Estimating the consequences of wildfire for wildfire risk assessment, a case study in the southern Gulf Islands, British Columbia, Canada

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Abstract: Wildfire risk assessment research has made considerable progress towards estimating the probability of wildfires but comparatively little progress towards estimating the expected consequences of potential fires. One challenge with estimating wildfire consequences has been to identify a common metric that can be applied to consequences measured in different units. In this paper, we use the preferences of representatives of local fire management agencies as the common consequences metric and apply it to a case study in the southern Gulf Islands, British Columbia, Canada. The method uses an expert survey and a maximum-difference conjoint analysis to establish the relative importance of specific fire consequences. A fire with a major potential for loss of life was considered to be about three times worse than major damage to houses and 4.5 times worse than loss of a rare species. Risk ratings were very sensitive to changes in fire consequences ratings. As the complexity of values at risk and number of stakeholders increase, the most efficient allocation of wildfire prevention, protection, and suppression resources becomes increasingly challenging to determine. Thus, as the complexity of stakeholder representation and values at risk increases, we need to pay increasing attention to quantitative methods for measuring wildfire consequences.

Résumé : La recherche qui porte sur l'évaluation des risques de feu de forêt a fait des progrès considérables concernant l'estimation de la probabilité des feux de forêt mais comparativement peu de progrès concernant l'estimation des conséquences anticipées de feux potentiels. Un des défis de l'estimation des conséquences des feux de forêt consiste à identifier une mesure commune applicable aux conséquences mesurées avec différentes unités. Dans cet article, nous utilisons les préférences de représentants des organismes locaux de gestion du feu comme mesure commune des conséquences et nous l'appliquons à une étude de cas dans le secteur sud des îles Gulf en Colombie-Britannique, au Canada. La méthode utilise un sondage auprès des experts et une analyse conjointe pour établir l'importance relative des conséquences du feu. Un feu qui a de fortes possibilités de causer des pertes de vie a été considéré environ trois fois pire que des dommages importants aux habitations et 4,5 fois pire que la perte d'une espèce rare. L'estimation des risques était très sensible aux changements dans le classement des conséquences du feu. À mesure que la complexité des valeurs menacées et le nombre d'intervenants augmentent, il devient de plus en plus difficile de déterminer comment allouer le plus efficacement les ressources à la prévention, à la protection et à la suppression des feux de forêt. Par conséquent, à mesure que la complexité de la représentation des intervenants et des valeurs menacées augmente, il faut accorder une attention de plus en plus grande aux méthodes quantitatives pour mesurer les conséquences des feux de forêt.

[Traduit par la Rédaction]

Introduction

Forest fires are increasing in both number and size across North America (Westerling et al. 2006). Since 1986, the number of wildfires in the western United States has jumped by 400%, and forest area burned has increased by more than 600% compared with the period from 1970 to 1986. Similar increases have been documented in Canada from 1920 to 1999 (Gillett et al. 2004). Over the next 100 years, area burned by wildfires in Canada is projected to increase by 74% to 118% (Flannigan et al. 2005).

A variety of management challenges are associated with changing fire regimes: protecting communities from damages associated with forest fires is one such challenge. In the western US, the fire suppression budget has steadily increased from an average annual cost of less than $500 mil-

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lion in the 1980s to well over 1 billion after the year 2000 (National Academy of Public Administration 2002). These costs have been driven by record levels of area burned over the same period (Dombeck et al. 2004). Not only are more forests burning, but in many forests that experienced historically low severity fire regimes, fire suppression has resulted in increased fire severity (Noss et al. 2006). The combination of changing forests in response to forest management and changing fires in response to changing climate and forest structure has led to significant uncertainty around the nature of fire risk.

Land managers are now using forest fire risk assessment as a wildfire management approach that looks beyond simple fire suppression and prevention (e.g., Western Governors' Association 2002; Filmon 2004). Although it is not possible to prevent or suppress all forest fires, forest fire risk assessments are a tool for establishing priorities and achieving the most efficient allocation of fire management resources such as fire suppression crews, forest fuel treatments, evacuation planning, and public education efforts (Haight et al. 2004). Risk assessments can also evaluate the relative effectiveness of wildfire risk mitigation projects by simulating proposed management actions in the model and then comparing the resulting changes in risk levels (e.g., Ohlson et al. 2003; B.A. Blackwell and Associates Ltd. and Compass Resource Management Ltd. 2004).

Defining forest fire risk

The term "fire risk" is often used to mean the probability of a fire (e.g., Haight et al. 2004; Fiorucci et al. 2008; National Wildfire Coordinating Group 2008); however, within the broader field of risk assessment, "risk" is defined as the probability of an event multiplied by the consequences associated with the event (i.e., fire probability × fire consequences) (e.g., Finney 2005). The probability × consequences definition of risk is used in quantitative risk assessment (QRA) and has been applied successfully in such fields as health sciences (Lee et al. 2006), environmental engineering (Bernatik et al. 2008), conflict resolution (Maguire and Boiney 1994), and wildlife conservation (Drechsler 2000). QRA has been found useful because it promotes (*i*) a better understanding of accident scenarios, (*ii*) a better understanding of the complex interactions between events and systems, (*iii*) communication among stakeholders and a common understanding of the problem, and (*iv*) an integrated approach that allows researchers to combine contributions from diverse disciplines such as forestry, biology, and the social sciences (Apostolakis 2004).

