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Economic evaluation of research to improve the Canadian forest fire danger rating system

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Canada is a largely forested country, and the economic, environmental, and social effects of the country's wildland fire management are of great importance from an industry and public policy perspective. Investment in research can improve the efficiency of wildland fire management and has an important role in the decision-making process. There is a long history of research investment in Canada related to wildland fire management, including the development of the Canadian Forest Fire Danger Rating System (CFFDRS). To demonstrate the range of net benefits of the CFFDRS to Canadian society, a cost-benefit study was conducted on research related to enhancing the current system. The benefits of research were measured as the difference in economic returns with additional investment in research, primarily achieved through reduction in damages to timber resources and savings in suppression expenditure (the "with-research scenario") and those that would have resulted with no changes to the current CFFDRS (the "without-research scenario"). A triangular probability distribution was used to address uncertainty and the results indicated high levels of net economic benefit if the CFFDRS were to be enhanced by additional research investment, with "most likely" estimates of net present value ranging from $30 million to $1.5 billion ($Cdn).

Introduction

Wildland fires generate a myriad of economic, environmental, and social effects. Knowledge of both the short- and long-term effects of wildland fire is essential for effective risk assessment, policy formulation, and wildland fire management. In Canada, forest fires pose a serious threat to nearby communities and the environment in terms of potential damage to valuable timber assets, property and infrastructure, biodiversity, air and water, cultural heritage, and the health and safety of the population. Conversely, fire is a vital component in maintaining healthy and productive ecosystems, especially in the boreal forest (Hirsch and Fuglem, 2006). Thus, sustainable management of fire-dependent ecosystems requires optimizing both the socio-economic effects of fire and its ecological benefits. Effective management of these various consequences is of great importance from a public sector perspective. Over the past three decades, about 8,600 wildland fires have occurred in Canada with an annual average of about 2.5 million ha of forest and wooded land burned and annual costs for suppression and wildland fire management exceeding Can$500 million (Taylor *et al.*, 2006). The number of fires is not the only determinant of specific outcomes; their frequency, intensity, and location are also important in determining human response and overall effects. The risks to property and community safety will continue to grow as forested areas become more populated (i.e., through increases in wildland–urban interface areas). Flannigan *et al.* (2005) projected a 74% to 118% increase in annual area burned in Canada by the end of this century with a 3× carbon dioxide climate change scenario. This projection is a main driver of the expectation that suppression and management costs may double by 2040.

Wildland fire management involves decision-making at various stages, including prevention, preparedness, response, and recovery. Science and technology (S & T) play an important role in the decision-making process, providing scientific evidence for agencies engaged in a range of wildland fire activities. The Canadian Forest Fire Danger Rating System (CFFDRS) is a well-established decision support tool incorporating scientific information for risk management in relation to wildland fire. Its overall aim is to maintain healthy and productive ecosystems, as well as to minimize or avoid potential and actual threats to public health and safety, property, and other assets (Forestry Canada Fire Danger Group, 1992).

The aim of the current study was to quantify the net benefits that S & T activities are expected to have on management agencies in terms of their wildland fire management and mitigation activities. We present a conceptual framework to analyze the likely outcomes, and associated net benefits from the advancement and uptake of wildland fire research outputs. This framework shows the flow of information of the input, output, and outcome matrices for economic evaluation of activities occurring within wildland fire S & T programs. We use the development of the next generation of the CFFDRS (Wotton, 2010) as a case study to assess the expected change associated with advancement and application of new scientific knowledge and to illustrate the net benefits associated with research and adoption of scientific outputs.

Need for enhanced fire danger and fire behaviour

Fire danger rating is defined as 'a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of fire spread, difficulty to control and fire impact (Merrill and Alexander, 1987). The process of systematically evaluating and integrating the individual and combined factors influencing fire danger is referred to as fire danger rating. A fire danger rating system produces qualitative and/or numerical indices of fire potential that are used as guides in a variety of wildland fire management activities. In Canada, the Canadian Forest Fire Danger Rating System (CFFDRS) is the principal source of intelligence for wildland fire management activities including strategic and tactical levels from fire prevention to fire fighter safety (Taylor and Alexander, 2006).

The structure of the current system was conceptualized 30–40 years ago and has changed little since then. However, in the intervening period, numerous changes both in Canada and globally have affected wildland fire management and the expectations placed on fire and land managers. Changes such as the advent of information technology systems and the rapid growth and development of computing capacity have dramatically altered the information and data available to wildland management agencies at both temporal and spatial scales. In addition, the recognition of multiple values and various issues related to public health, biodiversity, and carbon emissions, among other topics, as well as the complexity of risk management in wildland fire management, have added new layers of complexity for policy- and decision-makers (Wotton, 2010). Therefore, more accurate, higher-resolution fire danger rating and behaviour prediction are needed to allow effective management action before and during fires (Canadian Council of Forest Ministers, 2005). More specifically, fire prediction systems must accurately describe the fire environment and the level of uncertainty in predictions, so that fire managers can better understand the consequences of their actions and the interactions of those actions with natural and managed wildland fire events.

Reliable predictions of various elements of fire danger and fire behaviour are critical to decision-making for a variety of wildland fire strategies. As such, development of the next-generation models for the CFFDRS will form the foundation for future operational wildland fire decision support system in Canada. These models will include a national framework for predicting the occurrence of fires; models for predicting the effects of fire in terms of load-specific fuel consumption; and flexible fuel and fire behaviour models for important new fuel types (e.g., forests affected by mountain pine beetle or thinned stands). They will be developed through empirical and physical modelling and proposed experimental burning projects (e.g., in forests affected by mountain pine beetle, in boreal mixed forest, and in other key forest types or structures).

