development.



Executive Summary

At the January 2019 Workshop on wildfire fuel treatments and cost-benefit analysis that was part of this research effort many participants argued that there was an urgent need to do something to reduce risk from wildfire. This sentiment seems to appear in reviews of the wildfire economics literature as well[1]. Statistics Canada reports the economic impact of the wildfire that affected Fort McMurray at \$3.7 billion[2] and this naturally drives interest in exploring risk management options besides suppression that would be justified economically when these kinds of losses and damages are observed.

This interest has resulted in a drive to catalogue the costs of wildfire and develop very complex decision tools that make use of simulation and probabilistic models. A conclusion of this report is that this is unnecessary to get started on urgent work.

Colonel John Boyd of the US Air Force introduced and popularized the OODA-loop[3]. OODA standing for Observe-Orient-Decide-Act. Somehow, in the wildfire economics literature the process has become stuck in the orientation stage. A lot of the focus is on improving modelling tools, mapping and simulation in well-studied areas and less work has been done making use of simple economic logic to find the projects on the margin that make obvious sense.

This report is an effort to overcome this inertia and offer a tool that finds projects that can be decided and acted on in the near term. The learning from finding effective projects and doing fuel treatments at scale will be worth much more than any simulation effort or correlation found in Big Data.

The key results in this report are:

- The development of a new heuristic approach to making economic decisions about risk that makes use of the implicit knowledge of front-line staff.
- The BC Wildfire Service Resource Sharing Wildfire Allocation Protocol (RSWAP) identifies priorities for protection of values-at-risk. Start here in an economic analysis. This first-order analysis frequently identifies assets of significant economic and social value. Sometimes these values make the other values look like rounding errors. There is no point in detailed analysis when this is the case. The economic case-studies herein indicate that the economic values are consistent with the RSWAP priorities.
- Maintenance of fuel treatments makes financial sense. Funding for maintenance should go with funding the original project.

- Budgets are always going to be limited for fuel treatments given the massive amount of potential work to be done. Prioritizing the work and not the modelling is important. Make use of the Provincial Strategic Threat Analysis (PSTA). Further modelling for economic purposes is only justified as we approach an optimal arrangement of fuel treatments on the landscape and tie breaks need to occur. We aren't there yet. Go for the low hanging fruit.
- The purpose of this tool is to evaluate the economic reasonableness of individual fuel treatments, but it does offer some insight into how to make the business case for fuel treatments. The costs of cataloguing all the possible damages from catastrophic wildfire likely outweighs the benefits at this point. Start by making funding requests for projects that are justified by the top RSWAP priorities evacuation and critical infrastructure. Do an analysis of what it would cost to treat all of the areas around evacuation routes or all of the critical infrastructure identified in the PSTA. These analyses can be tidy and straight-forward.

Introduction

Colonel John Boyd of the US Air Force introduced and popularized the OODA-loop[3]. OODA standing for Observe-Orient-Decide-Act. This tool for decision-making under uncertainty has since made its way into business management and medical practice. Somehow, in the wildfire economics literature the discourse has become stuck in the orientation stage. A lot of work is be put into improving modelling tools, mapping and simulation in well-studied areas and less work has been done making use of simple economic logic to find the projects on the margin that make obvious sense.

We are in a state of ignorance with respect to what is possible in terms of fuel-treatment costs, reducing risk from wildfire with fuel treatments and the impacts on a great variety social values that include climate change risks and ecosystem services. This isn't going to change any time soon. The situation is dynamic and the learnings from one geography to another do not generalize very well. Values-at-risk tend to concentrate on the landscape (e.g. oil and gas assets and the fire around Ft McMurray) and different ecosystems burn differently. It is easy to get caught in the details and a perfectionism that manifests itself in finding optimal allocations of fuel treatment dollars on the landscape or cataloguing every possible cost incurred during catastrophic wildfire events.

What we offer below suggests that there is work to be done that can be justified right now. The budget constraints are real, and we are far from the optimum. There's a lot more value in taking a decision and acting and learning from those decisions than further detailed orientation sessions. Rather than chasing the optimum, it makes more sense to make decisions today that we can learn from and are most likely to provide the best protection for the dollar. A modelling analogy would be that we are trying to find the path of steepest ascent and taking the first step rather than finding the optimal path of ascent before even beginning to move. Because of the dynamic nature of the problem the landscape will change before the optimization calculations are finished. Hopefully, this document provides a decision-making tool and some impetus to get on with it.

CBA and Decision Making for Wildfire Fuel Treatments

This project started with an attempt to apply traditional Cost-Benefit Analysis (CBA) to the problem of evaluating landscape-level wildfire fuel treatments. Unfortunately, we ran into both theoretical and practical limitations of the CBA approach and few examples of landscape-level wildfire fuel treatments. In response to this we have developed a modified approach to cost-effectiveness that provides a required probability of success for a project to be worth doing and uses completed and proposed fuel treatments as case studies. These fuel treatments are almost all in the WUI.

The challenges with economic evaluation of wildfire fuel treatments begin with the fact that there is no technological solution that makes the problem of wildfire go away. There is no vaccine for wildfire. And, unlike building a new highway or dam, even if we can catalogue all the categories of benefits and costs from a proposed fuels mitigation, we have few established methodologies for estimating them¹. We have difficulty even putting minimum and maximum bounds on many of the possibilities. In addition to this, we are dealing with a system that has ongoing interventions in the form of active fire suppression. Any fuels mitigation, short of turning the forest into a parking lot, is going to reduce risk from wildfire some relative amount but will never eliminate the risk entirely. The need for suppression remains. In a conventional economic analysis this relative risk has to be measured in some way. For this particular problem, I do not believe that quantification of this relative risk adjustment can happen at a reasonable cost. To overcome this problem I suggest making use of what Friedrich Hayek called “the knowledge of the particular circumstances of time and place” in his essay *The Use of Knowledge in Society*[4]. It has since been referred to as *implicit knowledge*, but in our case, it refers to the understanding that practicing wildfire fighters have of their craft that is not, and perhaps, cannot be captured in a probabilistic model of the world.

In what follows, we will (1) describe the limitations of CBA in the domain of wildfire fuel treatments (theoretical and practical), (2) review the existing literature, (3) discuss the variety of costs that could be included in a cost-benefit analysis and examine which ones are practical and which are not, (4) offer an alternative methodology to conventional CBA, (5) review four case studies where the methodology is applied and (6) discuss how the results of this approach could inform an evaluation of the broader social value of funding wildfire fuel treatments.

Difficulties with Cost-Benefit Analysis

There are two fundamental challenges with Cost-Benefit Analysis as applied to economic evaluation of wildfire fuel treatments. The first, is that ‘shape’ of the risk models that are appropriate for use in describing wildfire costs are not well-suited for cost benefit analysis. By shape we mean the probability distribution that can be used to describe cost outcomes in wildfire. I use this term ‘shape’ because while

¹ As discussed in the literature review some of the established methodologies may be questionable because of the nature of the risk.

there is agreement that the costs from wildfire are best described with ‘fat-tailed’ distributions, different papers have come up with different best fitting distributions for their data sets². In all cases, these distributions are not well suited to cost-benefit analysis.

The second challenge is the scarcity of models that connect measures of wildfire behaviour to impacts of wildfire on values-at-risk. In practical terms, if we wanted to measure how a fuels mitigation was going to reduce the public health impacts from smoke inhalation we might want to start by using fire behaviour models that might give us measures of probability of burn, rate of spread and a fire intensity in kw/m. We then need to be able to translate that into a measure of smoke density over settled areas and finally describe a function that relates those smoke conditions to public health outcomes. Estimates of these costs in general for wildfire have been made [5] but creating a mathematical description of the change in public health costs from a fuel treatment is another problem all together that we don’t have a good handle on. As will be discussed in some detail in the discussion of including different cost categories in these analyses this is not unique to the public health impacts of wildfire smoke.

And of course, this is all the more complicated by the fact that climate change is driving an increase in the risks of wildfire with longer, hotter, and drier wildfire seasons [6]–[9]. This means that past events on which we collect data and build our models are not necessarily informative for future events. This degree of hard-to-quantify uncertainty requires a different approach but before we offer a discussion of the ‘shape’ of the cost distribution and its implications for economic analyses of wildfire mitigation.

The Shape of Wildfire Cost Data

To make sense of this issues I will use contagions as an analog because they share similar properties in their mathematical description to wildfire costs and they are likely top of mind for all the potential readers of this document.

When a new infectious agent is detected it is not possible, beforehand, to know how many people will become infected, how quickly it will spread and how many lives it will take. Not only is it uncertain but the distribution of outcomes is very fat-tailed. It might be an event like SARS with relatively few deaths (774) or something much more devastating like the Spanish Flu that was estimated to have killed 17-50 million [10] or the Black Death that was estimated to kill 75-200 million people [11]. Differences in

² It can, in fact, be shown that there is no way to prove that any given distribution offers the ‘best fit’ when a data set displays fat-tailed characteristics[13].

outcomes are measured in orders of magnitude. If an economist were to try and do a cost-benefit analysis on different control measures, the expected or average outcome is not a useful measure for evaluating these costs. As more time passes, the analyst becomes more certain about the parameters that can be used to estimate costs and benefits of an intervention for a particular infectious agent but by this time it is too late. If the world is facing a truly catastrophic pandemic the control measures have to be in place before the data is available to evaluate the costs and benefits of the control measures. By necessity, we have to manage to the worst-case scenario, not the historic “average”.

While more limited in geographic scope and less costly in terms of human life, wildfire damages can be described using similar mathematical tools to the ones used in the analysis of infectious agents. An American estimate of wildfire suppression costs in California estimated that 1% of fires resulted in 93% of suppression expenditures. In the suppression costs data (2017-2019) provided by the BC Wildfire service for the province as a whole, 1.8% of the fires accounted for 60% of costs Figure 1.

In Figure 2, we can see the histogram of suppression costs for the period 2003-2019 in the Cariboo and Kamloops fire district. In this data 0.8% (99 of 12,080) of fires resulted in 60% of suppression costs. In absolute terms, that's \$364 million over 20 years in just 99 fires. If we take the average suppression cost for a fire in this data set it is about \$50,000. Clearly this average is not informative.

Suppression costs in British Columbia appear to be reasonably modeled by an extreme, fat-tailed distribution that looks nothing like the normal or Gaussian distribution that is usually used when conducting cost benefit analyses. When one adds in evacuation costs, timber losses and public health impacts from smoke on the largest fires one can see that the largest, most damaging fires are many times more damaging than the most frequent fires and that it is meaningless to talk about averages.

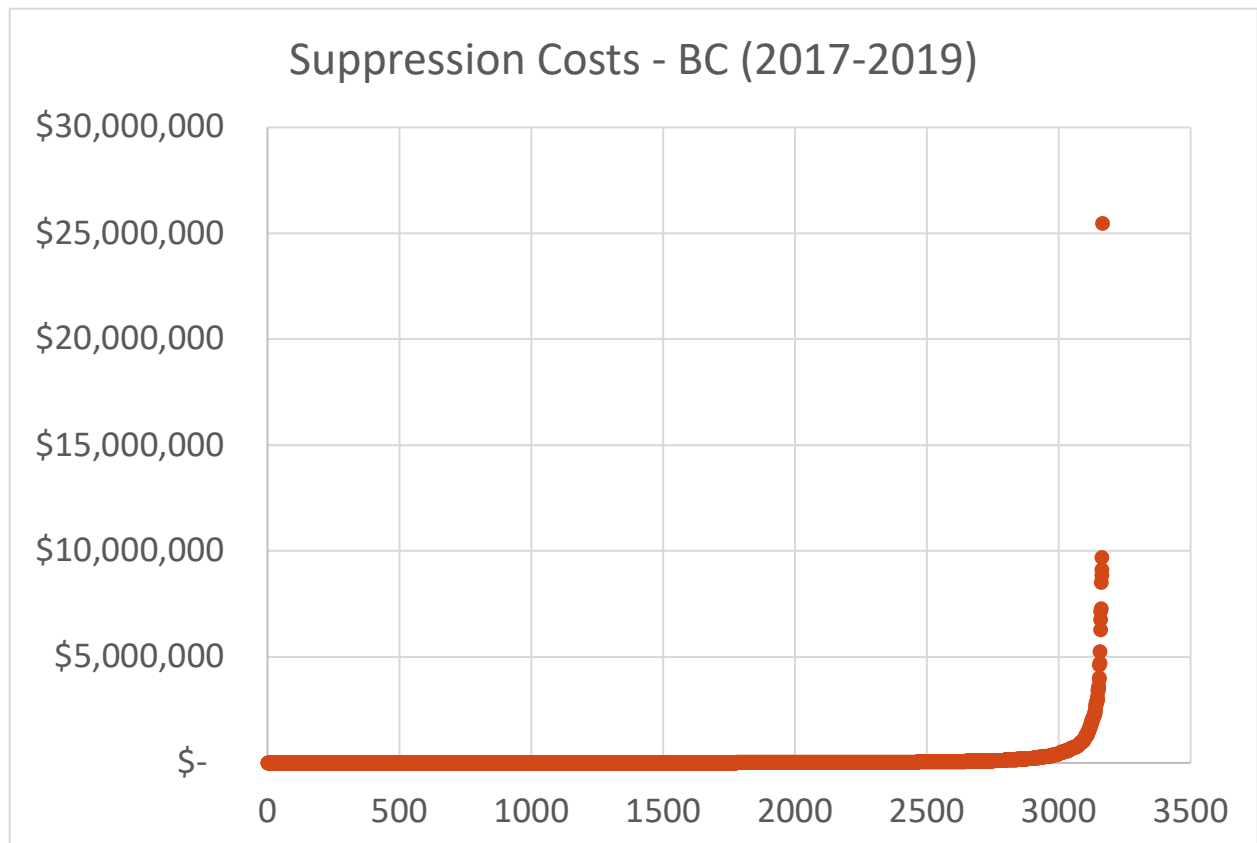


Figure 1 Individual fire suppression costs ordered from least costly to most costly. The vast majority of fires result are less than \$500,000 but there are very few at the end that are orders of magnitude more expensive. Here 78 of the 4287 fires in the dataset, or 1.8% of observations result in 60% of the Suppression Costs. This is indicative of fat-tailed distributions.