In contrast to a definition of risk focused entirely on the probability of occurrence of fire, defining risk as equal to probability × consequences means that fire consequences can play an important role in determining risk ratings. Risk levels become just as sensitive to fire consequences as fire probability. In this context, it thus becomes critically important that we obtain accurate estimates of fire consequences.

Estimating expected fire consequences

Wildfire risk assessment research has made considerable progress towards measuring the probability of fire occurrence (Misoula Fire Sciences Laboratory 2000; Preisler et al. 2004) but comparatively little progress towards estimating the consequences associated with a potential fire. For example, several recent risk assessments still apply the risk-equals-fire-probability definition and do not include fire consequences when identifying high risk areas (e.g., Haight et al. 2004; Fiorucci et al. 2008; Sturtevant et al. 2009). However, this approach has the potential to overlook high risk areas that have only moderate fire probabilities but very high fire consequences.

Finding a common metric that can be applied to all consequences has been a primary challenge to estimating wildfire consequences (Finney 2005). Wildfire consequences can range from damage to nonmarket goods such as endangered species and human life to the loss of market goods such as timber and residential homes. In recent years, the most advanced methods used by industry for estimating fire consequences use the educated guesses of local experts or community members to identify values at risk and weight them according to their relative importance (e.g., Government of Alberta Sustainable Resource Development 2004; B.A. Blackwell and Associates Ltd. 2006; Sanborn Total Geospatial Solutions 2006). This method becomes problematic, however, when more than two values at risk are present, as it is extremely difficult to accurately estimate the importance of one single fire consequence relative to all other consequences. Nevertheless, considering these values more holistically is important, because how we set the relative importance of specific wildfire consequences will directly influence wildfire risk findings (B.A. Blackwell and Associates Ltd. and Compass Resource Management Ltd. 2004).

In this paper, we describe a novel approach for assessing forest fire consequences that reflects the values of local fire managers more holistically. The method incorporates expert consultation as a tool for establishing values at risk from fire and then uses an expert survey to establish the relative importance of specific fire consequences. Based on that information, a fire consequences map can be produced by combining predicted fire intensity with established values at risk for each spatial unit of analysis and calculating the perceived consequence for each of these locations. We demonstrate this approach in a case study in the southern Gulf Islands, British Columbia, Canada, where our study is part of a larger wildfire risk assessment. The study also integrates other risk elements such as predicted fire intensity, ignition probability, and escape probability with fire consequences to evaluate wildfire risk (M. Tutsch, R.C. Walker, K. Lertzman, A.B. Cooper, and W. Haider, unpublished).

We use the maximum difference conjoint analysis (MDC) technique to measure the relative importance of various components of fire consequences. This method has been commonly used in the health sciences (e.g., Marley and Louviere 2005; Flynn et al. 2007) and lately in fisheries management (Dorow et al. 2009) to measure preferences for several variables that are conceptually related but measured in different metrics. In this case, the method will provide an understanding of how fire managers undertake crucial trade-offs such as how much more important is the loss of one life compared with the loss of 10 houses, how much more important is the loss of an endangered species compared with

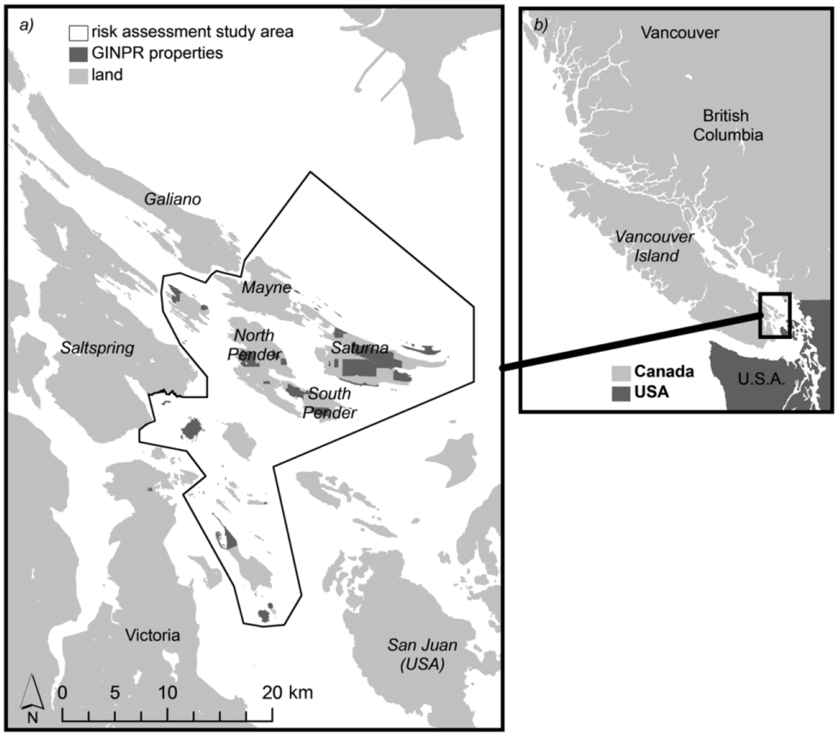


Fig. 1. The risk assessment study area (*a*) is located between the mainland and Vancouver Island (*b*). The wildfire risk assessment study area encompassed Mayne Island, Saturna Island, and North and South Pender islands, as well as many smaller islands. The risk assessment was completed for all of the islands within the study area boundary with the exception of the evaluation of the mitigation scenarios, which were limited to North Pender Island. For ease of presentation, only results for North Pender Island are shown in the figures of this paper. GINPR, Gulf Islands National Park Reserve.