The next-generation CFFDRS will attempt to better integrate fuels, terrain, weather, and climate patterns as inputs to describe fire spread, crowning, spotting, and other behavioural elements of prescribed and wildland fire. From a strategic planning perspective, the new system will need to generate better knowledge and prediction to assist management agencies in making better decisions about where and how often to conduct fuel treatments. The prediction aids may also allow more accurate mapping of the risk to communities and the environment associated with wildland fire. At a tactical level, the new CFFDRS may assist suppression agencies to make better decisions about positioning of resources and timing of evacuations. Other outputs may include updated training procedures and updated software and information systems.

Historically, efforts have been made to retrospectively quantify the economic benefits of fire research. For example, researchers working in the CFFDRS research program estimated that a total of about $750 million (1988 Canadian dollars) of benefits nationwide could be attributed to the CFFDRS for the period 1971 to 1982 (Agriculture Canada, 1988; Moore and Newstead, 1992). According to Agriculture Canada (1988), area losses during that period would have been 20% higher in Alberta alone in the absence of the 1970 version of the Fire Weather Index System (1970 FWI) (Van Wagner, 1974) (which is an important component of the CFFDRS). Agriculture Canada (1988) also estimated that if further improvements in the "1970 FWI" undertaken during the seventies and early eighties had been available at the time of the 1980, 1981 and 1982 severe fire seasons in Alberta, it is estimated that between $63 million and $222 million (1984 Canadian dollars) in losses and fire suppression costs would have been avoided. These improvements were an integral part of Alberta Forest Service pre-suppression and preparedness systems which became operational in 1982 would have prevented additional area losses between 12% and 34% (Agricultural Canada, 1988).

The Centre for International Economics (CIE, 2001) concluded that the future risk and severity of wildfires in Australia could be expected to decline by 15% (in terms of the average area burned annually) with adoption of an improved forest fire behaviour prediction system (Gould *et al*., 2007). The CIE study distinguished between minor events (< Aus$10 million damage) and major events (> Aus$10 million damage), because the effects of research will manifest differently according to the scale of the event. In the case of minor events, it was expected that better knowledge and better fire behaviour prediction would reduce the proportion of forested area burned but would not reduce the annual number of ignitions (CIE, 2001). In contrast, major fires are more sporadic and infrequent and it was therefore more appropriate to analyze the benefits of research in terms of reduced frequency of major fires (from one every 17 months to one every 24 months), because of improved fuel reduction strategies.

The Canadian Forest Service (CFS) has been investing about $90 million per year in research, extension and education activities making it the largest provider of science and technology to the forestry sector in Canada. The opportunity cost of this investment is the benefits to Canadians were these resources used in other areas such as health and education. Hence it is important that the CFS can demonstrate that it uses these resources in a way that enhances the welfare of Canadians. Here we present an evaluation to assess the economic, social and environmental impact of a key area of investment in wildland fire research by the CFS.

Methods

Framework for cost–benefit analysis of wildland fire science and technology

A cost–benefit analysis (CBA) involves the enumeration and evaluation of socially desirable and undesirable effects of proposed public projects or public sector investment (Davis, 1990), with the overall objective of estimating the net benefits of a policy change or investment. For the purpose of the current analysis, the costs and benefits of wildland fire, fire management, and fire research were enumerated in the context of a baseline situation (i.e., no changes to the existing CFFDRS). The baseline then compared with the costs and benefits of alternative scenarios involving increased investment in wildland fire research (e.g., enhancing the CFFDRS at various levels of investment and with various lags in adoption of the research). Once research results are incorporated into wildland fire management guidelines, policies and decision support systems, it is expected that an improved rating system will reduce the incidence of large-scale, high-intensity wildfires by providing an improved system for prescribed burning and better knowledge of how to suppress fires. To the extent to improve preparedness and response decisions to wildfires the fire rating research is expected to reduce the damage to forest resources. The range of economic, environmental and social benefits from wildland fire science and technology investment is depicted in Figure 1.

The CBA of wildland fire S & T followed the framework described in the Canadian Cost–Benefit Analysis Guide (Treasury Board of Canada, 2007). Broadly speaking, CBA involves identifying the potential effects of a change in approach, determining how those effects are related to fundamental variables, and making projections of the fundamental variables and the related benefits and costs over time. The final step involves applying a decision criterion to determine the preferred option. This might be the option yielding the greatest net present value, the greatest social benefit, the largest benefit–cost ratio, or the highest internal rate of return. For the purpose of the current analysis, the preferred evaluation criterion was the net present value of socio-economic benefits.

Research investment

In this study, "costs" were considered to be the research dollars (i.e., labour costs in terms of full-time equivalents [FTEs] for researchers) invested over and above baseline, and "benefits" were considered to be the desirable effects in terms of reductions in the negative effects of wildland fire achieved through S & T outputs that induced changes in decision-making related to wildland management policies and practices. As such, monetary estimates were required for all of the major effects associated with wildland fire. If the present value of the benefits of reduced wildfire effects due to S & T was greater than the present value of the increased costs of wildland fire research, then the benefit–cost ratio was deemed favourable.