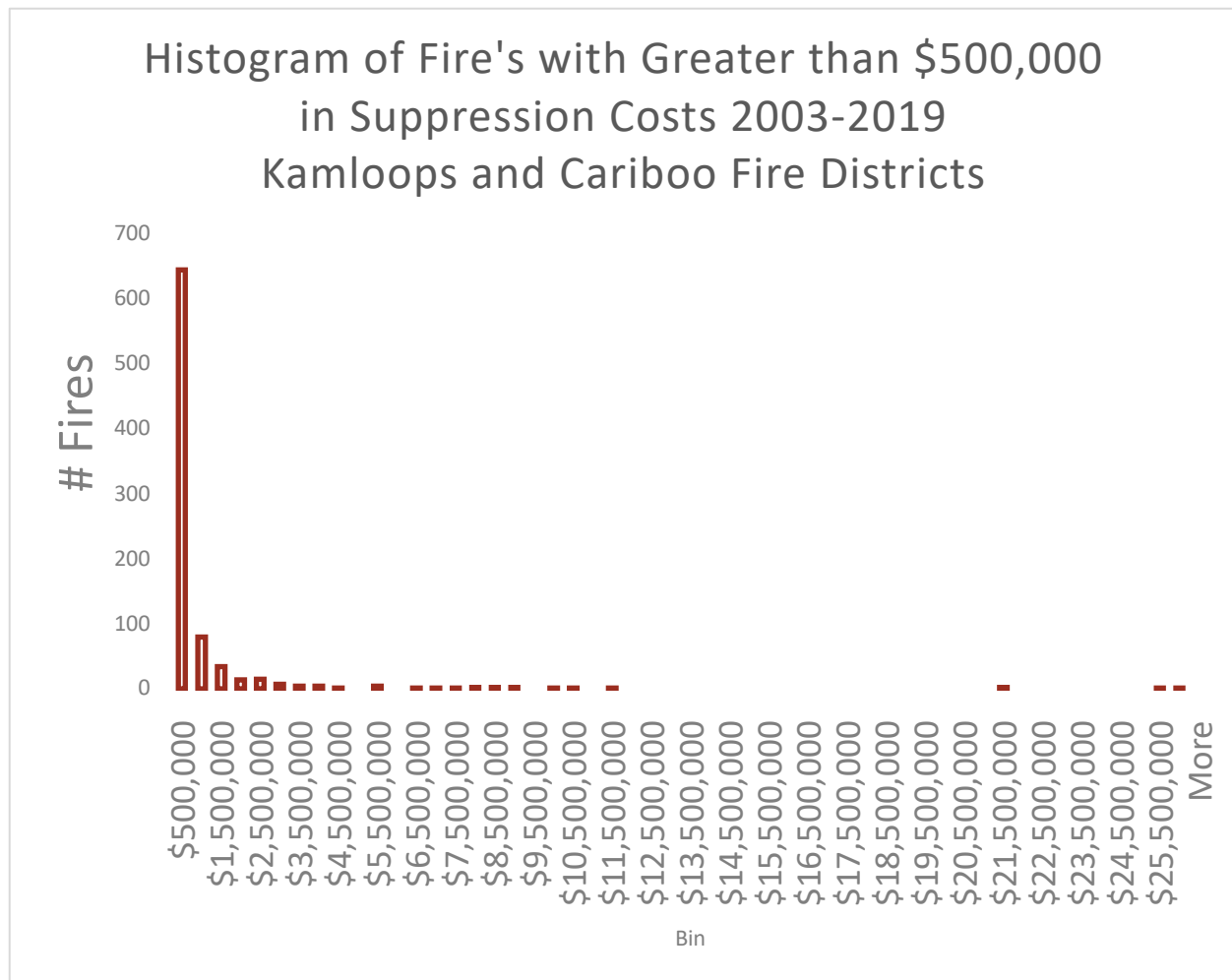


Figure 2 Far from 'Normal', this histogram shows a very long tail for suppression costs in the Kamloops and Cariboo Fire Districts from 2003 – 2019. We can safely reject the null hypothesis that a normal distribution is a suitable fit for modeling this data.

What are the implications of fat-tails for doing a cost-benefit analysis?

In the OECD review of CBA used for applications in environmental problems by Pearce et al. [12] the authors described two general approaches to dealing with uncertainty in a CBA. The first category of uncertainty was what they described as 'risk'. Risk, in their terminology, is uncertainty sufficiently well-behaved that each state of the world can be assigned a probability and the estimates of the probabilities don't move around very much as new data comes in. In other words, uncertainty can be described as risk when the Central Limit Theorem applies, probability estimates converge as more data comes in. In the context of 'risk' Pearce et al. recommend using mean values or expectations of the observed costs and benefits used in the CBA.

For fat-tailed distributions the risk assumption isn't appropriate and expectations cannot be used. In general, for data that can be described with fat-tailed distributions new observations occasionally change the parameters used to best fit the distribution. In other words, probability estimates don't necessarily converge and as a result, statistical estimators of variance and mean also do not converge[13]. Another way of describing this is that the average benefits and costs are not a meaningful measure of the possible outcomes. Using the average to summarize data that is drawn from a fat-tailed distribution ignores the extreme possibilities that can be several orders of magnitude larger than the average as we saw in the BC wildfire suppression cost data above. The other problem with this is that taking the expectation or average discounts catastrophic or ruinous events assumes that we can take every future path and choose the best one. This is not how it works in reality; we only get one chance at getting things right in life. If we calculate event frequencies to estimate average statistics when there are path dependencies, we ignore the fact when a community is burned over or the loss of timber supply shuts down a local mill there is no going back in time. If you die, or go bankrupt, there are no second chances.

When we cannot assign stationary probabilities to events Pearce et al. describe this as uncertainty and argue that a scenario planning approach should be taken. They offer that many practitioners build a matrix of likely scenarios, estimate the costs and benefits for those states of the world and assign them weights to come up with a weighted average of these states to estimate the cost-benefit ratio for the project or policy.

There are two challenges with taking this approach for the problem of wildfire fuel treatments. First, we have to choose the scenarios and second we have to translate the things we can model (fire behaviour) into measurable changes in the stuff we care about (values-at-risk).

In terms of choosing the scenarios, we have to start by noting that most of the fires in our dataset have suppression costs less than \$500,000. For these fires, suppression efforts are successful in putting the fires out before they get out of control and incremental management effort in the form of fuels mitigation is unlikely to offer significant benefit. A consequence of this is that we should focus on the larger fires that are not well-handled by suppression efforts. Because these large and difficult to control fires are rare and surprising, we cannot get convergent estimates of their likelihood. In this case, as I argue below it makes sense to take a 'stress-test' approach. This means choosing the most damaging fires as our scenarios that need to be protected against with fuels mitigations. If a fuel treatment is

justified under those conditions, then it is justified under all of the other potentially less damaging outcomes as well.

Finally, we come to the problem of translating fire behaviour that are induced by fuel treatment efforts into differences in outcomes of the values-at-risk that we choose to measure. What does success look like for a fuel treatment in relation to protecting infrastructure, homes, evacuation routes or environmental values or any other number of potential values-at-risk? In discussions with members of the BC Wildfire Service it came up repeatedly that there is no 'sure thing'. No fuel treatment is going to 100% protect an asset under all conditions. What we get from a fuel treatment is greater 'defensibility'. In poking at the notion of defensibility we did not settle on a quantitative metric that could be used as proxy for defensibility. The outcomes we really care about³, the change in defensibility after a fuel treatment cannot be measured. This makes it difficult to create scenarios in the sense that Pearce et al. suggest.

To get around this problem we recommend inverting the usual Cost-Benefit problem and rather than estimating probabilities we don't and can't know, or guessing at changes in defensibility that can't be measured it is better to make use of the implicit knowledge of the wildfire fighters and estimating defensibility threshold. That is, given the cost of a treatment and the value of the assets that are protected, we can estimate the likelihood that the treatment will succeed in making the assets more defensible in order to be worthwhile. This approach is described in detail below but before turning to the new methodology, we review the existing literature on the cost-effectiveness of wildfire fuel treatments and look at the values that we include in the analysis and the justification for including them.

Existing Literature

Consistent with textbook economic theory the wildfire economics literature is generally considered with finding optimal expenditures under equilibrium conditions on suppression and pre-suppression efforts [1]. This approach to analyzing wildfire expenditures begins the work of Sparkhawk[14]. Sparkhawk introduced the idea of Least Cost plus Damage or Least Cost plus Net Value Change. The idea was to model a production function that takes pre-suppression expenditures as an input and the output is the

³ I am entirely ignoring the fact that there can be beneficial outcomes for ecosystems with wildfire, this discussion takes place entirely in the context of a suppression effort intended to protect specific assets.

decrease in fire damage and suppression costs. Pre-suppression in this case can refer to staffing fire watchtowers, purchasing water bombers or hiring seasonal staff prior to the fire season. An analyst using this model should set the marginal pre-suppression expenditure increase equal to the marginal decrease in damages to get the optimal expenditure. Any increase in pre-suppression expenditures beyond this point provides less benefit than the costs.

Least Cost plus Net Value Change was an addition to this model that recognized that fire can have positive effects for wildlife and ecosystems generally. Donovan [15] updated this model to account for the fact that suppression is not a direct output of pre-suppression expenditures (it is an input itself that is limited, but not determined by pre-suppression expenditures) and these expenditures are not in fact negatively correlated. In a busy fire year an increase in pre-suppression expenditures could make even higher variable suppression expenditures possible because more resources are available to be used.

In practice these models are impractical because we never have enough information to know where marginal benefits are equal to marginal costs so we cannot find the optimal allocation of pre-suppression expenditures. Despite repeated efforts to improve this model Least Cost plus Damage approach has found little utility in the field. Martell [16] noted that it is likely impossible to parameterize a production function that relates expenditures on fire towers, aircraft, firefighters etc. to fire damages. He also notes that the model is deterministic and does not account for the stochastic nature of fire behaviour and damages.

Despite this, much of economics literature on fuel treatments works with models in the spirit of Least Cost plus Damages and try to find the optimal expenditures where expected marginal benefit is equal to expected marginal cost. Most of these studies focus on a single benefit like reduced fire intensity or increase in deer harvest. Hesseln [17] completed a review of the literature on the economic analysis of prescribed burning from the 80s and 90s in which she describes four requirements of a framework for use in fuel management:

1. A description of the relationship between fuel management strategies and the change in fire behaviour.
2. A description of the relationship between observed fire behaviour and economic variables over the longer-run. These could include suppression costs, timber and property values, tourism and recreation as well as non-market values.
3. A consideration of the risk management aspect of fuel management decisions.

4. Collecting and storing data in a way that is conducive to analyses of the economic efficiency of fuel management strategies.

All of the studies Hesseln reviews fall far short of meeting these criteria. While there has been some improvement since the year 2000, all of the studies that have been published since then also fail one more of these requirements to varying degrees.

We found 20 studies that included a cost--effectiveness and cost-benefit analysis of fuel treatments since 2000.

Considerable effort have been made to improve the understanding how fuel mitigation changes fire behavior[18]–[20] and some of these efforts have made it into the fire behavior models that have been integrated into economic analyses. Eleven of the studies made use of a fire behavior model to describe the relationship between fuel management strategies and change in fire behavior. These included studies in Australia[21]–[23], China[24], Italy[25] and four in the United States[26]–[29]. The remaining studies [30]–[36] avoided making explicit modeling assumptions and made use of case studies and linear regression estimates to model changes in fire behaviour as a function of fuel mitigation efforts.

Most of the studies evaluated benefits from fuels mitigation for a small number of well-studied values. These studies that do consider a larger number of values tend to find that treatments are positive or have a positive net present value.

In general, there have not been improvements in understanding the relationship between wildfire behavior and economic variables over the longer-run. The studies almost exclusively consider short-run costs and use observed case-study values or simple correlations to describe these relationships. There is a good reason for this. The second-order effects (e.g. changes in long-run employment, differences in tree growth rates) and non-linear changes in values-at-risk (e.g. regime changes in ecosystems, or the long-term shutdown of a mill) under some wildfire behaviour scenarios make it very difficult or impossible to parameterize a functional relationship between fire behaviour metrics and measurable changes in the values-at-risk.

It is interesting to note that there appears to be a trade-off in this literature between more realistic efforts at simulating wildfire behaviour and addressing multiple values-at-risk. Simulation intensive approaches tended to only look at a single variable like timber damages[24], property[21], [22], [25], [28], suppression costs[26], [37] and erosion [29][38]. More back-of-the-envelope style, case study

approaches [30], [33] were able to include a far greater number of values-at-risk and get a better picture of the potential magnitude of benefits from fuel-treatments.

All modeling is expensive. With a finite budget it is necessary to choose between capturing the impacts of fire on a wide variety of values-at-risk or more accurately simulating fire's impacts on a single value of interest.

Finally, as far as risk management is concerned, only a few efforts have been made to tackle uncertainty in a deeper way. Penman et al. [22] used a Bayesian Network analysis to model the interaction between uncertain ignitions and fire spread and damage to property. They tried to capture the likelihood that fuel-treatment would actually be tested. Again this approach was used by Penman et al. [39] in a multi-objective model. These models are complicated, labor intensive and time consuming and ultimately impractical for decision making. Furthermore, the Bayesian approach to decision making with fat-tailed risks has its problems. Working with Bayesian models requires that we can form reliable priors which are not observable under fat-tails [40] which results in a problem that Taleb summarizes thus "The mistake in the rational expectations literature is to believe that two observers supplied with the same information would necessarily converge to the same view. Unfortunately, the conditions for that to happen in real time or to happen at all are quite specific." [13] The complexity of these models and the shaky foundational assumptions make them poor candidates for real-world decision making.