the loss of 10 houses, and is the loss of an endangered species more important than the loss of a cultural heritage site? These are challenging questions, the answers to which are subjective by nature and may differ, even between experts.

A quantitative approach to incorporating the preferences of stakeholders in risk assessment is not new. Several studies have applied multi-attribute utility theory (MAUT) to evaluate the risk preferences of stakeholder groups (e.g., Teeter and Dyer 1986; Ananda and Herath 2005; Brito and de Almeida 2009). A quantitative approach such as MAUT or MDC provides a method to elicit the opinions of stakeholders in a consistent and repeatable manner when multiple values at risk are present. The output of the method is easily incorporated into the probability × consequences approach to risk assessment (e.g., Maguire and Boiney 1994; Drechsler 2000; Lee et al. 2006; Bernatik et al. 2008). A quantitative approach is especially useful when the consequences must be elicited from expert or stakeholder opinion because they do not naturally occur in easily convertible measurement units such as replacement cost. The difference between the MDC approach and MAUT is described in Methods.

Study area

This wildfire consequences assessment was applied to a portion of the southern Gulf Islands, which includes the Gulf Islands National Park Reserve (GINPR). The Gulf Islands are located in southwestern British Columbia in the Strait of Georgia between the city of Vancouver and Vancouver Island (Fig. 1). The study area includes Mayne Island, Saturna Island, and North and South Pender islands, as well as many smaller surrounding islands. The GINPR was established in 2003 and holds parcels of land on each of the larger southern Gulf Islands and manages several of the smaller surrounding islands completely.

Mayne Island, Saturna Island, and North and South Pender islands all host rural residential development and are characterized by discrete residential areas in a matrix of second-growth mixed-species forests, including Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), Pacific madrone (*Arbutus menziesii* Pursh), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), seaside Juniper (*Juniperus maritima*; Adams 2007), bigleaf maple (*Acer macrophyllum* Pursh), and red alder (*Alnus rubra* Bong.). Wildfire risk is exacerbated further by the fact that many residential areas can only be accessed by one road, creating evacuation challenges. In addition to human values at risk, the Gulf Islands host some of Canada's most endangered plant communities (British Columbia Ministry of Environment, Land and Parks 1999) and associated species at risk.

Methods

Mapping values at risk

To identify features in the study area that could be damaged by wildfire, we started by selecting specific values at risk to map. We define values at risk as elements that can be damaged by a forest fire and selected priority values at

Table 1. The values at risk in the study area and the information sources used to map them.

Value At Risk	Information source
Residential areas — residential development in the southern Gulf Islands is almost entirely rural residential with forested lots	2007 Terrestrial Ecosystem Mapping information
Residents and park visitors — problem evacuation areas were identified within the GINPR and in residential neighbourhoods; evacuation problem areas were defined as residential areas with only one road access; residential areas with well established marine docks or helicopter evacuation points were not included	Terrain Resource Information Mapping (1 : 20 000 scale), personal communication with GINPR planners and Fire Chiefs
Cultural heritage sites — historical buildings and lighthouses within the GINPR	GINPR staff
Park assets — park camp sites, research houses, heritage houses, radio towers, and cabins	GINPR staff
Rare species — rare species (animals, plants, or plant communities) designated as red- or blue-listed by the Government of British Columbia	BC Conservation Data Centre rare-elements mapping
Ecosystem values — areas that will benefit ecologically by a low- or moderate-intensity fire, areas that will be ecologically damaged by a high-intensity fire, and areas where the net ecological impact of a fire is unclear or zero	This value at risk was not mapped due to time constraints

Note: GINPR, Gulf Islands National Park Reserve.

risk to map through consultation with local fire managers. This consultation included local fire chiefs, fire behaviour specialists from federal agencies, and experts in terrestrial ecology, emergency services, and fire management from regional and federal agencies. The fire managers consulted for this project were believed to represent all local expertise in wildfire management, as well as the interests of all fire management stakeholder agencies in the southern Gulf Islands. The selected values at risk were then mapped in a geographic information system (GIS). Table 1 lists the values at risk that we selected and the data sources used to map them. Internet-based interactive mapping approaches are an alternative tool to elicit values at risk and wildfire consequences (Beverly et al. 2008). An internet-based approach allows for a broader set of respondents but does not provide for the potential consensus-building benefits of convening respondents in person to discuss local values at risk. Values at risk have also been mapped by using expert judgement to model a predicted distribution (Neupane et al. 2007).