Economic impact from wildland fires

The potential benefits or reduced losses associated with wildland fires can be viewed from the perspective of economic, environmental, and social outcomes. The economic or financial outcomes may involve reduced damage to timber assets, property, infrastructure, activities of business, and personal belongings, as well as reduced expenditures for fire suppression. Environmental outcomes would include benefits arising from appropriately managing ecosystems, water, and amenity values and from reduced greenhouse gas emissions. Social outcomes could include reductions in human fatalities and injuries, psychological trauma, and destruction of personal memorabilia. The balance sheet for the benefits and costs associated with wildland fire will therefore cover a range of societal benefits and costs. Some of these will have market (tangible) value and can be easily quantified, whereas others have nonmarket (intangible) value and may not be easily quantified. Table 1 lists the main types of benefits and costs associated with wildland fire and a variety of techniques for estimating their economic value.

It can be argued that current and future S & T outputs, once incorporated into decision-making processes (related to operations, guidelines, and policies), as well as the various activities of fire management agencies, will assist those agencies to better mobilize their resources and thus to operate more efficiently and effectively. A wide range of economic, environmental, and social effects are associated with the provision and use of current and enhanced S & T knowledge. A common view holds that communities in wildland-urban interface areas and the economy at large receive considerable benefits (or experience fewer losses) because of the application of wildland fire S & T products. However, quantifying all of the benefits or reduced losses is almost impossible, and such assessments are limited by poor availability of data and limited understanding of the relationships among S & T activities, changed management capacity, and changed fire effects. Therefore, the effects considered in this study were limited to timber damage, property damage, fatalities and injuries, evacuations, and costs of wildfire prevention and suppression (both fixed and variable), as shown in Table 2. Although this list is far from comprehensive, we offer the caveat that our assessment likely underestimates both the damage and the ecological benefits. Impact valuation data were drawn from a variety of sources including the Atlas of Canada (Natural Resources Canada, 2009), timber damage tables (Government of Alberta, 2009), human life valuation (Gordon, 2000), and the National Forestry Database (Canadian Council of Forest Ministers, 2009).

Area burned and timber damage

Historical data were compiled and a statistical analysis of trends was undertaken to determine average annual changes in variables and the association of each variable with area burned, the most common metric used to describe the extent of wildfire in Canada. Simple regression analysis was conducted with each individual variable against area burned. As a result, area burned was assumed to be the key driver of all estimates of the extent of future wildfire. Future area burned was estimated as a linear increasing trend based on growth predictions outlined by Flannigan *et al.* (2005). The linearized increase amounted to an additional 13,110 ha burned per year, on average. In the absence of agency estimates or timber supply models of the volume and value of timber lost to fire, simplified assumptions were made to estimate timber losses. First, the amount of carbon (tonnes) released by wildfire, by region, was derived from the CFS Carbon Budget Model for all of Canada for the years 1990 to 2007. The data for the amount of carbon were converted