Some more recent models attempted to handle multiple values and uncertainty with simulation models. Thompson et al. [41] used three measures of effectiveness for fuel treatments, avoided area burned, avoided suppression costs and avoided damages. This model required pre-existing model inputs that included maps of fuel treatment constraints, biophysically driven fuel treatment prescriptions and spatial risk assessment models as well as a pre-existing model of suppression costs and fuel hazards. The spatial suppression cost model [42] is problematic because it uses least squares models to estimate costs where a normal distribution is an inappropriate assumption⁴. The parameter estimates from these models are unreliable and are likely severely underestimate potential realized costs [13].

Many of the models, either implicitly or explicitly assume that fuel treatments have an infinite lifespan (they do not as fuels grow back) and that the probability of a fuel treatment being tested over its lifespan is one. In addition to this, not all of the studies addressed uncertainty in fire weather conditions.

⁴ These assumptions of normality have been mistakenly repeated elsewhere in the literature, see Fitch et al. [50]

In the studies that used fire behaviour simulation the fuel treatments were sometimes exposed to different and extreme fire weather conditions. In the back of the envelope and regression models there is an implicit assumption that fuel treatments will perform the same in 99th percentile fire weather as in the 75th percentile fire weather.

Taken together, no accounting for variation in fire weather, no lifespan for fuel treatment effectiveness, and no probability of a fuel treatment being tested calls into question these results. How much benefit does a fuel treatment confer if it fails in extreme fire weather? What is the shelf-life of a fuel treatment? What happens to the magnitude of the benefits associated with a fuel treatment when the probability that it is actually tested is close to zero?

Many of the models that do address these questions require large investments in data collection, fire behaviour simulation, statistical modelling and detailed mapping. Much of it needs to be repeated for each fuel treatments at great cost. These approaches all start from the assumption that they are attempting to optimize the use of resources and so this level of detail is required to find the optimum. I will argue in the following sections that we are so far from an optimum that we can use a simpler approach to deal with uncertainty, identify the low hanging fruit and move closer to the possibility frontier where it might actually make sense to worry about optimal outcomes on the margin.

A Framework for BC

In trying to understand the trade-offs involved in undertaking fuel treatments, we worked to create a list of values-at-risk that could be used to measure the effectiveness of these interventions on the landscape. Historically, cost-benefit analyses of fuel treatments have primarily focused on suppression costs as the primary cost avoided in these exercises [43]. This is likely due to the fact that suppression costs are some of the more immediate costs realized during these crises, as well as the fact that these costs are usually easier to document. However, in measuring the effectiveness of fuel treatments solely against avoided suppression costs one excludes many of the other costs, this potentially understates the effectiveness of any interventions evaluated in the cost-benefit framework. It is also possible for given areas of interest that suppression costs are not the most important risk.

Obstacles to accurate cost accounting of wildfires arise when costs are incurred over a long period of time (e.g. employment insurance), or there are no market prices. For instance, loss of critical wildlife habitats or carbon sequestration arising from wildfires are two costs that are gaining increased attention

in recent literature but have yet to be included in a complete and comprehensive cost benefit analysis due to their characteristics as non-market goods. As will be shown in the case studies, for the methodology described below, we decided to include only the values that are most likely to result in the greatest damages for the area of interest. It is the facts on the ground that are driving what is included, not a pre-determined set of values. This is justified because we ultimately are not trying to find the optimal allocation (something we cannot find under the dynamic uncertainty we are faced with) but trying to rank projects based on how cost-effectively the fuel treatments improve defensibility of critical assets.

Nonetheless, in the review below we look at different cost categories and how easy or difficult it is to collect data and model or estimate damages as a reference for future modelers.

We initially chose to filter cost categories on the basis of two criteria, availability of data, and ease of estimation. This is summarized in Figure 3. After this we considered how these values corresponded to the priorities in the BC Wildland Fire Strategy [44].

Cost Category	Data Availability	Ease of Estimation
Property and Structural Damages and Value Loss	***	**
Suppression	***	**
Destruction of Habitat	**	*
Loss of Life	*	*
Clean up, Forest Restoration, Rehabilitation	***	***
Flooding and Changes in Hydrology	*	*
Fire Evacuation	**	**
Smoke Costs	*	*
Lost Recreation Value	***	**
Productivity/Business Income Losses	*	*
Timber and Forest Product Loss	***	**

Figure 3 Data Availability runs low (*), medium (**), high (***). Ease of estimation: easy (*), moderate (**), difficult (***).

Justifications for our rankings are as follows:

Property and Structural Damages and Value Loss

Property valuations data can be obtained from the Catastrophe Indices and Quantification (CATIQ)[45] database and the BC Assessment Authority[46]. This data is good down to the resolution of a forward sorting area in a postal code. Estimating the total potential loss is straight-forward with this data.

To estimate a number for total property and infrastructure value-at-risk we will make use of the BC Assessment Authority data [46]. Each jurisdiction⁵ in the BC Assessment data has value estimates for a variety of property classes that include Residential, Utilities, Major and Light industry, Commercial and Agricultural. Every property class has an estimate of the total bare land and land improvement value for each jurisdiction as well as the number of properties in that property class. We can calculate the average value for each property subclass for each jurisdiction in the study area.

With these averages we will have to count individual structures in the study area and multiply the number by the average values to give the total value-at-risk. For the purposes of sensitivity analysis, we can adjust the number of structures that are damaged or destroyed.

Suppression Costs

Historical suppression cost data has been provided by the BC Wildfire Service. Regression approaches to estimating suppression costs have been used in the wildfire literature[42], [47]–[50]. As discussed in the literature review these methods have ignored the fat-tailed nature of the data which violates some of the fundamental assumptions in statistical analysis (e.g. The Central Limit Theorem). For the purposes of the methodology below the most straight-forward way of including suppression costs would be by using comparable fires in the region as case studies. In the Okanagan for instance it might make sense for using the 2003 Okanagan Mountain Fire as an analogue for suppression efforts under extreme fire weather conditions. Suppression costs ultimately were not included in the case studies below because it was determined with BC Wildfire Service staff that the fuel treatments being evaluated are not likely to significantly reduce the costs of suppression for a fire that starts out of town and burns its way in⁶.

Clean-Up, Forest Restoration, Rehabilitation

⁶ They are, however, likely to improve defensibility of the key assets that are considered.

⁶ They are, however, likely to improve defensibility of the key assets that are considered.

Data was provided by the Forest Carbon Initiative on reforestation. In the Summer of 2020, the all-in costs of site preparation and planting were estimated to be \$1.10/seedling. For the purposes of the Forest Carbon Initiative they were planting at 2000 stems/ha, giving a cost per hectare of \$2200.

Fire Evacuation

Evacuation is difficult to model because the consequence of failing to evacuate is death. Creating scenarios around failed or aborted evacuation is challenging because we have few examples. For the purposes of the methodology described below we use the Value of Statistical Life (VSL). This is described in the Canadian Regulatory Cost-Benefit Guide put out by the Canadian Treasury Board [51]. In discussion with ministry staff we have settled on a VSL value of \$8million dollars. The second challenge with this is deciding how many deaths to include under a failed evacuation scenario. This is treated, simply, with a sensitivity analysis. Examples where deaths did occur can be read about in descriptions of the 2018 Camp Fire [52] and the 2009 Victoria Bushfires in Australia[53].

Productivity/Business Income Losses

There is no data available in the literature on estimating productivity or business income losses generated by major wildfire events. Collection of this data is difficult as the total cost of business interruption unfolds over a long period of time or at a local scale for which economic data is not readily available.

Timber Loss

It is possible to use the latest available provincial inventory data and log pricing reports to generate a reasonable estimate of timber losses. Using geophysical modelling of wildfires, we believe it is possible to use model outputs such as hectares burned, and fire intensity, for given wildfire management regimes, that will in turn allow us to produce accurate estimates of timber lost in a given area (likely in timber volume). The amount of assessed value lost depends on whether or not a tree is exposed to fire and what the intensity of the fire is when it is burned over. Work has been done in the Boreal[54]and in California [55]to estimate regression equations that relate fire intensity/char height to a probability of mortality for a given size class. There has also been some empirical work on the probability of tree survival after fuel treatments [56], [57].

These values can be included in the economic analysis tool, FAN\$IER, of the provincial stand dynamics model TIPSYS[58]. These values have not been modeled in the case studies below because proposed fuel treatments provided limited improvements in defensibility against loss of timber values.

Damage and Destruction of Habitat

Some attempts have been made to estimate loss of habitat by area for particular species like the spotted owl [59] but there has been less attention paid to putting a dollar value on these estimates. For non-market values the US Forest Service has employed a methodology they call implied minimum value or IMV [60]. The example given in their explanatory paper is one of protecting the Bitterroot Flower. If a treatment reduces the probability of extirpation of the flower from 50% to 20% and costs \$5000 then they calculate a probability adjusted cost is $\frac{\$5000}{0.5-0.2} = \frac{\$5000}{0.3} = \$16,667$. This is the implied minimum value. Policy makers must then make the decision whether the Bitterroot Flower is worth the \$16,667. This leaves a lot of the decision making up to the subjective judgement of policy makers. Alternatives like contingent valuation have received thorough criticism elsewhere as being unreliable and logically inconsistent [61]. In general valuation of habitat, species and ecosystems is expensive, difficult and prone to error. Venn[62] provides a review of the use of Non-Market Valuation in the study of wildfire economics. These values have not been included in the case studies below because there are very high value assets at risk that will take priority over these values given budget constraints.

Loss of Life

Death from wildfire in Canada has been relatively rare in Canada in the past century. While there is data collected by StatsCan on deaths in structural fires there is no similar data on wildfire losses. It is possible to use the Value of a Statistical Life used in Cost-Benefit Analyses for the Canadian federal government [51] to assess a value but it is not possible to estimate probability of loss for a given fire because there has been very little wildfire caused deaths in Canada in the past century. Hopefully, it stays that way. This has been tackled in the context of evacuation above with sensitivity analyses.

Flooding and Changes in Hydrology

It is well established that wildfire can have an impact on hydrology and increase the risk of flooding after major wildfire[63]–[65]. It is not clear that we have the data to model this. I know of no database in British Columbia that would allow us to estimate this in an expedient fashion. Estimating the effects of fire on hydrology is very difficult. Changes in surface soils depends on the intensity of the fire and the

probability of damaging floods will depend the weather the following season. Modelling this would require sophisticated probabilistic models. An example of an application of this modelling can be found in Gannon et al. [38]

Lost Recreation Value

It is relatively straight-forward to get a first pass estimate of losses from campsite and hotel revenues for a given fire scenario. Other declines in tourism revenue could be estimated using StatsCan data for a given fire size. For changes in other recreational values, such as mountain biking, snowmobiling and hiking it would be possible to make use of travel cost methodologies[66] . Travel cost estimations are significantly more time consuming and data hungry. We opted not to include this in the analysis because it is not high on the list of priorities when it comes to fighting wildfire and these values were not relevant for the case studies that were selected.

Smoke Costs

There is a substantial literature on the health effects and costs of illnesses due to wildfire smoke [5]. Costs tend to be in terms of sick days, medication, lost productivity or units similar to Quality Adjusted Life Years [67]. The values that have been arrived at are from historical fires. The challenge here is estimating the difference in smoke outcomes between no treatment and different treatment scenarios. If there are prescribed fires, how significant is the reduction in lost productivity, sick days, or medication. If it reduces the probability of future mega-fires, how far in the future does that occur? How should one discount these two streams of costs and benefits? Doing this properly would be its own project. There also business implications where wildfire smoke may impact recreation or tourism opportunities, an important contributor to many local economies in BC.

Methods for Estimating the Defensibility Value of A Fuel Treatment

Under the Hesseln framework [17] there were three things (besides better data management) that were needed to improve the quality of cost-effectiveness analyses of fuel treatments.

1. A description of the relationship between fuel management strategies and the change in fire behaviour.
2. A description of the relationship between observed fire behaviour and economic variables over the longer-run.

3. A consideration of the risk management aspect of fuel management decisions.

If we take these one at a time, we see that there has been little progress made over the 20 years since Hesseln wrote her article and there is good reason for this. Evaluating a fuel treatment using the cost-effectiveness methods requires that we have good simulation or statistical models relating changes in fuel density to changes in fire behaviour. We have models for doing this in BurnP3 [68] and a manual for fuel typing in British Columbia has been published to make this model more useful. Unfortunately, these models are time consuming to learn to use, set-up and run and the labor cost involved is unacceptable if the goal is to significantly scale the size and number of fuel treatments in the province. A great number of counter-factual burn scenarios have to be run in order to evaluate the relative merits of a single fuel treatment. A more straight-forward, less technologically intensive approach is necessary to make this framework useful.

If we turn to the second point, we are faced with the reality that little progress has been made and is unlikely to come in the foreseeable future. From the fire behaviour models we can retrieve three measures of fire behaviour, the rate of spread, the probability of crown fire and the probability of burn. Satisfactorily meeting the second condition would require that we take one or more of these fire behaviour measures and come up with a function that relates it to the damages we are interested in. That is, can we relate, on a specific landscape the rate of spread to the probability of community evacuation? Or the loss of critical infrastructure? Attempts have been made to create response functions in ArcGIS[41], [69]. The response functions turn expert opinion into a mathematical description of how the changes in fire behavior change outcomes from the values-at-risk. These response functions are then subjected to sensitivity analysis. Again, we run into the problem of expense for scaling fuel treatment evaluations. These response functions are bespoke work by a professional with a high charge rate that does not generalize, so we can answer the questions above more generally with a no, there are too many confounding variables. We face the Curse of Dimensionality[70]. There are so many contributing factors that need to be analyzed that it is not reasonable to collect the necessary data in adequate time, at reasonable cost. The large cost of collecting enough data and consult with expert opinion to make headway on this problem likely outweighs the benefit of getting an answer.

Finally, because the efforts, on the margin, have been in improving the modeling of Fire Behaviour and including increasingly complex computational analyses into cost-effectiveness models there has been

little consideration given to risk management. This is unfortunate because I believe reframing this from a risk management perspective makes the challenges with Hesselin's first two criteria more manageable.