Measuring the relative importance of fire consequences

To determine the overall consequences of a fire, we first needed to establish the relative importance of specific consequences of fires. This type of challenge is usually addressed with one of the many methods provided by MAUT (Keeney and Raiffa 1976), which uses preferences or utility as the common unit of analysis. Although this is conceptually intriguing and simple, its execution is not necessarily so, as several attributes need to be evaluated jointly. In MAUT, many methods of preference elicitation have been developed to separate the weight (i.e., the importance of the consequence concepts) from the scale (a utility measure of the consequence's quantity). However, none of these methods is truly multivariate because these methods do not ask for a holistic evaluation or provide a joint estimation of weight and scale.

Instead, we used a MDC approach to design 18 hypothetical consequence scenarios, which were evaluated by the experts at a wildfire consequences workshop. The survey elicited the opinions 14 local fire managers about the relative importance of specific wildfire consequences. The MDC approach is similar to conjoint analysis as it contains one single profile for evaluation and similar to discrete choice analysis as respondents choose among the attributes. Thus it is possible to obtain a separate estimation of weight and scale from one single response task, whereas the MAUT methods require separate evaluations for weight and scale. In MDC, respondents are asked to identify the most distinct pair of attributes (i.e., the best and worst) in one scenario (Flynn et al. 2007), which they typically find to be a cognitively simple task. Figure 2 provides an example of one such scenario used in this study. Questions A and B represent the respective maximum difference response tasks, and question C represents a standard conjoint response task. Question C and the conjoint analysis were part of the study but are not used for the analysis in this paper.

Dorow et al. (2009) present the necessary statistical derivations and assumptions underlying MDC analysis. To separate weight and scale in the MDC analysis (questions A and B), the matrix of independent variables needs to be dummy coded to be consistent with the analysis of panel data (repeated evaluations of choice sets; see (Hensher et al. 2005)). The analysis follows regular random utility theory practice (Train 2003), applying a multinomial logistic regression with either the best choice or the worst choice as the dependent variable.

Mapping consequences of a fire

After estimating the importance weights of individual wildfire consequences, we mapped the total wildfire consequences by summing the individual fire consequences at each location in the study area. For example, the wildfire consequences in a residential area could be the result of both "major damage to 10 houses" and "major potential for loss of life" consequences. Each of these individual consequences is assigned a weight that is a measure of its importance relative to other consequences. Individual consequences were mapped by overlaying values at risk maps and a predicted fire intensity map (Tutsch 2009). Table 2 shows the consequence resulting from each value at risk and fire intensity combination. Note that the majority of the study area was predicted to sustain high-intensity fire.

Investigating the effect of alternate consequence scenarios on risk assessment results

To investigate the degree to which the location of high risk areas is sensitive to changing wildfire consequences,

Fig. 2. Sample page of the survey showing one consequence set and its three questions. Each of 18 consequence sets contained the same questions A, B, and C.

Instruction: Imagine a 10 hectare fire which has the following set of consequences:

Question A Pick the consequence that is the **worst** outcome	**Consequence Set 1**	**Question B** Pick the consequence that is the **best** outcome
☐	*Private Homes:* Major damage to 10 houses (e.g. structural fires)	☐
☐	*Evacuation Problem:* No potential for loss of life	☐
☐	*Cultural Heritage Sites:* Major damage (e.g. heritage building burns down)	☐
☐	*Ecosystem Benefits/Losses:* Major net ecological losses (e.g. a stand replacing fire)	☐
☐	*Rare Ecological Elements:* Rare element is lost due to the fire (e.g. rare flower, old growth forest)	☐

Question C: Do you consider the above consequence set (i.e. All six of the above consequences) to be an acceptable outcome for a 10 ha fire in the Gulf Islands?

Yes No

Table 2. The fire consequence associated with each value at risk by fire intensity.

	Fire intensity		
Value at risk	Low (<4000 kW/m)	Medium (4000 – 10 000 kW/m)	High (>10 000 kW/m)
Residential	Minor damage to 10 houses	Major damage to 10 houses	Major damage to 10 houses
Residential — FireSmarted	No damage to houses	Minor damage to 10 houses	Minor damage to 10 houses
Evacuation problem area	Minor potential for loss of life	Major potential for loss of life	Major potential for loss of life
Park asset — high	Damages < $40 000	Damages < $40 000	Damages > $40 000
Park asset — medium	No damages to park assets	Damages < $40 000	Damages < $40 000
Rare element	Rare element is damaged	Rare element is lost	Rare element is lost
Cultural heritage site	Minor damage to cultural heritage site	Major damage to cultural heritage site	Major damage to cultural heritage site
Area benefited by low-intensity fire	Major net ecological benefits	Ecological benefits are unclear or net benefit is zero	Major net ecological losses
Area damaged by high-intensity fire	Major net ecological benefits	Ecological benefits are unclear or net benefit is zero	Major net ecological losses

we created two alternate scenarios (no-loss-of-life and replaceability) to the consequence scenario described above (the base-case scenario) and performed the risk assessment for each. The no-loss-of-life scenario is identical to the base-case scenario but does not track evacuation problem areas (e.g., Haight et al. 2004; Santa Barbara County 2006) and the associated potential for loss of life (Table 3). The replaceability consequence scenario simulates a change in expert preference, focusing importance on irreversible wildfire consequences (loss of human life, endangered species, and cultural heritage sites) and assigning little importance to reparable wildfire consequences (damage to residential homes and park assets).