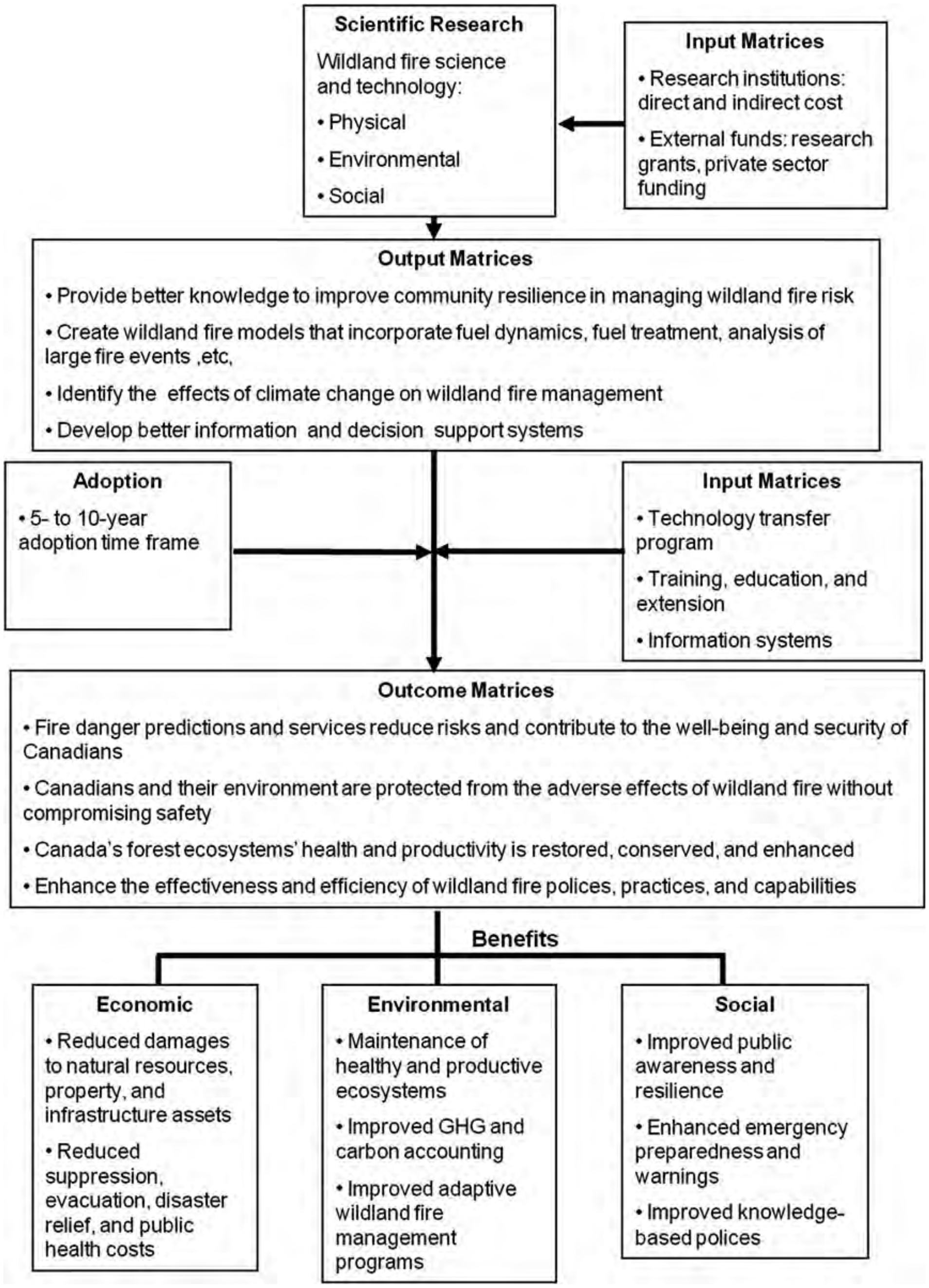

Figure 1 Flow of information for economic evaluation of a wildland fire science and technology program. GHG = greenhouse gas. Adapted from CIE (2001).

back to volumes of timber using the rough conversion factor 4 m^3 timber = 1 t carbon (Brian Simpson, Carbon Analyst, CFS, pers. comm., 2009). Second, timber composition was generalized across Canada at a breakdown of 66% coniferous and 34% deciduous (Canadian Council of Forest Ministers, 2009). Finally, because of a lack of data for the value of timber damage and salvage, the value of damaged timber was determined from the timber damage tables of the Government of Alberta (2009): Can\$20.84/m^3 for coniferous timber and Can\$2.78/m^3 for deciduous timber. This method of estimation is crude at best, and it is widely recognized that estimates of timber damage could be improved in the future by using timber supply models that account for shifts in harvest over the landscape (Peter and Nelson, 2005). The projection of baseline future timber damage was estimated at an average annual increase of 0.7% (Table 5).

Wildland fire management cost

Provincial and territorial agencies were surveyed for historical fixed and variable costs of wildfire management and suppression activities from 1970 to 2007. The provincial totals were summed to derive a total for all of Canada, and future costs were estimated according to the average

Table 1 Parameters for benefits and costs resulting from wildland fires

Benefit or cost parameter	Estimation technique
Market (tangible) items	
Damage to timber assets	Market value (timber royalties)
Damage to private property assets	Insurance payouts
Damage to infrastructure	Replacement or repair costs
Disruption of business	Loss of net income
Disruption of transportation services	Costs of delays incurred by affected businesses
Degradation of water quality in affected areas and catchments	Additional water treatment costs
Transaction costs (e.g., legal proceedings)	Estimates from previous events
Cost of fire mitigation programs	Actual expenditure or willingness-to-pay
Cost of suppression, evacuations, etc.	Actual expenditure
Cost of alternative wildland management programs	Least-cost-plus-loss method
Nonmarket (intangible) items	
Human fatalities	Value of statistical life
Human injury	Cost-of-illness method[a]
Loss of personal memorabilia	Stated preference method[b]
Psychological trauma	Stated preference method[b]
Damage to recreation sites	Stated preference method[b] or revealed preference
Damage to aesthetic values	Stated preference method[b]
Maintenance of health of forest and rangeland ecosystems	Stated preference method[b]
Greenhouse gas emissions	Estimated cost of carbon emissions under permit trading scheme

[a]Cost-of-illness methods estimate the explicit market costs resulting from a change in the incidence of a given illness or injury (Treasury Board of Canada, 2007).
[b]Stated preference methods involve direct survey approaches to estimate the value of nonmarket goods and services (Treasury Board of Canada, 2007).

Table 2 Economic, environmental, and social effects of wildland fires

Factor	Ecomomic	Environmental	Social
Total area burned[1]	✓	✓	✓
Cost of suppression[1]	✓		✓
Damage to timber resources[1]	✓	✓	✓
Maintenance of ecosystem health[1]		✓	
Public health and safety[1]	✓		✓
Human injuries and fatalities[1]	✓		✓
Damage to property and infrastructure[1]	✓		✓
Alteration of wildlife habitat		✓	
Damage to watershed and water supply	✓	✓	✓
Damage to public recreation facilities	✓	✓	✓
Evacuation of adjacent communities	✓		✓
Effects on tourism	✓		✓
Destruction of cultural and archeological sites			✓
Cost of rehabilitation and restoration	✓	✓	
Effects on transportation	✓		✓

[1]Factors used in the current study.

anticipated increase in area burned. For the sake of simplicity, this approach inherently discounted the stochastic nature of fire events. A simple linear trend was estimated and projected into the future over the study period. Variable costs were projected to increase at an average annual rate of 2% and fixed costs were projected to increase at an average annual rate of 1.4% (Table 5). These estimates could be refined in the future through more complex modelling. A rigorous link between area burned (and the stochastic nature of fire events) and wildfire management costs should be considered for improved cost/benefit estimates.