Insurance, not an Investment

The literature evaluating fuel treatments discussed above frames the question of fuel treatments as if we are getting a return on investment. This is an unfortunate analogy. When we evaluate a new highway or dam using cost-benefit analysis the underlying assumption is that these investments will raise the total factor productivity of society (we will be able to generate more economic output per unit of inputs) and the cost-benefit analysis is a way of comparing results between different public investment options.

This is not what we achieve with fuel treatments. A well-designed fuel treatment is going to reduce the risk of damage to productive assets. Expenditures on a fuel-treatment can be thought of as a buffer against the risks posed by catastrophic wildfire.

With this in mind, we propose that fuel treatments should be assessed on whether or not they provide adequate 'buffer' in the event of a wildfire. If a wildfire represents a risk that we can put a price on to the community, does the reduction in risk from a fuel treatment justify its price?

We call this buffer, *defensibility*. Since security of a value can never be guaranteed by fuel treatments we are concerned with how much more defensible the value has been made by the fuel treatment.

A Framework for Assessing Protection Adequacy of a Fuel Treatment

The goal here is to assess whether or not a fuel treatment increases the defensibility and reduces risks sufficiently to justify its price. Ideally, the process should be repeatable at low cost to evaluate hundreds or thousands of potential fuel treatments in a reasonable amount of time at reasonable cost.

This is a simple, four step process:

1. Identify the boundaries and methods used for the fuel treatment and their estimated costs.
2. Estimate the life of the fuel treatment and the likelihood that it will be challenged over its useful life or the costs of maintaining the treatment in perpetuity.

3. Choose 'stress-test' damages for the included cost categories⁷.
4. Calculate a defensibility threshold given the damages and cost of treatment.

The defensibility threshold identifies the likelihood of success that a fuel treatment needs to have in order to be worthwhile. If the result of the calculation is 10%, the project evaluator needs to believe that the fuel treatment is going to protect the identified values-at-risk at least 1-in-10 times that the treatment is tested under extreme fire weather conditions.

The BC Wildfire Service Fuel Management Prescription document prescribes that “prescribed fuel reduction targets should be sufficient to be effective to meet treatment objectives reduced fire behaviour under 90th Percentile Fire Weather Index Conditions.”[71] It makes sense for the practitioner to be judging defensibility according to this standard.

Fuel Treatment Costs

This should be straight-forward. In practice, a project proponent submits their estimated costs along with a project proposal. For the purposes of our test cases we will be using historical fuel treatment cost data from FESBC and completed or proposed and accepted fuel treatment boundaries in the case study areas.

Probability of Fire Testing Fuel Treatment

The probability of a fuel treatment being tested by a wildfire depends on two things. How long the fuel treatment is expected to do its job and the likelihood of a fuel treatment getting tested by fire in any given year. Plants keep growing every year and so fuel treatments need regular maintenance in order to maintain their usefulness. Different ecosystem have different rates at which biomass returns to dangerous levels[72]–[76]. One study from the Black Hills of South Dakota in Ponderosa Pine that is similar to the low-elevation forests of the Okanagan study area found that it was necessary to re-burn treatment areas at an interval shorter than 15 years to maintain efficacy[77].

In the case studies below, we use a sensitivity analysis to test different probabilities of a wildfire actually testing a fuel treatment over its lifespan. The values used in the sensitivity analysis are 0.05, 0.10 and 0.15.

⁷ These cost categories should be the ones that stand out as the most important for the area of interest.

In modelling a fuel treatment that is maintained in perpetuity the probability that fire tests the treatment is assumed to be 1.

Stress Testing

After the mortgage backed security crisis, as part of the Dodd-Frank Act [78], banks were required to survive stress tests to show that they had sufficient assets on hand to survive a drop in the markets or a credit market freeze. This idea of a stress test is useful for fuel treatments. Does a cost-category or value-at-risk do better under the fuel treatment or not? In the case of a bank stress test, we know that if there are sufficient liquid assets on hand a bank will survive a stress with certainty. In the case of wildfire, we do not have that certainty, we only have changes in defensibility. Adequacy of a wildfire fuel treatment in the event of an actual fire will depend on the prevailing fire weather and availability of firefighting resources. We address this in the final step.

The costs that make sense to include in the stress test should be the ones that are appropriate to the area of interest. In the 150 Mile House example there is a natural gas compressor station with a minimum \$125 million value (its replacement cost). This critical infrastructure value dwarfs all other potential values that could be included in the analysis, so we include that as the primary focus of the stress test. As has been emphasized throughout this document, it is more productive to get the first order costs and benefits modeled. The net benefit of including every value we can enumerate is usually minimal for the purpose of deciding which fuel treatments to fund.⁸ There are critical assets that are essential keeping the power grid online and food and essential services online that still need protecting. While this is true the use of a heuristic is more sensible than using sophisticated computer modelling for decision making.

The point of stress testing is to choose numbers that reflect costs arising from a catastrophic fire in the tail of the cost distribution. From that starting point, costs can be scaled to the limit (potential damages are not infinite) to see what happens under the worst possible case. For each category, it is necessary to estimate the costs with and without the fuel treatment.

Calculating the Defensibility Threshold

⁸ And, as I argue in the end, this is likely true for making the case for funding these programs as a whole. At least during the early stages of deciding what to fund.

The final step is calculating the Defensibility Threshold. Again, the defensibility threshold identifies the likelihood of success that a fuel treatment needs to have in order to be worthwhile. If the result of the calculation is 10%, the project evaluator needs to believe that the fuel treatment is going to protect the identified values-at-risk at least 1-in-10 times that the treatment is tested under extreme fire weather conditions.

To find this number we first, calculate the difference in estimated costs, with and without treatment. We will call this *Sum of Avoided Costs*.

It is possible that the fuel treatment does not get tested by fire over its useful life. So, the *Sum of Avoided Costs* has to be discounted by the probability of getting tested by fire. Multiply the Sum of Avoided Costs by this probability.

$$\text{Adjusted Avoided Costs} = pr.burn * \text{Sum Avoided Costs}$$

As discussed above there is limited research on what this probability should be so in the case studies below, we use a sensitivity analysis to test different probabilities of a wildfire actually testing a fuel treatment over its lifespan. The values used in the sensitivity analysis are 0.05, 0.10 and 0.15.

If we divide the estimated cost of the fuel treatment by the *Adjusted Avoided Costs* we have an implied probability that we denote d for defensibility.

$$d = \frac{(\text{Fuel Treatment Cost})}{(\text{Adjusted Avoided Costs})}$$

The implied probability is interpreted as the incremental improvement in defensibility that would justify the calculated avoided costs. The actual improvement in defensibility is estimated by the project evaluator because we do not have a cost-effective means of estimating changes in defensibility using computer simulation or any other tools. If the project evaluator believes that the improvement in defensibility is at least as good as d in percentage terms then the project should go ahead.

If d is greater than 100% the project automatically fails the stress test and should not go ahead. A value for d of greater than 100% suggests that even a guaranteed defensibility of the values-at-risk is insufficient to justify the expenditures on the fuel treatments.

Different projects within the same study area can be ranked using the method. A lower d is better than a higher one.

It is intuitive that we want the adjusted avoided costs to be larger than the fuel treatment costs. So, all else being equal a smaller d is better than a larger d . We can get a smaller ratio, either by increasing the amount of avoided costs through the increase of the avoided costs or the decrease of fuel treatment costs.

Suppose we have a 1 ha treatment that costs \$10,000. This treatment is intended to protect \$1,000,000 in assets. This gives a $p=0.01$. One would think that this is pretty good!

The project evaluator has to believe that the fuel treatment will improve the defensibility of the assets by at least 1%. In other words, if there to be 100 extreme weather fire events that test the fuel treatments, the fuel treatment would have to protect against at least one more of them relative to business as usual. If the evaluator realizes that this 1 ha treatment is actually useless for improving defensibility of the assets included in the evaluation, then the project is rejected.

Now, if you have two projects, one with a treatment cost of \$200,000 protecting \$1,000,000 in assets and another that costs \$300,000, also protecting \$1,000,000 in assets then their respective ds are going to be 0.2 and 0.3.

If the evaluator agrees that both projects will make the values-at-risk defensible (relative to the base case) at least 2/10 and 3/10 more of the time, then the lower cost project is the one to go with. It provides the same insurance at lower cost. You may protest that the \$300,000 project is provided protection at least 1 out of 10 times more than the \$200,000 project but this ignores the fact that by choosing the \$200,000 project we have \$100,000 more to work with and we could, presumably, protect assets of an even greater value. The value at risk per dollar spent is reduced more with the \$200,000 project.

An Example

To get a sense of how the cost adjustments and discounting of future value might work, imagine we had a large landscape level fuel treatment that was going to cost \$1,000,000.

The estimated avoided damages for this project are as follows:

Cost Categories	Avoided Damages
Suppression	\$ 1,000,000
Evacuation	\$ 5,000,000
Timber Loss	\$ 3,000,000
Property Loss	\$ 10,000,000
Total Damages	\$ 19,000,000

The life of the project is 15 years and we believe that the likelihood of the fuel treatment being tested during that time with a high severity fire is 30%. *The Adjusted Avoided Costs* are then \$19,000,000*0.3=\$5,700,000.

Then we can calculate d .

$$d = \frac{\$1,000,000}{\$5,700,000} = 0.18$$

We can read this as saying that the fuel treatment has to provide the conditions for keeping the stress test wildfire at bay roughly 1/5 more times in order to justify the expenditures.

Adjusting for a Regularly Maintained Fuel Treatment

What if we wanted to account for the fact that the fuel treatment will be managed continuously with regular prescribed burning? Treat the costs of maintenance as a Perpetual Bond and discount the costs to the present at the discount rate r . Extending the example above, if we have to \$50,000/year in perpetuity and the discount rate is 5%. The new fuel treatment cost would be

$$\text{fuel treatment cost} = \$1,000,000 + \frac{\$50,000}{0.05} = \$2,000,000$$

We also no longer have to adjust avoided costs. If a fuel treatment is being maintained in perpetuity, it will be tested at some point in its life. Our new d for the perpetually maintained fuel treatment is

$$d = \frac{\$2,000,000}{\$19,000,000} = 0.11$$

If the fuel treatment maintenance is only done every five years, we can adapt the Land Expectation Formula[79] to calculate the present value of the costs.

$$\text{Present Value} = \frac{\text{Maintenance Cost}}{(1 + r)^t - 1}$$

Where t is the maintenance interval and, in the case, takes the value $t = 5$.

We can recalculate the fuel treatment cost:

$$\text{fuel treatment cost} = \$1,000,000 + \frac{\$50,000}{(1.05)^5 - 1} = \$1,180,974$$

And the defensibility threshold:

$$d = \frac{\$1,180,974}{\$19,000,000} = 0.06$$

If the fuel treatment only needs to be maintained every 5 years, the required improvement in defensibility drops to only 6% in this example. It's worth spending money on maintaining fuel treatments.

Limitations and Shortcoming of the Method

There are three primary shortcomings of this approach from the perspective of the economist modeller:

1. Limited number of values are included
2. Requires expertise of frontline wildfire operators
3. Defensibility may not be intuitive

Limited Value Inclusion

This is not an inherent failure of the model nor is it unique to this approach. To a greater or lesser extent all of the other approaches have also suffered from this. The number one challenge with modeling this problem in general is that the interactions between variables are complicated and highly uncertain. The costs of modelling additional variables within acceptable error bounds is very expensive. Sufficiently expensive that it interferes with the advancement of the fuel treatment projects themselves in a timely manner.

The greatest let-down in this is that completing a project evaluation in a cost-effective and timely manner does not allow for the evaluation of the long-term effects of catastrophic wildfire. There are important and difficult questions to be answered around the long-term viability of some of the forest-based communities in British Columbia in the face of catastrophic wildfire. Can landscape-level fuel

treatments protect against the loss of their economic lifeblood? This modelling approach doesn't have anything to say about that. It focuses only on the near-term effects.

One upside of this approach is that it quickly identifies the assets with the greatest value at risk for easier prioritization. We also find that the economic prioritization aligns with the priorities of the BC Wildfire Service.

Frontline Expertise

Unlike a cost-benefit analysis, which in theory, can be done without direct decision-making capacity being required of experienced frontline staff, this method does require that. The vast majority of economists are not going to have the experience to judge whether or not a fuel treatment is sufficient to protect assets for some fraction of the exposures to extreme fire.

One way of looking at this is that the framework is not intended to be a (computationally) model driven approach. It is a systematic way for experienced frontline professionals to think their way through the economic problem of evaluating potential fuel treatments. Hopefully with the help of economists to do some of the leg work on the valuations.

Compared to other approaches the expertise demands are in-fact lower. The more advanced approaches used in [69], [80] are very time consuming and expensive relative to this approach.

Implied Probabilities are not Intuitive

Trying to understand the ratio of costs as an implied probability is not terribly intuitive for most people. I think this can be overcome by simply asking the question, "How many times in 10 would this fuel treatment have to protect these values in the event of a fire in the 95th percentile of fire weather?" If that number exceeds the implied probability, then it is worth doing the project.

Including Other Values

The case studies only deal with a handful of values that are relevant to the areas of interest and the priorities of the BC Wildfire Service. In discussions and at the workshop in Victoria, three values came up repeatedly as of being interest to potential modellers. These are Greenhouse Gas emissions, and habitat destruction.

A process for estimating these values is sketched out in the following sub-sections.

Greenhouse Gas Emissions

Continuing to work from the perspective of a stress test, estimating initial emissions from an extreme fire weather scenario without a fuel treatment should not be too difficult. If we make use of the timber value loss model to build an estimate of above ground carbon losses and then add on an estimate of surface fuel combustion the initial emissions could be estimated for both with a treatment and without treatment scenario.

To fully account for the differences in emissions though would require modelling stand dynamics with and without the treatment. We would have to assume that the burned area is being replanted immediately and calculate the differences in stored carbon over the lifetime of the stand discounted to the present. Are there differences in growth between burned and unburned? Changes in the costs of silviculture between the two scenarios?