Results

Survey results

The results in Table 4 contain the coefficients, standard errors (SEs), and z values, as well as the results of the Wald statistics and their associated p values. The first block of coefficients contains the importance weights of the attributes, and the subsequent blocks contain the respective scale values for each attribute, which are also relative values to its base.

The MDC analysis showed that experts had a strong inherent relative ranking of values based on choosing the best–worst consequence pairs. Loss of life was considered

Table 3. The relative importance weight as percentage of total consequences assigned to each wildfire consequence for each wildfire consequence scenario (base-case, no-loss-of-life, and replaceability).

	Total consequences (%)		
Wildfire consequence	Base-case	No-loss-of-life	Replaceability
Major potential for loss of life	35	0	20
Minor potential for loss of life	22	0	10
Major damage to 10 houses	12	27	5
Rare element is lost	8	18	20
Rare element is damaged	7	17	10
Minor damage to 10 houses	6	14	0
Major damage to cultural heritage sites	6	14	20
Damages > \$40 000	2	4	5
Minor damage to cultural heritage sites	1	3	10
Damages < \$40 000	0	1	0

Note: The base-case scenario uses weights derived from the expert survey. The no-loss-of-life scenario simulates a wildfire risk assessment that does not account for evacuation problem areas, and the replaceability scenario assumes that only irreversible wildfire consequences are important.

Table 4. The relative importance of each consequence type (i.e., weight) and the level within each consequence type (i.e., scale) (model summary statistics: LL = –345.235; BIC(LL) = 735.335; L^2 = 648.148; $R^2(0)$ = 0.6856; R^2 = 0.7279).

Model results	Coefficient	SE	z value	Wald statistics	p value
Weight					
Damage to homes	0	—	—	36.3467	8.10×10^{-7}
Loss of life	–2.9233	1.2926	–2.2615		
Damage to park asset	0.3863	0.2521	1.5321		
Damage to cultural heritage	0.058	0.2408	0.2407		
Damage or benefit to ecosystem	1.0737	0.2272	4.7259		
Damage to rare species	–0.0703	0.2333	–0.3012		
Scale					
Damage to homes					
No damage to houses	0	—	—	140.3578	3.30×10^{-31}
Minor damage to 10 houses	–2.9403	0.4442	–6.6188		
Major damage to 10 houses	–5.5008	0.4654	–11.8201		
Loss of life					
No potential for loss of life	0	—	—	271.8849	9.10×10^{-60}
Minor potential for loss of life	–7.3652	0.4507	–16.3417		
Major potential for loss of life	–13.6807	3.8588	–3.5453		
Damage to park asset					
No damages to park assets	0	—	—	5.9953	0.05
Damages < \$40 000	–0.6345	0.5054	–1.2554		
Damages > \$40 000	–1.2956	0.5295	–2.4468		
Damage to cultural heritage					
No damage to cultural heritage sites	0	—	—	36.5522	1.20×10^{-8}
Minor damage to cultural heritage sites	–0.7897	0.4715	–1.6747		
Major damage to cultural heritage sites	–2.9557	0.497	–5.9472		
Damage or benefit to ecosystem					
Major net ecological losses	0	—	—	129.2437	8.60×10^{-29}
Ecological benefits are unclear or net benefit is zero	2.4409	0.4728	5.1628		
Major net ecological benefits	5.5073	0.4931	11.1694		
Damage to rare species					
No rare elements are damaged	0	—	—	71.4399	3.10×10^{-16}
Rare element is damaged	–3.3159	0.4765	–6.9582		
Rare element is lost	–3.6364	0.487	–7.4672		

Note: LL, log-likelihood; BIC(LL), Bayesian information criterion (based on the LL statistic); L^2, goodness of fit based on χ^2 goodness-of-fit test; $R^2(0)$ = pseudo-R^2 for a model based solely on the constants; R^2, McFadden's pseudo-R^2 for the full model.

the worst possible consequence of a fire, whereas damage to ecosystems elicited the least concern from participants. Damage to residences, park assets, cultural heritage sites, and rare ecological elements were regarded as concepts having approximately equal consequence values (z values do not differ significantly from each other). Within each attribute, however, its specific state or level also significantly affected its contribution to fire consequences. As expected, higher damages within each attribute were viewed more negatively than lower levels of damage (i.e., many houses destroyed vs. few houses destroyed).

The potential for loss of life was found by all respondents to be a far worse consequence than any of the other fire consequences. Many respondents felt that even comparing the loss of life with other fire consequences was unwise, and this dominant treatment of the attribute combination "major loss of life" by some respondents shows up in the much larger SE for this estimate compared with the remaining estimates in the model. However, for the purpose of identifying the most efficient allocation of fire management resources, it is important to establish how much more important the loss of life is relative to other fire consequences.