Public safety and property

Elements of public safety were also considered in the CBA. Much like information about timber losses from wildfire, data on property losses, evacuations, and fatalities and injuries were also scant. Most of the data were derived from a database created by combing through media releases and other disaster databases (Beverly and Bothwell, 2011). Property losses for the intensive protection zone were compiled from the Canadian National Forestry Database (Canadian Council of Forest Ministers, 2009) for the period 1970 to 2007. A historical trend analysis was performed, but the annual data appeared to be essentially random, and no clear trend was apparent. As a result, the baseline annual average value of property losses was held constant over the future study period at a level of $4.3 million (2008 Canadian dollars) (Table 5). Evacuation data specifically related to forest fires were not well documented for Canada. Partial data existed for 18 fire-related evacuation events in Canada. Because of the small number of observations available, the value of historical evacuations was estimated, and a constant level of future evacuations was assumed (Table 5). The average cost of evacuation per person per day was estimated as total evacuation cost divided by the number of people evacuated divided by the number of days of evacuation. The baseline annual average value of evacuations was assumed to be constant for the future study period, at a level of $1.9 million (2008 Canadian dollars). Data on fire-related fatalities were available for the period 1986 to 2005 (Natural Resources Canada, 2009). There was no clear trend in fatalities over time and no clear association with area burned. On average, there were approximately two fatalities per year related to wildfire in Canada. Applying data on the statistical value of a human life in Canada (Gordon, 2000), the average annual fatality value associated with wildfire was $10 million (2008 Canadian dollars). Future fire-related fatalities were also held constant over the future study period (Table 5). Holding property losses, evacuations, and fatalities constant over the future study period likely led to underestimation of the cost of damages, but it was important to include these factors in the overall assessment, because of their effect on public safety.

Research scenarios

The approach used to analyze the likely outcomes and associated benefits from the provision and use of wildland fire S & T outputs was to compare the outcomes emanating from a baseline situation or "status quo" scenario with those of "alternative" research scenarios. The status quo scenario described the future expected effects of wildland fire over a specified period, elicited as best guesses from surveys of experts and assuming use of the current effort in S & T outputs to assist the prevention and control procedures applied to manage wildland fires. Given the fiscal environment under the current Canadian government (and, to a broader extent, globally), it seemed appropriate to assume a baseline level of research expenditure held constant or even declining. The alternative scenarios were cases in which there would be changes in the effects of wildland fire (both detrimental and beneficial) through the application and uptake of better information to assist the prevention and control procedures applied to manage wildland fires. The gross benefits from better information were represented by the difference between the damages, effects, and benefits of wildland fire and the cost with and without adoption of better scientific information.

An alternative scenario may reflect improvements to the current state of S & T outputs, including improved timeliness, enhanced accuracy, and better information. Under such a scenario, it is expected that fire management agencies and the community will make better use of improved S & T findings and applications. The likely outcomes from an enhanced S & T program may include better fire danger and fire behaviour rating system, more effective fuel treatments, and greater reduction in the incidence of large, high-intensity forest fires. In addition, new scientific information will enable wildland fire agencies and other agencies and service providers to better pre-position their resources, through relocation, deployment, and mobilization, which could reduce the effects of wildland fire, in terms of damage and losses. The potential benefits of an alternative scenario could be wide-ranging, depending on the location and circumstances of the specific case.

The anticipated level of adoption of the research outputs needs to be accounted for when evaluating research activities. This parameter is difficult to measure or forecast for research related to the CFFDRS, and adoption values were therefore elicited from expert wildland fire managers. These values represent the expected uptake of research outcomes by wildland fire managers, policy-makers, and the scientific community, for the baseline (status quo) and increased research (alternative) scenarios. The lag time before adoption of applicable S & T outputs was specified as a random value, to reflect uncertainty about the adoption process for both increased research scenarios, and was represented by triangular probability distribution (Vere *et al*., 2004).

Three research scenarios were evaluated in this study, along with three adoption options for each scenario. The research effort and resources (including cost of research adoption activities during the life of the project) required to develop the next generation of the CFFDRS were based on current research effort in the CFS and two alternative research investment scenarios (Table 3). The baseline situation represents current provision of S & T outputs to assist wildland fire agencies and the community to prevent or minimize the effects of wildland fires. A plausible assumption is that, with other relevant factors remaining unchanged, the use of current goods and services in the baseline situation will be similar to the highest likelihood of expected changes from the current research effort, i.e., the status quo research scenario.

Table 3 Anticipated project lifespan, human resources required, period of research adoption, and costs for various research scenarios

Research scenario	Project lifespan (years)	Human resources (FTE[a])	Options for research adoption period (years)	Project cost/ year ($ millions)
Option 1 (status quo)	16	6	14, 12, 8	0.525
Option 2	10	10	11, 9, 5	0.850
Option 3	6	12	9, 7, 3	1.170

[a]FTE = full-time equivalent.