Finally, the modeler would also have to account for lower stand density in the stands that have been treated to reduced risk.

Habitat Loss

There are two challenges with modelling the avoided damages to habitat loss. The first is the complicated interactions between ecosystem components and fire and the second is the valuation of ecosystem values.

Many species in British Columbia ecosystems benefit from low-to-moderate severity fire but high severity fire often does not provide the same opportunities for growth. Modelling the with treatment and without treatment effects of fire would require modeling the distribution fire severity in the geography of interest. There may be trade-offs between organisms within the study-area boundary. Some species are going to do better after fire than others. How do we choose which ones should be valued?

To address the explosion of possibilities here a focused model would consider species-at-risk alone. How is there habitat affected given changes in the severity of fire?

The valuation of these factors is another challenge. In general, we want to keep people away from species-at-risk, even as tourists. This makes the use of hedonic pricing methods like travel costing unusable. This leaves us with contingent valuation. To my mind, the willingness-to-pay, willingness-to-accept literature has been thoroughly put to rest as unreliable and inconsistent[61]. Unfortunately, this

is the only way forward for species and ecosystem values that have no instrumental value to society in this kind of analysis which demands everything be evaluated in terms of dollar values.

For ecosystem services related to hydrology there are more established methods. For instance researchers have developed models for the economic estimation of post-wildfire flood effects[65]. These are involved models however, that require at least as much effort as estimating the impacts of fire to the carbon cycle.

Case Studies

We selected 4 case studies in two regions of the province for this study. In the central Cariboo we selected an area around 150 Mile House and the South Lakeside neighborhood of Williams Lake. In the Okanagan, we selected the Glenrosa neighborhood in West Kelowna and the Greata Ranch area just south of Peachland. In all cases we are working with data for proposed or completed fuel treatments.

The different treatments areas were selected to highlight different scenarios and different types of values at risk. The *South Lakeside – Williams Lake* scenario was selected to look at treatments in the Wildland-Urban Interface that primarily protected residential homes. The *150 Mile House* scenario includes residential homes and a new compressor station that is being constructed on an Enbridge gas pipeline. The *Greata Ranch* scenario is intended to capture the costs of not being able evacuate and the *Glenrosa* scenario contains a combination of residential values, a middle school and a water treatment plant. The Glenrosa scenario is also useful for looking at how different real-estate valuations impact the decision making relate to the South Lakeside example where land improvements are valued by the market at about half the amount of Glenrosa.

For each of the scenarios we consider sensitivity analyses on the probability that wildfire, under extreme fire weather conditions will test the fuel treatment as well as number of homes burned, or the number of people trapped when evacuation routes are not safe.

In addition to this, for the scenarios that included residential houses two different perspectives are considered. A purely public expenditure perspective which only accounts for foregone property taxes and a more holistic perspective that accounts for the entire replacement value of the home based on its assessed value based on the BC Assessments Roll Totals [46].

A Description of the Fuel Treatment Data

In the case studies described below, a standard cost for mechanical fuel treatments of \$2000/ha was used. This number was settled on after examining data provided by the Forest Enhancement Society of BC (FESBC) and discussing the trends in fuel treatments with one of the staff members from FESBC who is responsible for evaluating proposed fuel treatment projects.

The data provided by FESBC contained information on 83 different fuel treatments in 7 regions of the province. A summary of the average cost for mechanical treatments is found in Table 1.

Region	Avg. Cost / ha
Cariboo	\$ 1,784.03
Kootenay	\$ 3,125.38
Kootenay-Boundary	\$ 2,480.31
Okanagan	\$ 1,975.40
Omineca	\$ 2,087.18
South Coast	\$ 8,558.76
West Coast Region	\$ 14,033.64
All Regions	\$ 2,348.92

Table 1 Average mechanical fuel treatment costs in British Columbia. Data provided by the Forest Enhancement Society of British Columbia.

The way in which the specifics of the fuel treatments were recorded meant that individual cost components (e.g. type of thinning, machinery used, etc) were not consistently reported. Because of this the data could only be separated into two groups, mechanical and hand treatments for the different regions in the data set. Data for hand-treatments are provided in Table 2.

Region	Avg. Cost / ha
Cariboo	\$ 5,105.18
Kootenay-Boundary	\$ 3,313.82
Okanagan	\$ 6,394.29
South Coast	\$ 15,200.79
All Regions	\$ 6,302.83

Table 2 Average hand fuel treatment costs in British Columbia. Data provided by the Forest Enhancement Society of British Columbia.

We have plotted individual fuel treatments in Figure 4. At this time, the operators have not found an efficient operating frontier. We would expect there to be clear returns to scale in the fuel treatments and we could draw a line that shows that there has been some drop in costs as a function of treatment size but there is a great deal of noise in the dataset. In the bottom left of the figure we can many treatments of small size with similar costs to the largest treatments in the dataset. In discussions with staff at FESBC the project evaluators were confident that operators have learned a lot about fuel treatments and project proponents are starting to settle on an appropriate mix of equipment and it would be reasonable to see mechanical fuel treatment costs average \$2000/ha and on large projects the interviewee expected to see \$1200/ha in the near future.

Projects that removed overstory are shown as a triangle in Figure 4. This is correlated with removing more merchantable timber. Examination of the figure does suggest that sites where overstory removal is permitted lowers the cost per hectare as we would expect.

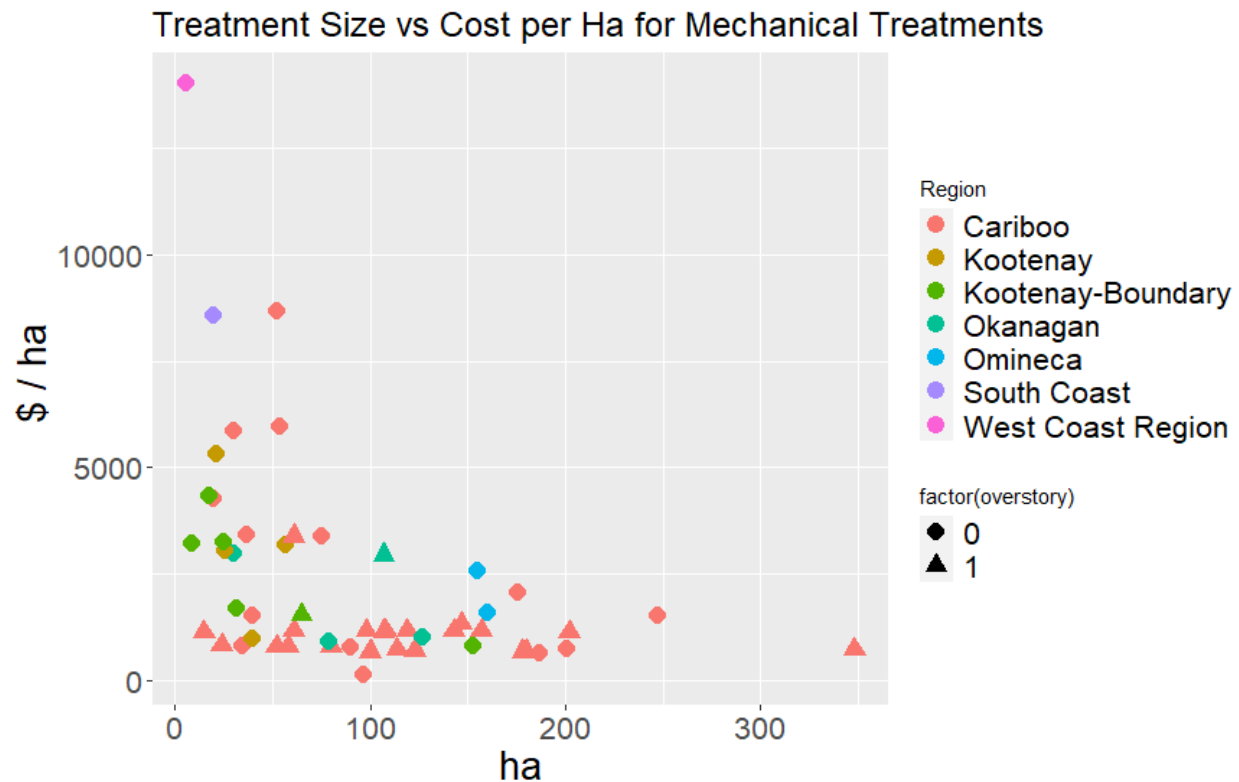


Figure 4 Individual mechanical fuel treatments by size and cost (\$/ha). Region indicated by colour and a triangle indicates that there was overstory removed which is correlated with removal of merchantable timber.

Greata Ranch

Greata Ranch is a large winery-vineyard south of Peachland along Highway 97 in the Okanagan (Figure 4). There are few residences here but there is a critical evacuation route for the region. I have included the replacement value of the vineyard, but the focus is on the potential lives lost when evacuation routes cannot be kept open. I had tried to avoid putting a price on life, but it was unavoidable for the purposes of attempting to value the potential loss of life from not being able to keep an evacuation route open. Life is priced using the Value of a Statistical Life (VSL) method recommended by the Canadian federal governments Treasury Board of Canada Secretariat's *Canadian Cost-Benefit Analysis Guide* [51]. The specific value of \$8 million used for a VSL was determined in discussion with economists at the ministry. As loss of life from unsuccessful evacuation, even in extreme wildfire conditions, is rare we don't have a good sense of what the correct number of lives is to use in the model and I have used a sensitivity analysis with 10,50 and 100 lives lost.



Figure 5 Treatment area for the Greata Ranch area just south of Peachland, British Columbia

The replacement stock for the vineyard is valued at \$75,861 / ha [81] totaling roughly \$3.5 million for the entire vineyard and is fixed for all scenarios. This value is dwarfed by the total VSLs for the lives at risk.

The area of the fuel treatment is 22.4 ha for a cost of \$44,800 at \$2,000/ha.

The defensibility values are given in Table 1 below.

		<i>Probability of Treatment Being Tested</i>			
		d	0.05	0.1	0.2
<i>Loss of Life</i>	10		1.07%	0.54%	0.27%
	50		0.22%	0.11%	0.06%
	100		0.11%	0.06%	0.03%

Table 3 Defensibility criteria for the Greata ranch area with three scenarios for potential loss of life from failed evacuation (10,50, and 100 people). \$2000/ha for treatment costs.

Given these estimates, even with the most conservative assumptions the fuel treatment is justified if it succeeds in improving defensibility of the highway only 1% of the time. Given the small size of the fuel treatment (22 hectares) it is a legitimate question whether or not this fuel treatment would succeed in keeping the highway open. If we flipped this problem around and asked, how big of a treatment could be justified if the treatment is only tested by extreme fire once in twenty years and there are only 10 lives at risk? The answer is about 2200 hectares. A very large treatment by the standards of what has been funded so far.

Glenrosa

The Glenrosa neighbourhood, part of West Kelowna is the second set of treatments to be considered. The Values at Risk here include a middle school, a water treatment plant and residential homes.

The total area treated in this case study is 405 ha. I have included two fuel treatment cost scenarios for this case study. One at the \$2000/ha that has been used for the other case studies (Tables 4 & 5) and another scenario using \$4000/ha (Tables 6 & 7). The \$4000/ha scenario has been included because some of the planning that has been done in the area described some of these treatments being done by hand[82]. In the dataset provided to me on fuel treatment costs hand treatments averaged \$6300 / ha. I have assumed a roughly half - half balance of hand treatments to mechanical treatments for the second treatment scenario. The sensitivity analysis for these scenarios are included in Tables 6 & 7. Total treatment costs for the \$2000/ha scenarios are about \$800,000 and for the \$4000/ha scenario they are \$1.6 million.

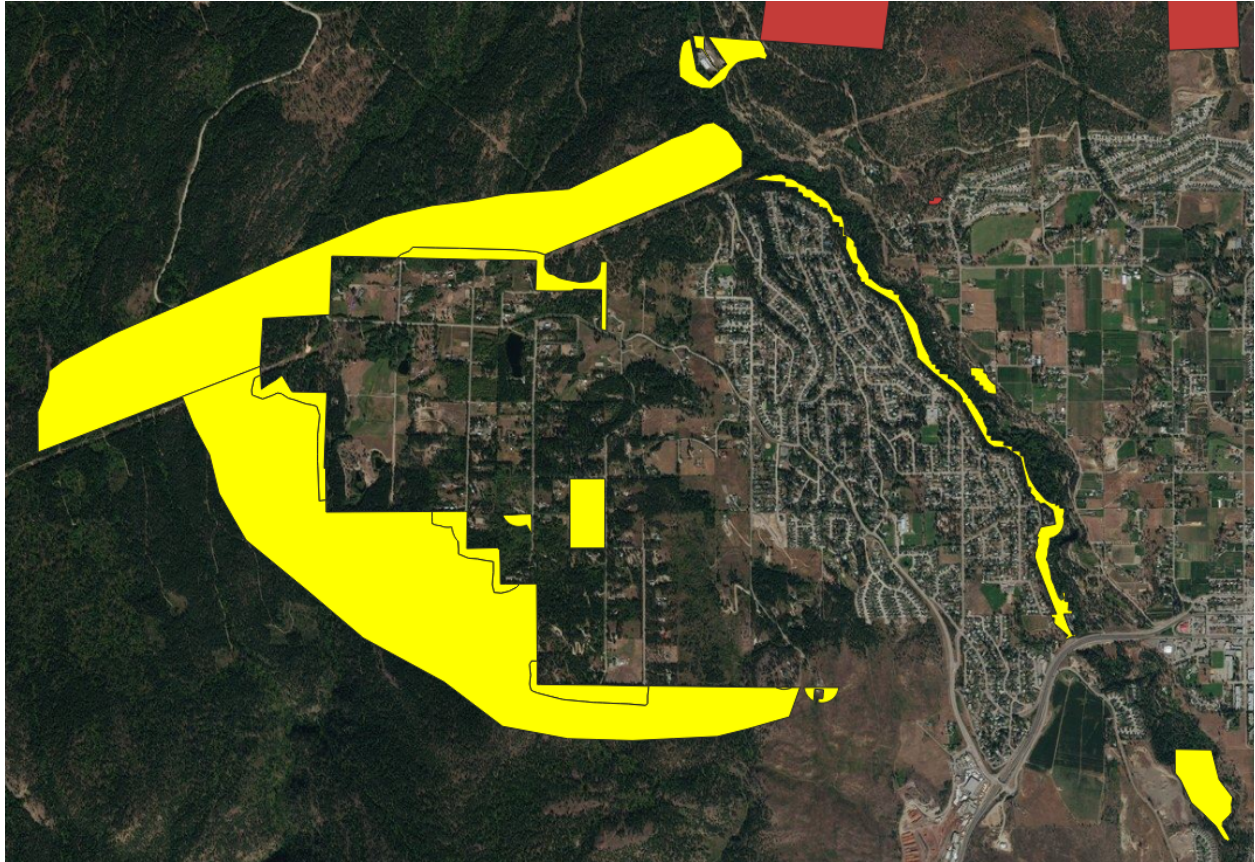


Figure 6 The neighbourhood of Glenrosa is surrounded by the fuel treatments marked in yellow.