Combining the weight and scale coefficients for each attribute produced an interval scale index of the relative importance of these fire consequences (Table 5). Respondents felt that a fire that has a "minor potential for loss of life" (–10.3) was twice as bad as "major damage to 10 houses" (–5.5) A fire with a "major potential for loss of life" (–16.6) was felt to be about three times worse than "major damage to 10 houses" (–5.5) and 4.5 times worse than "rare element is lost due to the fire, e.g., rare flower, old growth forest" (–3.7). Of note is that "major net ecological losses, e.g., a stand-replacing fire" was of very little importance to respondents. This somewhat surprising result may be explained by the respondents' perception that "major net ecological losses" are commonly associated with forest fires and simply accepting them as such. In contrast, "rare element is lost due to the fire, e.g., rare flower, old growth forest" was ranked as a very bad consequence (–3.7). Although the two outcomes are very similar in nature, we believe that the loss of a rare species was rated worse because it was interpreted as an irreversible event and is supported as a negative event by provincial and federal legislation and policy.

Table 5. The relative importance from worst to best of each fire consequence as the sum of weight and scale.

Consequence	Overall score
Worst	
Major potential for loss of life	–16.604
Minor potential for loss of life	–10.2885
Major damage to 10 houses	–5.5008
Rare element is lost	–3.7067
Rare element is damaged	–3.3862
Minor damage to 10 houses	–2.9403
No potential for loss of life	–2.9233
Major damage to cultural heritage sites	–2.8977
Damages > \$40 000	–0.9093
Minor damage to cultural heritage sites	–0.7317
Damages < \$40 000	–0.2482
No rare elements are damaged	–0.0703
No damage to houses	**0**
No damage to cultural heritage sites	0.058
No damages to park assets	0.3863
Major net ecological losses	1.0737
Ecological benefits are unclear or net benefit is zero	3.5146
Major net ecological benefits	6.581
Best	

Mapping results

The complexity of the consequences map arising from this analysis illustrates the complex distribution of wildfire consequences across the study area (Fig. 3). The locations with the highest consequence ratings are those where multiple values are at risk. These are generally residential areas that are predicted to sustain moderate- or high-intensity fires and have problematic evacuation routes. The second highest rated locations are residential areas predicted to sustain moderate- or high-intensity fires with no evacuation problems. Almost as high as these locations are areas known to host endangered species predicted to sustain moderate- to high-intensity fires.

Most residential areas received very similar fire consequences ratings as locations hosting endangered species. This is because respondents rated major damage to 10 houses only slightly worse than minor and major damage to endangered species. This is a significant departure from the results of many other risk assessments that do not include endangered species as fire consequences (e.g., Municipality of Anchorage 2004; Five County Association of Governments 2007) or generally rate residential areas or infrastructure locations with much higher fire consequence ratings than locations with other endangered species (e.g., B.A. Blackwell and Associates Ltd. and Compass Resource Management Ltd. 2004). Note that this map does not include any potential ecosystem benefits or losses associated with fire. Although we established the relative importance of ecosystem benefits or losses associated with fire, delineating specific areas that would benefit or be damaged by fire was not within the scope of this project.

Investigating the effect of alternate consequence scenarios on risk assessment results

When compared with the base-case consequence scenario, the replaceability and no-loss-of-life consequence scenarios produced dramatically different areas mapped as high risk (Fig. 4). Thirty-five percent of the locations mapped as high risk (i.e., sites where risk was greater than or equal to 3) in the base-case scenario were no longer high risk when the no-loss-of-life consequence scenario was used in the risk assessment. Sixty percent of the locations mapped as high risk in the base-case scenario were no longer mapped as high risk when the replaceability scenario was used. When the no-loss-of-life consequence scenario was used, wildfire risk became focused on all residential homes as opposed to mainly homes in evacuation problem areas. Locations with endangered species also became higher risk sites. When the replaceability method was used, wildfire risk was equally

Fig. 3. The fire consequences map produced shows a mosaic of fire consequence evaluations. Red and orange areas host the highest consequences ratings and are typically residential areas with poor evacuation potential and predicted moderate- to high-intensity fires.