Expert elicitation

Expert elicitation is the process of determining what expert knowledge is relevant to support a quantitative analysis and eliciting this information in a form that supports analysis or decision-making. Here we used an elicitation process to determine experts' knowledge and beliefs about the likelihood of expected outcomes and changes in wildland fire management from the various research scenarios (the "status quo" scenario and the two "alternative" scenarios). A survey sample of 14 participants from provincial, territorial, and national park wildland fire management agencies and other non-CFS researchers, were asked to provide their best guesses of the lowest, highest, and most likely expected changes from the research scenarios for a range of parameters that are affected by fires and wildland fire management (Table 4). For example, the experts were asked to give their opinion on the expected changes in wildland fire management activities from the three different research scenarios using questions such as the following:

(1) *Lowest* = can you please give your *best guess* of the ***lowest*** percentage value for the expected change in area burned;
(2) *Highest* = can you please give your *best guess* of the ***highest*** percentage value for the expected change in area burned; and
(3) *Most likely* = can you please give your *best guess* of the ***most likely*** percentage value for the expected change in area burned.

Area burned, fire management expenditure, use of fire, public health and warnings, and research adoption were the key assessment factors which formed 13 questions for the experts to give estimates on changes expected from research outcomes in terms of either no-change or improvements to the fire danger rating system (see Table 4). The uncertainty in the future risk and severity of wildland fires, which are expected to change with the adoption of S & T outputs from the various research scenarios, were defined as the triangular probability distribution parameters.

Probability distribution

In the evaluation of wildland fire S & T benefits are influenced not only by pre-suppression and suppression activities, but also by the extent to which research results are adopted. When combined with annual variation, these factors introduce uncertainty into the evaluation process. This uncertainty can be evaluated with stochastic methods, where the main parameters, such as shifts in the effects of wildland fire (Table 4) and levels of adoption of research outcomes are a set of random variables. To account for this uncertainty in estimating the likely research benefits and considering the fact that adopting research results will yield benefits over time for wildland fire agencies, a probability distribution approach was used for the economic evaluation of research. More specifically, following the studies of Sprow (1967), Zhao *et al.* (2000), Hyde and Engel (2002), Vere *et al.* (2004), and Faron *et al.* (2009), a subjective probability distribution was used to measure economic changes due to technical changes.

Table 4 Elicitation summary of experts' lowest, highest and most likely (bold) mean and range (in italics) estimates of percentage change in wildland fire management activities for status quo and alternative research scenarios for improving the fire danger rating system

Parameter	"Status quo research" scenario (option 1)			"Alternative research" scenario (options 2 and 3)		
	Lowest value	Highest value	Most likely value	Lowest value	Highest value	Most likely value
Percentage change in area burned[a]						
Protected zones: full response to control the fire as soon as possible, consistent with resource availability and values at risk (%)	−4	1.5	**−2**	−8	−2	**−5**
	−10 – 10	*0 – 5*	*−10 – 5*	*−20 – 8*	*−10 – 3*	*−20 – 4*
Limited protection zones: modified response to control the fire in alimited way, such that isolated values threatened by fire are protected, or to monitor a fire until it is extinguished naturally	1	5	**4**	1	11.3	**6.6**
	0 – 8	*0 – 17*	*0 – 10*	*0 – 3*	*4 – 20*	*2 – 10*
Percentage change in expenditures for fire management						
Fixed costs (i.e., prevention and preparation)	1	4.4	**2.5**	−6	1	**−2.8**
	−13 – 12	*−2 – 18*	*−5 – 10*	*−30 – 10*	*−7 – 10*	*−10 – 8*
Variable costs (i.e., suppression)	−1	6	**1**	−22	−2	**−13**
	−2 – 6	*−20 – 20*	*−15 – 16*	*−50 – −5*	*−14 – 8*	*−30 – 12*
Increased use of wildfire for development of healthy and productive ecosystems (%)	1.6	11.5	**6.5**	7	46	**22**
	0 – 5	*7 – 20*	*2 – 10*	*0 – 10*	*8 – 50*	*7 – 50*
Increased use of prescribed fire for development of healthy and productive ecosystems (%)	1	10.2	**5**	6	30	**22**
	0 – 5	*5 – 20*	*2 – 10*	*0 – 10*	*8 – 50*	*2 – 50*
Change in number of evacuations (%)	−2	1	**−1.3**	−21	−1.6	**−11.5**
	−10 – 5	*0 – 5*	*−10 – 8*	*−75 – 8*	*−10 – 3*	*−30 – 5*
Change in health−related costs (%)	−5	0	**−1**	−40	−2	**−10**
	−12 – 0	*−6 – 3*	*−6 – 7*	*−60 – 0*	*−15 – 2*	*−30 – 0*
Changes in smoke related health costs (%)	−3	1	**−2**	−20	1	**−12**
	−10 – 7	*−1 – 5*	*−10 – 5*	*−50 – 5*	*−5 – 1*	*−30– 3*
Changes in fatalities and injuries						
Fatalities (%)	− 4	0	**−2**	−10	−1	**−6**
	−20 – 1	*0*	*−10 – 0*	*−30 – 0*	*−5 – 0*	*−20 – 0*
Injuries (%)	−6	−1	**−2**	−26	−2	**−12**
	−30 – 0	*−2 – 0*	*−10 −2*	*−50 – 3*	*−5 – 0*	*−30 – 2*
Research adoption (%)	35	70	**45**	45	87	**60**
	0 – 80	*40 – 100*	*15 – 90*	*0 – 80*	*70 – 100*	*40 – 90*
Lag time in adopting research outputs (years)	2	7.4	**5**	1	5.4	**2.2**
	1– 3	*2.5 – 12*	*2 – 10*	*0.5 – 1*	*1 – 10*	*1 – 3*

[a]The estimated percentage change in area burned is in addition to the increase in area burned caused by climate change (Flannigan *et al.*, 2005).