Two different viewpoints for valuing lost home values are considered. An exclusively public expenditure perspective which only makes use of the foregone property taxes (0.6% of property value) and whole home replacement cost perspective. The average land improvement assessment for this area is \$391,000. About twice that of the Williams Lake area.

The Helen Gorman Middle School was costed at replacement value of \$9.9 million based on square footage and a Canadian public sector construction costing index for schools[83].

The Powers Creek Water Treatment plant replacement value was taken from construct costing data published by a local newspaper at the time of construction[84]. It was valued at \$18,000,000 at the time of construction in 2007 and inflated to 2020 dollars this is roughly \$22,000,000.

		Probability of Treatment Being Tested		
	d	0.05	0.1	0.2
Homes at Risk	50	50.6%	25.3%	12.6%
	100	50.4%	25.2%	12.6%
	200	50.0%	25.0%	12.5%

Table 4 Defensibility criteria given a public expenditure perspective (property taxes only). Treatment costs averaging \$2000/ha.

Table 2 contains results for a public expenditure perspective with residential homes valued with lost property tax revenue only and an assumption that treatments are done using mechanical means only. Given the most conservative set of assumptions where there are only 50 homes at risk and 1 in 20 year chance that the fuel treatment will be tested under extreme fire weather conditions the treatments have to make the assets defensible 50% of the time to make it worthwhile. As the number of homes at risk is increased, we don't see much of a change in the defensibility criteria because it is valued only as the lost property taxes.

		Probability of Treatment Being Tested		
	d	0.05	0.1	0.2
Homes at Risk	50	31.5%	15.7%	7.9%
	100	22.8%	11.4%	5.7%
	200	14.7%	7.4%	3.7%

Table 5 Defensibility criteria with total value of homes lost. Treatment costs averaging \$2000/ha.

In Table 3 the entire value of the homes are included and this improves the desirability of the fuel treatment. As a result of including the full value of the home when the number of homes at risk is increased to 200 the fuel treatment only needs to work about 1 in 8 times to be worthwhile.

		Probability of Treatment Being Tested		
	d	0.05	0.1	0.2
Homes at Risk	50	101.1%	50.6%	25.3%
	100	100.8%	50.4%	25.2%
	200	100.0%	50.0%	25.0%

Table 6 Defensibility criteria given a public expenditure perspective (property taxes only). Treatment costs averaging \$4000/ha.

When the average cost of the fuel treatments is doubled to account for potential hand treatments the treatments appear less economic. From the property tax only perspective, the treatments are not worth

doing at all if they are only being tested once in twenty years (Table 4). If the full cost of the home is included, and 50 homes are at risk, the fuel treatment needs to be effective 2/3rds of the time (Table 5). Unsurprisingly, the more area that can be treated mechanically the smaller chance of success it needs to be to be worthwhile.

Homes at Risk	d	Probability of Treatment Being Tested		
		0.05	0.1	0.2
	50	63.0%	31.5%	15.7%
	100	45.6%	22.8%	11.4%
	200	29.4%	14.7%	7.4%

Table 7 Defensibility criteria with total value of homes lost. Treatment costs averaging \$4000/ha.

150 Mile House

The 150 Mile House region (Figure 6) was chosen largely because it is home to critical infrastructure for the gas supply of the southern half of the province. An Enbridge gas compressor station. When a pipeline exploded in 2018 on the same gas transport system, it resulted in curtailed gas use for Canadian customers with the Fortis gas system running at 40% capacity [85], American refineries and power plants had to shut down, 750,000 residential power prices increased more than two orders of magnitude [86] and in personal conversations with energy traders two utilities nearly lost their entire gas systems from loss of pressure and large parts of the electrical grid in the PNW were close to extended black out. Total additional costs from the loss of that transport line relative to business as usual likely ran in excess of a billion dollars. Providing an accurate valuation of this outage would be as large a project as this entire report so I have limited the value-at-risk to the replacement value of the 2020 Enbridge compressor station upgrades, \$125 million [87]. I do this because the investment cost of the plant is the minimum bound for the social value of the plant. If Enbridge was not going to see present value returns at least as much as \$125 million it wouldn't be making the investment.

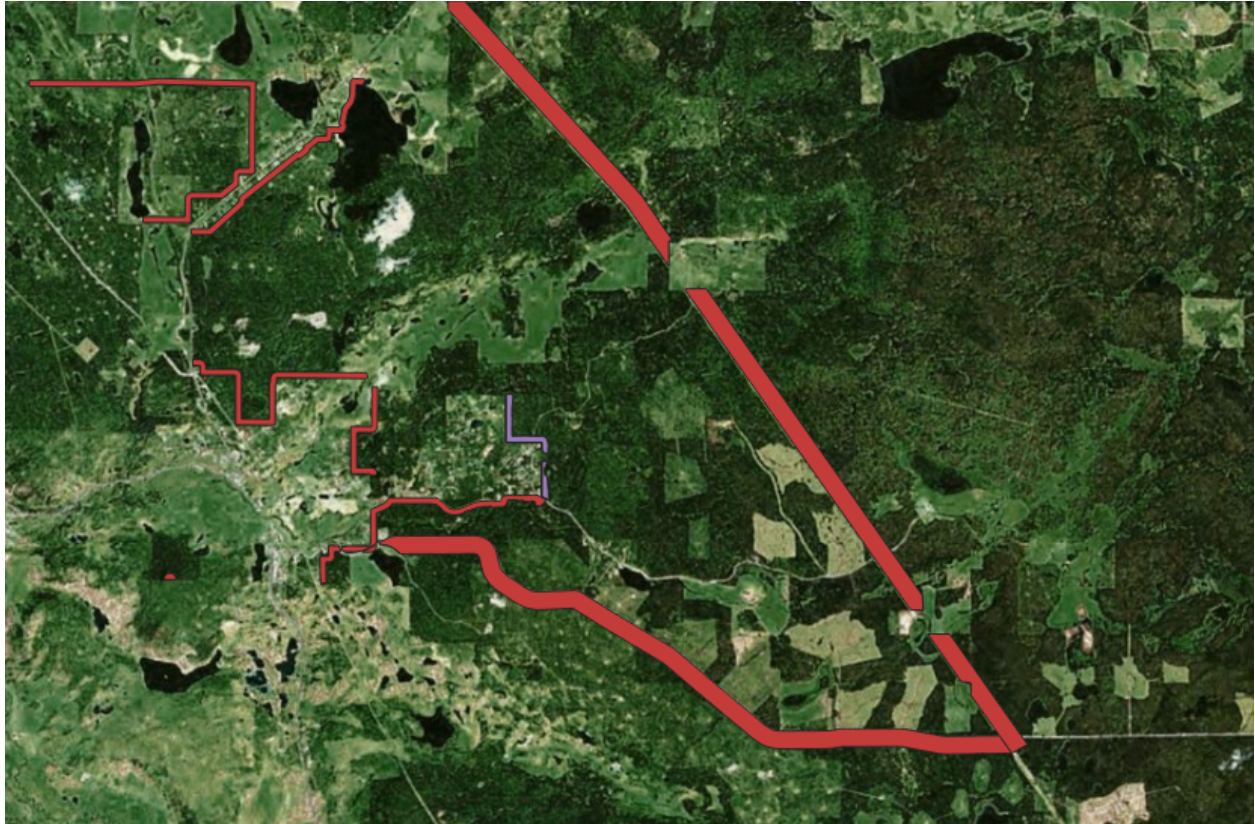


Figure 7 150 Mile House case study region

This is the largest treated region in the 4 case studies. The fuel treatments shown in Figure 6 total 1,577.5 hectares. At \$2000/ha this totals over \$3 million.

In addition to the compressor station there are homes at risk. Once again two scenarios are included with Table 7 including only foregone property taxes and Table 8 including the full value of the homes. Property taxes are calculated at 1.14% of assessed value and the mean land improvement is \$178,218 for the region[46].

	d	Probability of Treatment Being Tested		
		0.05	0.1	0.2
Homes at Risk	50	50.4%	25.2%	12.6%
	100	50.4%	25.2%	12.6%
	200	50.3%	25.2%	12.6%

Table 8 Defensibility criteria given a public expenditure perspective (property taxes only). Treatment costs averaging \$2000/ha.

If the fuel treatments are to be tested under extreme fire weather conditions once in twenty years need to make the assets defensible 50% of the time. If the true cost of a gas line outage is in fact closer \$500

million this would drop to 12.5% and at a billion dollars in costs the fuel treatment only needs to make the asset more defensible 1 in 20 times. Consistent with the Wildfire Service placing a high priority on critical infrastructure the economics of this also place a high priority on the protection of these assets.

Homes at Risk	d	Probability of Treatment Being Tested		
		0.05	0.1	0.2
	50	47.1%	23.6%	11.8%
	100	44.2%	22.1%	11.0%
	200	39.3%	19.6%	9.8%

Table 9 Defensibility criteria with total value of homes lost. Treatment costs averaging \$2000/ha

South Lakeside - Williams Lake

The South Lakeside case study (Figure 7) is the most straight-forward in its valuation. Only residential home values have been included. Both the foregone property tax and full-assessed values are included.

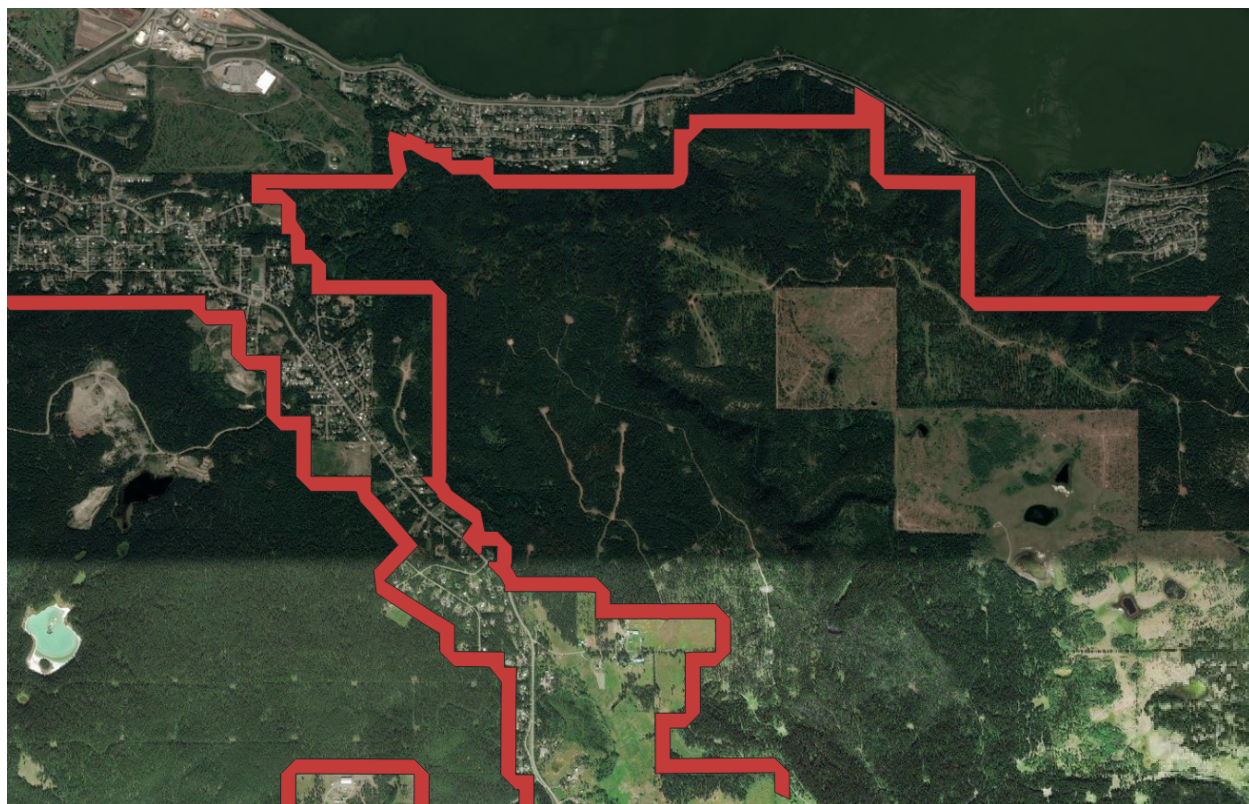


Figure 8 South Lakeside - Williams Lake case study area

Mean land improvements are assessed at \$173,671 dollars and property taxes assessed at 1.14% of assessed value. The treated area is 315ha at \$2000/ha for a total cost of \$630,000.

		Probability of Treatment Being Tested		
	d	0.05	0.1	0.2
Homes at Risk	50	12728%	6364%	3182%
	100	6364%	3182%	1591%
	200	3182%	1591%	796%

Table 10 Defensibility criteria given a public expenditure perspective (property taxes only). Treatment costs averaging \$2000/ha.