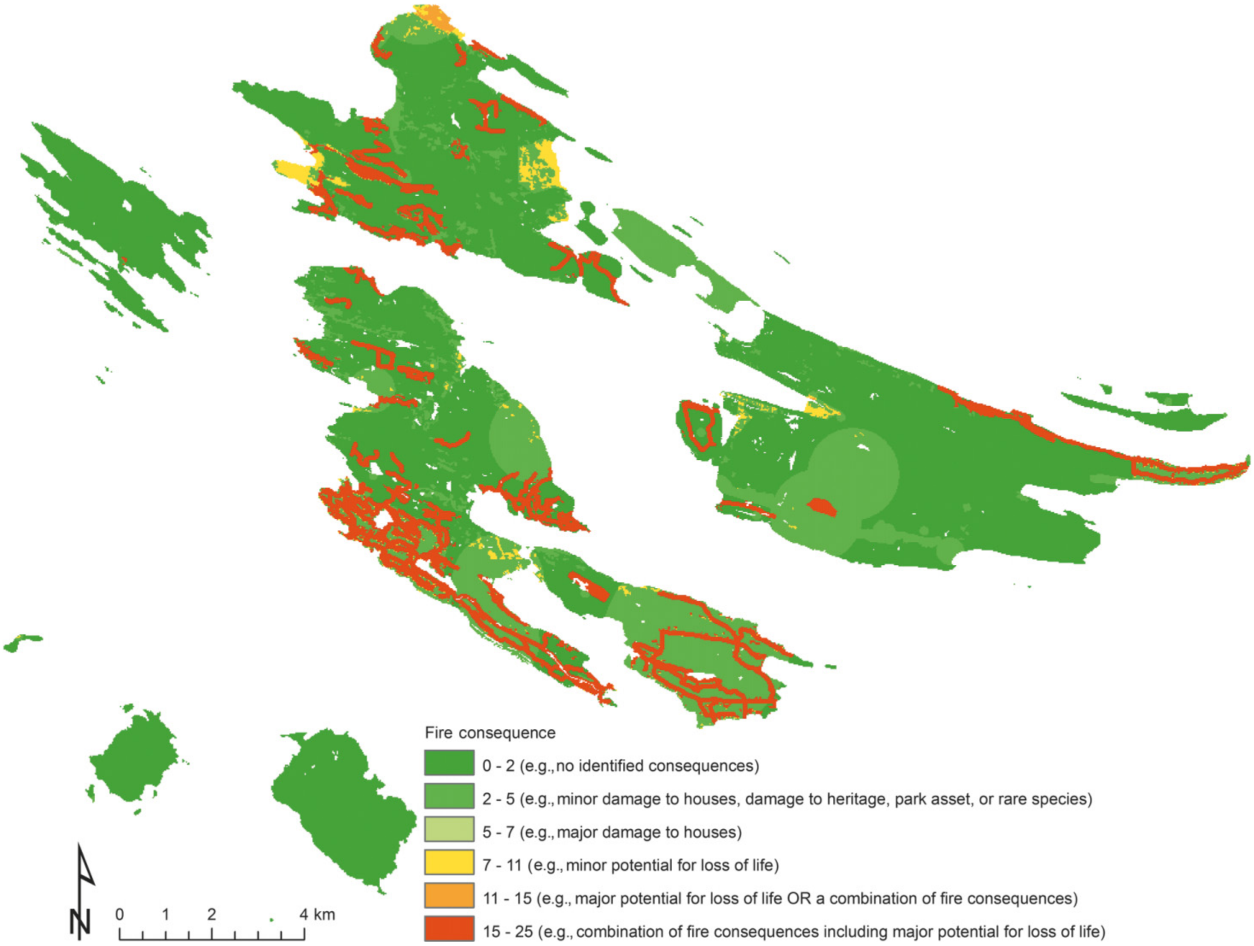
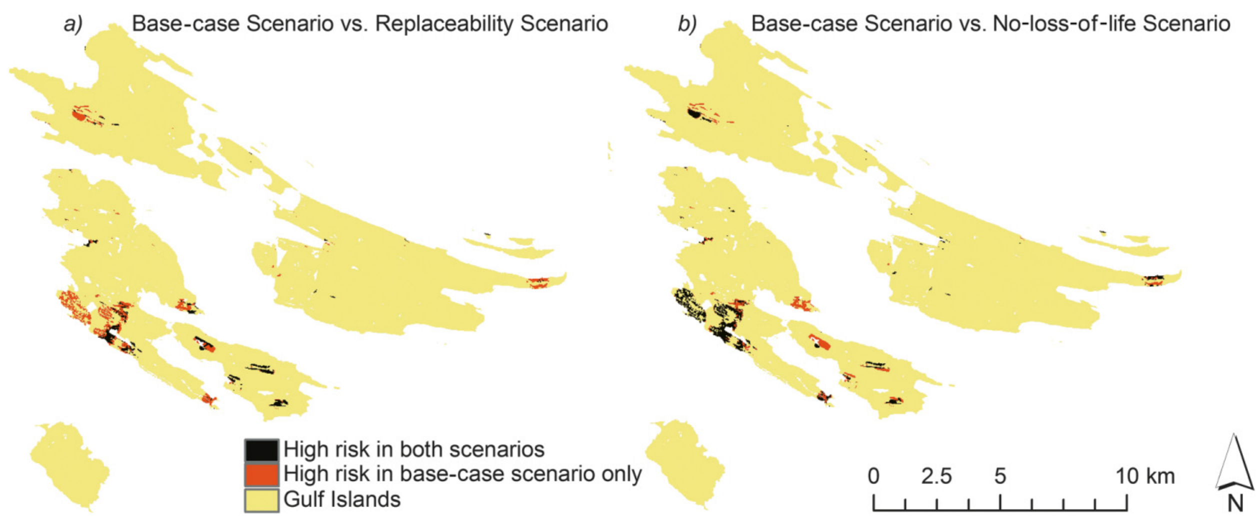


Fig. 4. The sensitivity of risk results to changing consequence scenarios are illustrated. Red areas are high risk locations when the base-case consequence scenario is used that change to low or moderate risk locations when (*a*) replaceability or (*b*) no-loss-of-life consequence scenarios are used for the risk assessment.



distributed on locations with endangered species, evacuation problem areas, and cultural heritage sites as opposed to risk being focused mainly on evacuation problem areas and residential home sites.