Triangular probability distribution (Kotz and van Dorp, 2004; van Dorp and Kotz, 2002) was chosen to represent the random variables pertaining to shifts in consequences, uptake, and lag time of research. This continuous probability distribution is useful for situations when data are missing or limited and parameter estimates must be elicited (Garthwaite *et al.*, 2005; Johnston and Gillingham, 2004; Vere *et al.*, 2004). The triangular probability distribution is specified from three parameters, notably, the minimum (lowest), most likely, and maximum (highest) values. The direction of skew of the distribution is set by the size of the most likely value relative to the minimum and maximum values (Figure 2).

Results

The changes in wildland fire management activities for the different research scenarios were elicited from expert wildland fire managers in different regions of Canada. For the alternative research scenario the experts' best estimates in reducing the fire management variable cost expenditure was 22%, the most likely 13%, with a minimum cost reduction of 2% from the expected efficiency in wildfire suppression preparedness and planning based on the assumption of an enhanced fire danger rating system. The elicited experts suggested there will be a slight reduction up to a small increase in their variable cost expenditures if the current research efforts remain the same (i.e., status quo scenario) with limited changes to the fire danger rating system (Table 4). Figure 3 presents the cumulative probability of the percentage changes for the two research scenarios (status quo and alternative) for the experts' best estimates on reduction area burned, fire management variable cost expenditure and public health cost. The experts expect that there will be significant benefits of an improved fire danger rating system, compared to the limited changes to the current

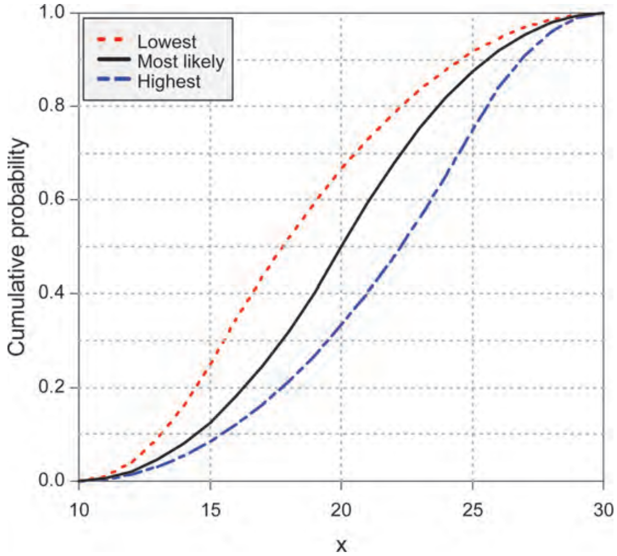

Figure 2 Triangular distribution of a random variable (*x*) with minimum and maximum values of 10 and 30, respectively, and corresponding cumulative frequency distributions for different values of "lowest" (dotted line = 15), "most likely" (solid line = 20), and "highest" (short-long dash line = 25).

system current status quo research effort. The results from the triangular distribution analysis indicated a 75% chance in reducing the area burned by 5% if the CFFDRS was enhanced to provide better intelligence for wildland fire management activities. The without research scenario will likely (i.e., 75% chance) produce a 1% reduction in the area burned (Figure 3). There is a high probability (i.e., 90% chance) in reducing the fire management variable cost and public health cost by 7% and 10%, respectively by adopting the research outputs. In maintaining the current CFFDRS (status quo research), the experts indicated that there would be no change or a small increase in these cost (Figure 3). These associated changes were used to measure the economic return from additional investment to enhance the rating system, compared to the status quo research effort of limited changes to the CFFDRS.

The baseline projection for the value of future wildland fire costs in Canada is presented in Table 5. The fixed and variable costs of wildland fire suppression and management were the two largest cost categories representing approximately 80% of the total costs considered in this analysis in period 1 increasing to 84% by the end of the study period. The largest cost savings in terms of total dollar values were achieved through reductions in timber damage and the variable cost of wildland fire suppression. However, the largest percentage savings from baseline for the research dollars invested were achieved through reducing the variable cost of suppression and through reduced evacuation costs (Figure 4).

The present value of the cost of wildfire research and the benefit of an improved CFFDRS are summarized in Table 6, using both a 0% discount rate and a 3% discount rate. Table 7 summarizes the net present value and benefit–cost ratios associated with each scenario and set of assumptions. The results indicate that wildland fire research has the potential to generate