In Table 10, we can see that if only the foregone property taxes are included no combination of the assumptions comes anywhere close to justifying the expenditure on the fuel treatments. From the public expenditure perspective this absolutely should not be done.

		Probability of Treatment Being Tested		
	d	0.05	0.1	0.2
Homes at Risk	50	145%	73%	36%
	100	73%	36%	18%
	200	36%	18%	9%

Table 11 Defensibility criteria with total value of homes lost. Treatment costs averaging \$2000/ha.

In Table 11, if we account for the full value of the homes the fuel treatments still cannot be justified if under conservative assumptions of 50 homes being at risk of being burnt down and the fuel treatments being challenged 1 in 20 years. If the fuel treatments were expected to be tested 1 in 5 years and the number of homes at risk is 200 (very generous assumptions for this scenario given the recent 2017 fires) then the fuel treatments only need to work 1/10 times to be worthwhile.

This case study shows that the economics suggest prioritizing expenditures on critical infrastructure and other public infrastructure, like schools and water treatment plants before residential homes. This is consistent with existing risk priorities.

An Example with Perpetual Maintenance

In each of the case studies above we include a probability of treatment being tested because fuel treatments have a finite life if they are not maintained. As fuel treatments are currently funded on a project by project basis this approach makes sense but what if funding was available for maintaining fuel treatments?

To treat this case I will return to the 150 Mile House example with the compressor station and assume that the fuel treatments are being maintained at two year intervals (likely an aggressive assumption) in perpetuity. I have only one example of a pure prescribed burn in my fuel treatment dataset and over 182 ha the treatment costs came to \$74/ha. To provide some padding I will round up to \$100 /ha.

These costs will be incurred every two years forever. We can modify the Land Expectation Value formula to account for these costs [79]:

$$Present\ Value = \frac{Rx\ Burn\ Cost}{(1 + r)^t - 1}$$

If we use a social discount rate of 3% as recommended in the Canadian Cost-Benefit Analysis Guide [51] with a 2 year repeat and a prescribed burn cost of \$100/ha we get:

$$PV = \frac{\$100}{(1.03)^2 - 1} = \$1,642$$

If we add this present value of the perpetual prescribed burns to the initial mechanical treatment costs at year 0, we can recalculate the defensibility threshold.

If I take the most conservative example for 150 Mile House with the \$125 million value for the compressor station and 50 homes at risk, only counting foregone property taxes the present value of prescribed burning all 1,577 hectares is \$2,590, 311 and a probability of 1 that the treatment will get tested over its lifetime⁹ we get $d = 4.6\%$. We interpret this to mean that the fuel treatment only needs to work 4.6% of the time to be justified.

Under the one-time treatment model with a 1 in 20 year likelihood of the treatment being tested over its life the same treatment resulted in a defensibility threshold of 50%. The prescribed burning cost at two-year intervals would have to be \$2300/ha in order to achieve a defensibility threshold that high.

It really makes sense to maintain these fuel treatments!

⁹ If the treatment is maintained in perpetuity it will eventually meet with a wildfire under extreme fire weather conditions.

Conclusions

We have presented a new approach to evaluating risk management projects in the form of a *defensibility threshold*. This approach is intended to overcome three limitations of the existing approaches. The first limitation of the existing approaches to economic modelling in wildfire economics do not take the irreducible uncertainty of fat-tailed distributions seriously and reduce the problem by modelling with traditional tools that require an assumption normality. This effectively throws out information carried by the data to simplify the problem. The second problem is that of describing the relationship between wildfire behaviour modelling outputs and potential damages to values-at-risk. The defensibility threshold bypasses both problems by relying on the *implicit knowledge* of people who have worked in the field with wildfire. Finally, there are modelling efforts that have attempted to get around the above through very thorough simulation efforts and translating expert feedback into spatial response functions[41], [69]. We argue that from the perspective of scaling real-world fuel treatment efforts, the cost in time and money of these models is too high. There needs to be a simpler approach that offers a quick filter for projects.

The core of the idea is captured in a metaphor from optimization. In the mathematics of optimization one way of categorizing algorithms that find minima and maxima is those that guarantee an optimal solution and those that search for the optimum in incremental steps. We can describe the entire world of study with equations that we know have a geometry that guarantees an optimal solution. We might lose important details of the world in this description, but we are also guaranteed an answer. Often when we take this approach in a complex environment, we find that we have made assumptions that make the model unactionable or when action is taken it is disastrous[88]. The temptation is to invest more resources in developing the model to make it better rather than acting.

The other approach is to look around in the immediate environment and to use a heuristic to find the path that is likely to take us in the direction we want to go and take the first step. After we take a few steps, we evaluate whether we have moved closer to our goal. If not, we change direction and take another path, if we have moved closer to the goal then we keep moving. In a dynamic and complex operating environment this leads to a tighter feedback loop with faster learning and better use of resources. The goal of the *defensibility threshold* approach is to provide a decision tool in this spirit.

Practically speaking this means using the BC Wildfire Service Resource Sharing Wildfire Allocation Protocol (RSWAP) as a tool for identifying priorities for protection of values-at-risk. This has already been done as part of the mapping effort in the Provincial Strategic Threat Analysis (PTSA). Start here in an economic analysis. Canada-wide work by Johnston and Flannigan[89] identified 32.3 million hectares of Wildland-Urban Interface (WUI) at risk, 10.5 million hectares Industrial WUI and 109.8 million hectares of Infrastructure WUI. From an economic perspective, there are parts of the Infrastructure WUI that represent critical risks for the entire economy because of the role they play in energy production and distribution. Just in improving the defensibility of these assets there is great opportunity for learning and study of these systems that can not be had through building elaborate simulation and optimization models. These are low-hanging fruit. Remarkably simple analyses, like the ones included in these case studies, can show that these projects are worth undertaking.

Finally, the simple discounting exercise above, shows that maintenance of fuel treatments is more cost-effective than funding individual projects and leaving them without maintenance funding. These projects have a finite life if they are not kept up and there is no guarantee that they will get to do their job over the lifespan of the fuel treatment.

We finish with a discussion of the more general ‘Business Case’ for fuel treatments. The focus of this project was on evaluating individual fuel treatments, but we were repeatedly asked about providing a methodology for decision-making on public funding of these projects in general. This *defensibility threshold* methodology cannot solve the problem directly, but it can point in the direction of reducing the complexity of the problem that is being asked.

On the ‘Business Case’ for Fuel Treatments

This effort has focused on evaluating and ranking individual landscape level fuel-treatments, not comparing them to FireSmart efforts or other government expenditures. It does not allow us to compare a dollar spent on a new hospital or school versus a dollar spent on a fuel treatment or any other attempt to reduce risks from wildfire. The question of whether or not it would be possible to do this has come up repeatedly over the life of this project.

If we were to tackle those questions, how should they be approached?

We already discussed how the evaluation of individual landscape fuel treatments does not make sense in a cost-benefit framework. This is not an investment that provides future returns to society. It is an expenditure that manages the risk of future losses. No one makes the argument that national defense expenditures or even wildfire service expenditures should exceed some hurdle return rate. Policy makers recognize that these are necessary expenditures to protect the future viability of the economy.

When comparing landscape level fuel treatments to FireSmart it should be made on this basis. Does the landscape level fuel treatment lower the cost of passing a stress test relative to the alternatives? In terms of regional economic viability what is the stress test? Certainly, it is not finding the lowest cost means of lowering the average fire damage. Instead, we should be thinking about protecting the viability of forest-based communities. How many forest industry communities can come out alright from a complex of fires like the one in the Cariboo? Where is the threshold beyond which economic recovery becomes difficult or impossible? This should define the stress test. Do landscape level fuel treatments make it less costly to survive this tail event relative to FireSmart or equivalent expenditures on increased Suppression?

This is a distinct way of thinking about this problem that differs from cost-benefit analysis. Rather than trying to improve the efficiency of expenditures by measuring the average benefit/avoided damages per dollar spent we are trying to find the most effective way of protecting against the worst-case events. One way of doing this is checking project adequacy using a *defensibility threshold* as described in the sections above.

Practically speaking, there is no need to do this for all values-at-risk at once. In justifying expenditures start at the top of the Resource Sharing Wildfire Allocation Protocol (RSWAP)[90]. The BC Wildfire Service has already identified and mapped evacuation choke points where lives are likely to be lost. Fuel treatments that increase the defensibility of these chokepoints can be evaluated as a package for a funding request. Moving down the RSWAP priorities to critical infrastructure. There are several pieces of infrastructure in the gas distribution network in British Columbia that are critical to the functioning of the entire Western power grid. These could be evaluated as a package and so on. As we move down the RSWAP priority list the economic justification for the work is likely to be weaker, the work will have to be more careful and require greater use of complicated modelling. Given the extent of the fuel treatments required this may never happen but there is utility in using these economic analyses in the context of the RSWAP.

Acknowledgments

We would also like to acknowledge a number of individuals from the BC government who contributed their time and expertise to this project.

Cited Works

- [1] M. Milne, H. Clayton, S. Dovers, and G. J. Cary, "Evaluating benefits and costs of wildland fires: critical review and future applications," *Environ. Hazards*, vol. 13, no. 2, pp. 114–132, Apr. 2014.
- [2] S. Canada, "Fort McMurray 2016 Wildfire: Economic Impact." .
- [3] C. R. John Boyd and M. Afb, "A Discourse on Winning and Losing Curtis E. LeMay Center for Doctrine Development and Education," 2018.
- [4] F. A. Hayek, "The Use of Knowledge in Society," *Am. Econ. Rev.*, vol. 35, no. 4, pp. 519–530, 1945.
- [5] I. Kochi, G. H. Donovan, P. A. Champ, and J. B. Loomis, "The economic cost of adverse health effects from wildfire-smoke exposure: a review," *Int. J. Wildl. Fire*, vol. 19, no. 7, p. 803, Nov. 2010.
- [6] M. Flannigan, A. S. Cantin, W. J. de Groot, M. Wotton, A. Newbery, and L. M. Gowman, "Global wildland fire season severity in the 21st century," *For. Ecol. Manage.*, vol. 294, pp. 54–61, Apr. 2013.
- [7] X. Wang, M.-A. Parisien, S. W. Taylor, D. D. B. Perrakis, J. Little, and M. D. Flannigan, "Future burn probability in south-central British Columbia," *Int. J. Wildl. Fire*, vol. 25, no. 2, p. 200, Feb. 2016.
- [8] M. D. Flannigan, K. A. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks, "Future Area Burned in Canada," *Clim. Change*, vol. 72, no. 1–2, pp. 1–16, Sep. 2005.
- [9] X. Wang, D. K. Thompson, G. A. Marshall, C. Tymstra, R. Carr, and M. D. Flannigan, "Increasing frequency of extreme fire weather in Canada with climate change," *Clim. Change*, vol. 130, no. 4, pp. 573–586, Jun. 2015.
- [10] P. Spreewenbergen, M. Kroneman, and J. Paget, "Reassessing the Global Mortality Burden of the 1918 Influenza Pandemic," *Am. J. Epidemiol.*, vol. 187, no. 12, pp. 2561–2567, 2018.
- [11] S. Austin Alchon, *A new pest in the land: new world epidemics in a global perspective*. University of New Mexico Press, 2003.
- [12] D. Pearce, G. Atkinson, and S. Mourato, *Cost-benefit analysis and the environment: Recent developments*, vol. 9789264010055. Organisation for Economic Cooperation and Development (OECD), 2006.
- [13] N. N. Taleb, *Statistical Consequences of Fat Tails: Real World Preasymptotics, Epistemology, and Applications*. RESEARCHERS.ONE, 2020.
- [14] W. N. Sparhawk, "The Use of Liability Ratings in Planning Forest Fire Protection," *J. Agric. Res. (Washington, D.C.)*, vol. 30, Jan. 1925.

- [15] G. H. Donovan and D. B. Rideout, "A Reformulation of the Cost Plus Net Value Change (C+NVC) Model of Wildfire Economics."
- [16] Martell, "Forest Fire Management," in *Forest Fires: Behavior and Ecology*, E. Johnson and K. Miyanishi, Eds. Academic Press, 2001, p. 594.
- [17] H. Hessel, "The Economics of Prescribed Burning: A Research Review," *For. Sci.*, vol. 46, no. 3, pp. 322–334, Aug. 2000.
- [18] E. L. Kalies and L. L. Yocom Kent, "Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review," *For. Ecol. Manage.*, vol. 375, pp. 84–95, Sep. 2016.
- [19] K. Barnett, S. Parks, C. Miller, and H. Naughton, "Beyond Fuel Treatment Effectiveness: Characterizing Interactions between Fire and Treatments in the US," *Forests*, vol. 7, no. 12, p. 237, Oct. 2016.
- [20] P. M. Fernandes, "Empirical Support for the Use of Prescribed Burning as a Fuel Treatment," *Curr. For. Reports*, vol. 1, no. 2, pp. 118–127, Jun. 2015.
- [21] R. A. Bradstock, G. J. Cary, I. Davies, D. B. Lindenmayer, O. F. Price, and R. J. Williams, "Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation," *J. Environ. Manage.*, vol. 105, pp. 66–75, Aug. 2012.
- [22] T. D. Penman, R. A. Bradstock, and O. F. Price, "Reducing wildfire risk to urban developments: Simulation of cost-effective fuel treatment solutions in south eastern Australia," *Environ. Model. Softw.*, vol. 52, pp. 166–175, Feb. 2014.
- [23] V. Florec, M. Burton, D. Pannell, J. Kelso, and G. Milne, "Where to prescribe burn: The costs and benefits of prescribed burning close to houses," *Int. J. Wildl. Fire*, 2019.
- [24] Z. Liu, H. S. He, Y. Chang, and Y. Hu, "Analyzing the effectiveness of alternative fuel reductions of a forested landscape in Northeastern China," *For. Ecol. Manage.*, vol. 259, no. 7, pp. 1255–1261, Mar. 2010.
- [25] M. Elia, R. Lovreglio, N. Ranieri, G. Sanesi, and R. Laforzezza, "Cost-Effectiveness of Fuel Removals in Mediterranean Wildland-Urban Interfaces Threatened by Wildfires," *Forests*, vol. 7, no. 12, p. 149, Jul. 2016.
- [26] J. P. Prestemon, K. L. Abt, and R. J. Barbour, "Quantifying the net economic benefits of mechanical wildfire hazard treatments on timberlands of the western United States," *For. Policy Econ.*, vol. 21, pp. 44–53, Aug. 2012.
- [27] D. E. Mercer, J. P. Prestemon, D. T. Butry, and J. M. Pye, "Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire," *Am. J. Agric. Econ.*, vol. 89, no. 1, pp. 63–77, Feb. 2007.
- [28] K. Stockmann, J. Burchfield, D. Calkin, and T. Venn, "Guiding preventative wildland fire mitigation policy and decisions with an economic modeling system," *For. Policy Econ.*, vol. 12, no. 2, pp. 147–154, Feb. 2010.