The degree to which the location of high risk sites changed depended in part on the amount of clustering of specific values at risk. Interestingly, many residential areas in the Gulf Islands are also evacuation problem areas, thus shifting the relative importance of consequences away from loss of life towards residential areas, as was the case in the no-loss-of-life consequence scenario, did not result in as much change in the location of high risk areas (40%) as when the replaceability scenario was used (60%). In the replaceability scenario, the relative importance moved away from loss of life towards the loss of rare species. Rare species and evacuation problem areas are rarely in the same location, thus using the replaceability scenario resulted in extensive movement of areas mapped as high risk.

Discussion

Estimating wildfire consequences is important

When wildfire risk is defined as fire probability × fire consequences, risk ratings are sensitive to changes in fire consequences ratings. In our case study, this phenomenon is illustrated by the dramatic shift of high risk locations observed when alternate consequence scenarios were used for the risk assessment (Fig. 4). To address this sensitivity of risk assessment results to wildfire consequences, we developed an approach for measuring consequences that represents local expert perceptions of the relative importance of wildfire consequences more accurately.

A common understanding of values at risk will be helpful as local fire managers collaborate on future fire management and risk mitigation projects (Ostrom 1992). By measuring fire consequences in detail, we helped to catalyze, identify, and characterize a common understanding among fire managers of forest fire consequences in the southern Gulf Islands. The provincial government, local fire halls, and Gulf Islands National Park all share responsibility for forest fire management in the southern Gulf Islands and will be working together on this issue in the future. The survey revealed that all respondents generally held similar views about the relative importance of values at risk.

The opportunity for fire managers to have input into a forest fire risk assessment also makes them more likely to help implement the results of the assessment (Ludwig 2001). This effect was observed at the risk assessment workshop held for the survey where fire managers agreed to collaboratively pursue further funding for the project. Some participants also volunteered to compile fire-ignition information to aid in the risk assessment project.

Limitations of this approach

This approach relies heavily on appropriate representation of value sets among fire managers. We included most of the local agencies involved with local fire. We also included the Canadian Forest Service, which has broader fire management perspectives and responsibilities. An expert-based approach such as this fit well within the scope of the project. However, to better understand the range of perceived consequences and potential inequities in vulnerability to burning events or mitigative activities, it would be worthwhile to consider values held by different resource users, stakeholders, or communities (Sorrensen 2003, 2009; Turner et al. 2008).

It is interesting to consider how our risk assessment results would change with changing representation among our experts. For example, how would risk assessment results change if First Nations were represented in the respondent group? Stakeholders may have varying perceptions as to what values at risk should be included in the risk analysis, as well as the relative importance of these value at risk. For example, First Nations may have unique vulnerabilities to burning events or mitigation activities because they impact cultural practices or food production (Sorrensen 2003; Trusler and Johnson 2008; Turner et al. 2008). We gained some insight into this question by looking at the degree to which survey responses diverged when we separated respondents by professional grouping (e.g., park employees and fire hall chiefs). In our case, we found no significant divergence between the subgroups of our respondent population, although they were all western "experts" and are unlikely to represent the cultural diversity that we might have had by a very different representation (e.g., First Nations). When this preference elicitation task (i.e., the MDC method) is applied to several stakeholders, the similarities and differences between the various groups quickly emerge. Because this method requires only small sample sizes, it would be possible to model the preferences of different user or stakeholder groups.

When should this method be applied?

As the complexity of values at risk and number of stakeholder agencies or fire managers increase, the geographic complexity of wildfire risk increases and the most efficient allocation of wildfire prevention, protection, and suppression resources becomes increasingly hard to find. Thus, increasingly detailed and quantitative methods for measuring wildfire consequences are appropriate as stakeholder representation and values at risk become more complex. One major advantage of our approach is that it is not limited to a small set of experts or key informants but would work equally well with a large sample size of stakeholders or the public at large.

As the geographic complexity of values at risk increases, the need for a thorough assessment of consequences will increase. If values at risk are clustered, then high-risk locations will undoubtedly be located at these clusters, regardless of the relative importance of specific wildfire consequences. Conversely, when the geographic layout of values at risk becomes more complex, establishing the relative importance of specific wildfire consequences becomes more relevant to risk assessment results. Wildland–urban interface and intermix areas are excellent examples of wildfire management areas with complex values at risk and fire management stakeholder representation (e.g., Santa Barbara County 2006). We illustrate how this method of estimating wildfire consequences can be applied to wildfire risk assessment in a wildland–urban intermix area in a second article (M. Tutsch, R.C. Walker, K. Lertzman, A.B. Cooper, and W. Haider, unpublished).

Perhaps most importantly, a rigorous assessment of wildfire consequences is appropriate when fire managers want to improve stakeholder participation, knowledge, and support for community wildfire protection projects such as community wildfire protection plans (Union of British Columbia Municipalities 2005) and FireSmart initiatives (British Columbia Forest Service 2005). This approach allows for multiple stakeholders or fire managers to come to a common understanding of the values at risk and their relative importance. Thus, the assessment process becomes a mechanism for building stakeholder knowledge and participation in future wildfire mitigation projects.

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