- [29] K. W. Jones *et al.*, "Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado," *J. Environ. Manage.*, vol. 198, pp. 66–77, Aug. 2017.
- [30] Deloitte Access Economics, "Scoping Study on a Cost Benefit Analysis of Bushfire Mitigation," 2014.
- [31] D. E. Mercer, J. P. Prestemon, D. T. Butry, and J. M. Pye, "Evaluating Alternative Prescribed Burning Policies to Reduce Net Economic Damages from Wildfire," *Am. J. Agric. Econ.*, vol. 89, no. 1, pp. 63–77, Feb. 2007.
- [32] G. Snider, P. J. Daugherty, and D. Wood, "The Irrationality of Continued Fire Suppression: An Avoided Cost Analysis of Fire Hazard Reduction Treatments Versus No Treatment," *J. For.*, vol. 104, no. 8, pp. 431–437, Dec. 2006.
- [33] C. L. Mason *et al.*, "Investments in Fuel Removals to Avoid Forest Fires Result in Substantial Benefits," *J. For.*, vol. 104, no. 1, pp. 27–31, Jan. 2006.
- [34] J. Loomis, P. Wohlgemuth, A. González-Cabán, and D. English, "Economic benefits of reducing fire-related sediment in southwestern fire-prone ecosystems," *Water Resources Research*, vol. 39, no. 9. John Wiley & Sons, Ltd, 01-Sep-2003.
- [35] C. E. Keegan, C. E. Fiedler, and T. A. Morgan, "Wildfire in Montana: Potential hazard reduction and economic effects of a strategic treatment program," *For. Prod. J.*, vol. 54, no. 7–8, pp. 21–25, Jul. 2004.
- [36] B. Heines, S. Lenhart, and C. Sims, "Assessing the economic trade-offs between prevention and suppression of forest fires," *Nat. Resour. Model.*, vol. 31, no. 1, p. e12159, Feb. 2018.
- [37] J. P. Prestemon, K. L. Abt, A. A. Ager, R. J. Huggett, M. A. Finney, and E. Twombly, "The costs and benefits of large scale treatment programs under conditions approximating real-world fire, climate, vegetation and economic conditions," 2007.
- [38] B. M. Gannon *et al.*, "Prioritising fuels reduction for water supply protection," *Int. J. Wildl. Fire*, vol. 28, no. 10, p. 785, Nov. 2019.
- [39] T. D. Penman, B. Cirulis, and B. G. Marcot, "Bayesian decision network modeling for environmental risk management: A wildfire case study," *J. Environ. Manage.*, vol. 270, p. 110735, Sep. 2020.
- [40] P. Diaconis and D. Freedman, "On the Consistency of Bayes Estimates," *Ann. Stat.*, vol. 14, no. 1, pp. 1–26, 1986.
- [41] M. Thompson, K. Riley, D. Loeffler, and J. Haas, "Modeling Fuel Treatment Leverage: Encounter Rates, Risk Reduction, and Suppression Cost Impacts," *Forests*, vol. 8, no. 12, p. 469, Nov. 2017.
- [42] M. S. Hand, M. P. Thompson, and D. E. Calkin, "Examining heterogeneity and wildfire management expenditures Examining heterogeneity and wildfire management expenditures using spatially and temporally descriptive data using spatially and temporally descriptive data," *J. For. Econ.*, vol. 22, pp. 80–102, 2016.

- [43] M. P. Thompson *et al.*, “Development and application of a probabilistic method for wildfire suppression cost modeling,” *For. Policy Econ.*, vol. 50, pp. 249–258, Jan. 2015.
- [44] BC Wildfire Service, “B.C. Wildland Fire Management Strategy,” 2010.
- [45] CatIQ, “Catastrophe Indices and Quantification Inc,” 2020. [Online]. Available: <https://www.catiq.com/>.
- [46] BC Assessment Authority, “Roll Totals by Jurisdiction and Historical Assessed Value Changes by Class and Jurisdiction - Roll Totals by Province and Property Class (2019 Revised) - Data Catalogue.” [Online]. Available: <https://catalogue.data.gov.bc.ca/dataset/roll-totals-by-jurisdiction-and-historical-assessed-value-changes-by-class-and-jurisdiction/resource/2920a6c6-7218-47ff-8a72-b9595376f4f3>. [Accessed: 13-Dec-2019].
- [47] K. M. Gebert, D. E. Calkin, and J. Yoder, “Estimating Suppression Expenditures for Individual Large Wildland Fires,” *West. J. Appl. For.*, vol. 22, no. 3, pp. 188–196, Jul. 2007.
- [48] J. Canton-Thompson, B. Thompson, K. Gebert, D. Calkin, G. Donovan, and G. Jones, “Factors affecting fire suppression costs as identified by incident management teams,” *USDA For. Serv. - Res. Note RMRS-RN*, vol. 030, no. 30 RMRS-RN, pp. 1–10, 2006.
- [49] D. T. Butry, D. E. Mercer, J. P. Prestemon, J. M. Pye, and T. P. Holmes, “What is the price of catastrophic wildfire?,” *J. For.*, vol. 99, no. 11, pp. 9–17, Nov. 2001.
- [50] R. A. Fitch, Y. S. Kim, A. E. M. Waltz, and J. E. Crouse, “Changes in potential wildland fire suppression costs due to restoration treatments in Northern Arizona Ponderosa pine forests,” *For. Policy Econ.*, vol. 87, pp. 101–114, Feb. 2018.
- [51] G. Jenkins, C.-Y. KUO, and J. GIRALDEZ, “Canadian Regulatory Cost-Benefit Analysis Guide,” *Dev. Discuss. Pap.*, 2007.
- [52] CalFire, “Burn Injuries,” 2018.
- [53] “2009 Victorian Bushfires Royal Commission.”
- [54] C. Hély, M. Flannigan, and Y. Bergeron, “Modeling tree mortality following wildfire in the southeastern Canadian mixed-wood boreal forest,” *For. Sci.*, vol. 49, no. 4, pp. 566–576, Aug. 2003.
- [55] J. Regelbrugge and S. Conard, “Modeling Tree Mortality Following Wildfire in *Pinus ponderosa* Forests in the Central Sierra-Nevada of California,” *Int. J. Wildl. Fire*, vol. 3, no. 3, p. 139, 1993.
- [56] K. W. Outcalt and D. D. Wade, “Fuels Management Reduces Tree Mortality from Wildfires In Southeastern United States,” *South. J. Appl. For.*, vol. 28, no. 1, pp. 28–34, Feb. 2004.
- [57] M. W. Ritchie, C. N. Skinner, and T. A. Hamilton, “Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire,” *For. Ecol. Manage.*, vol. 247, no. 1–3, pp. 200–208, Aug. 2007.
- [58] “Financial Analysis of Silviculture Investment & Economic Returns (FAN\$IER) - Province of British Columbia.” [Online]. Available: <https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest->

inventory/growth-and-yield-modelling/financial-analysis-of-silviculture-investment-economic-returns-fansier. [Accessed: 01-Feb-2021].

- [59] A. A. Ager, M. A. Finney, B. K. Kerns, and H. Maffei, "Modeling wildfire risk to northern spotted owl (*Strix occidentalis caurina*) habitat in Central Oregon, USA," *For. Ecol. Manage.*, vol. 246, no. 1, pp. 45–56, Jul. 2007.
- [60] D. Calkin, G. Jones, and K. Hyde, "Nonmarket Resource Valuation in the Postfire Environment," *J. For.*, vol. 106, no. 6, pp. 305–310, Sep. 2008.
- [61] J. Hausman, "Contingent Valuation: From Dubious to Hopeless," *J. Econ. Perspect.*, vol. 26, no. 4, pp. 43–56, Nov. 2012.
- [62] T. J. Venn and D. E. Calkin, "Accommodating non-market values in evaluation of wildfire management in the United States: challenges and opportunities," *Int. J. Wildl. Fire*, vol. 20, no. 3, p. 327, May 2011.
- [63] J. K. Agee, *Fire Ecology of Pacific Northwest Forests*. Island Press, 1993.
- [64] T. Meixner and P. Wohlgemuth, "Wildfire Impacts on Water Quality," *Southwest Hydrol.*, no. October, pp. 24–25, 2004.
- [65] D. G. Neary, G. J. Gottfried, and P. F. Ffolliott, "Post-Wildfire Watershed Flood Responses," *Second Int. Fire Ecol. Fire Manag. Congr. Orlando, Florida, 16-20 Novemb. 2003, Pap. 1B7*, pp. 1–8, 2003.
- [66] H. Hessel, J. B. Loomis, A. González-Cabán, and S. Alexander, "Wildfire effects on hiking and biking demand in New Mexico: a travel cost study," *J. Environ. Manage.*, vol. 69, no. 4, pp. 359–368, Dec. 2003.
- [67] G. W. Torrance and D. Feeny, "Utilities and Quality-Adjusted Life Years," *Int. J. Technol. Assess. Health Care*, vol. 5, no. 4, pp. 559–575, Oct. 1989.
- [68] M.-A. Parisien, V. G. Kafka, K. G. Hirsch, J. B. Todd, S. G. Lavoie, and P. D. Maczek, *Mapping wildfire susceptibility with the BURN-P3 simulation model*, vol. 405. 2005.
- [69] J. H. Scott, M. P. Thompson, D. E. Calkin, J. H. ; Scott, and M. P. ; Thompson, "A Wildfire Risk Assessment Framework for Land and Resource A Wildfire Risk Assessment Framework for Land and Resource Management Management 'A Wildfire Risk Assessment Framework for Land and Resource Management' (2013). USDA Forest Service / UNL Faculty Publications," 2013.
- [70] R. E. Bellman, *Adaptive Control Processes: A Guided Tour*. Princeton University Press, 1961.
- [71] "BCWS Fuel Management Prescription Guidance 2019."
- [72] P. J. van Mantgem, L. B. Lalemand, M. Keifer, and J. M. Kane, "Duration of fuels reduction following prescribed fire in coniferous forests of U.S. national parks in California and the Colorado Plateau," *For. Ecol. Manage.*, vol. 379, pp. 265–272, Nov. 2016.
- [73] S. J. Prichard and M. C. Kennedy, "Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event," *Ecol. Appl.*, vol. 24, no. 3, pp. 571–590, Apr. 2014.

- [74] S. J. Prichard, D. L. Peterson, and K. Jacobson, "Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA," *Can. J. For. Res.*, vol. 40, no. 8, pp. 1615–1626, Aug. 2010.
- [75] J. M. Lydersen *et al.*, "Evidence of fuels management and fire weather influencing fire severity in an extreme fire event," *Ecol. Appl.*, vol. 27, no. 7, pp. 2013–2030, Oct. 2017.
- [76] M. M. Boer, R. J. Sadler, R. S. Wittkuhn, L. McCaw, and P. F. Grierson, "Long-term impacts of prescribed burning on regional extent and incidence of wildfires—Evidence from 50 years of active fire management in SW Australian forests," *For. Ecol. Manage.*, vol. 259, no. 1, pp. 132–142, Dec. 2009.
- [77] M. A. Battaglia, F. W. Smith, and W. D. Shepperd, "Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests?," *For. Ecol. Manage.*, vol. 256, no. 12, pp. 2029–2038, Dec. 2008.
- [78] PwC Financial Services Regulatory Practice, "Stress Testing: First at Bar for Midsized Firms," 2014.
- [79] D. Zhang and P. H. Pearse, *Forest Economics*. Vancouver: UBC Press, 2011.
- [80] M. Thompson, K. Riley, D. Loeffler, and J. Haas, "Modeling Fuel Treatment Leverage: Encounter Rates, Risk Reduction, and Suppression Cost Impacts," *Forests*, vol. 8, no. 12, p. 469, Nov. 2017.
- [81] BC Ministry of Agriculture, "Financial Planning Information for Establishing a VINIFERA Wine Grape Planting," 2014.
- [82] Forsite Consultants Ltd., "Ntityix Resources Ltd. Wildfire Risk Management Plan," 2020.
- [83] bty Ltd., "Canadian Cost Data Parameters Comparison." 2020.
- [84] "Powers Creek Plant," *Castanet*, 2007.
- [85] Y. Brend, "How the pipeline explosion affects you - and whether you're going to run out of natural gas," *CBC.ca*, 11-Oct-2020.
- [86] "BC natural gas pipeline explosion affects US energy markets," *EnergiMedia*, Oct-2018.
- [87] M. Lamb-Yorski, "Enbridge, WLIB compressor station upgrade project a 'significant' partnership," *Williams Lake Tribune*, 19-Mar-2020.
- [88] J. C. Scott, *Seeing like a state : how certain schemes to improve the human condition have failed*. New Haven: Yale University Press, 1998.
- [89] L. M. Johnston and M. D. Flannigan, "Mapping Canadian wildland fire interface areas," *Int. J. Wildl. Fire*, vol. 27, no. 1, p. 1, Feb. 2018.
- [90] "BC WILDFIRE SERVICE WILDFIRE RISK REDUCTION PLANNING STANDARD 2018."