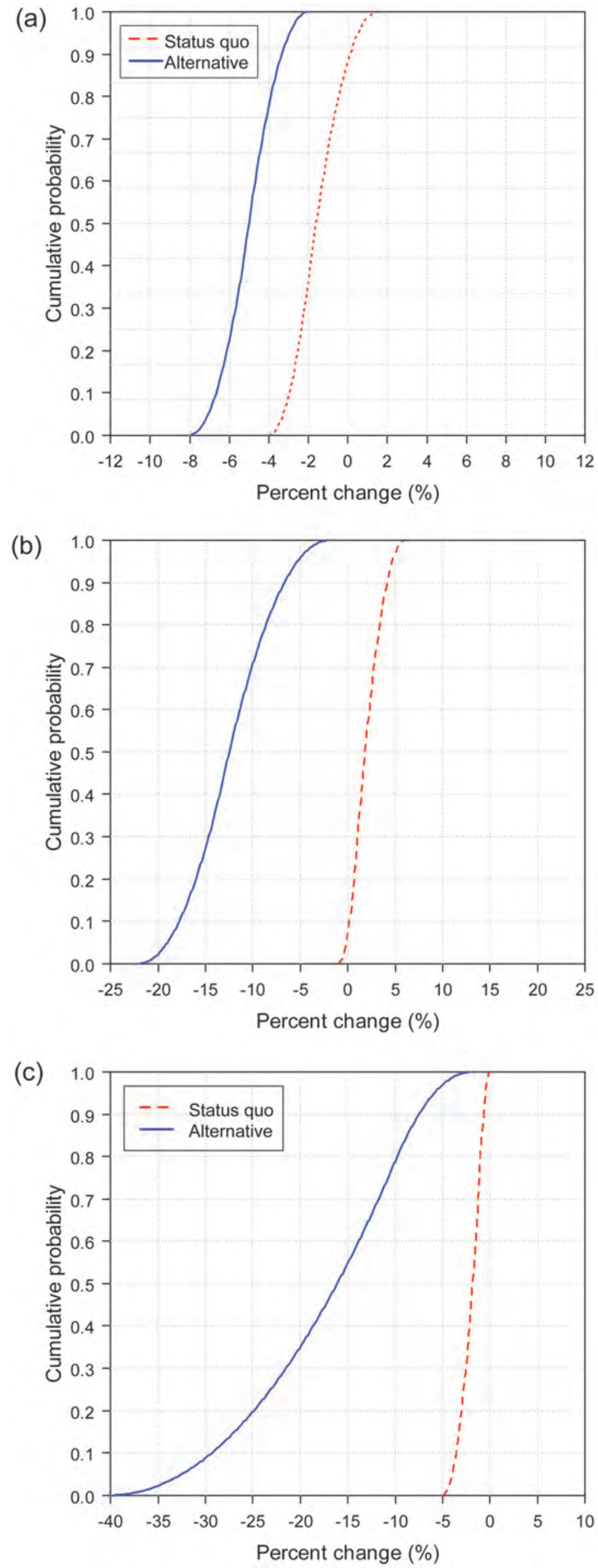

Figure 3 Cumulative probability distribution of the elicitation of experts' best estimates of percentage change in wildland fire area burned (a) fire management variable cost expenditure (b) and public health cost (c) for status quo (without research- dash line) and alternative (with research- solid line) scenarios.

Table 5 Baseline future projections of the value of wildland fire impacts (2008 Canadian $)

Future Period	Value of timber damage	Fire suppression - variable costs	Fire suppression - fixed costs	Property losses	Evacuation costs	Mortality and injury costs
1	197,958,910	494,544,193	384,210,004	4,312,223	1,909,452	10,000,000
2	199,352,194	504,639,331	389,926,261	4,312,223	1,909,452	10,000,000
3	200,745,477	514,734,469	395,642,517	4,312,223	1,909,452	10,000,000
4	202,138,761	524,829,607	401,358,774	4,312,223	1,909,452	10,000,000
5	203,532,045	534,924,746	407,075,030	4,312,223	1,909,452	10,000,000
6	204,925,328	545,019,884	412,791,287	4,312,223	1,909,452	10,000,000
7	206,318,612	555,115,022	418,507,543	4,312,223	1,909,452	10,000,000
8	207,711,896	565,210,160	424,223,800	4,312,223	1,909,452	10,000,000
9	209,105,179	575,305,298	429,940,057	4,312,223	1,909,452	10,000,000
10	210,498,463	585,400,437	435,656,313	4,312,223	1,909,452	10,000,000
11	211,891,747	595,495,575	441,372,570	4,312,223	1,909,452	10,000,000
12	213,285,030	605,590,713	447,088,826	4,312,223	1,909,452	10,000,000
13	214,678,314	615,685,851	452,805,083	4,312,223	1,909,452	10,000,000
14	216,071,598	625,780,990	458,521,339	4,312,223	1,909,452	10,000,000
15	217,464,881	635,876,128	464,237,596	4,312,223	1,909,452	10,000,000
16	218,858,165	645,971,266	469,953,852	4,312,223	1,909,452	10,000,000
17	220,251,449	656,066,404	475,670,109	4,312,223	1,909,452	10,000,000
18	221,644,732	666,161,542	481,386,365	4,312,223	1,909,452	10,000,000
19	223,038,016	676,256,681	487,102,622	4,312,223	1,909,452	10,000,000
20	224,431,300	686,351,819	492,818,878	4,312,223	1,909,452	10,000,000
21	225,824,583	696,446,957	498,535,135	4,312,223	1,909,452	10,000,000
22	227,217,867	706,542,095	504,251,391	4,312,223	1,909,452	10,000,000
23	228,611,151	716,637,233	509,967,648	4,312,223	1,909,452	10,000,000
24	230,004,434	726,732,372	515,683,904	4,312,223	1,909,452	10,000,000
25	231,397,718	736,827,510	521,400,161	4,312,223	1,909,452	10,000,000
26	232,791,002	746,922,648	527,116,417	4,312,223	1,909,452	10,000,000
27	234,184,285	757,017,786	532,832,674	4,312,223	1,909,452	10,000,000
28	235,577,569	767,112,924	538,548,930	4,312,223	1,909,452	10,000,000
29	236,970,853	777,208,063	544,265,187	4,312,223	1,909,452	10,000,000
30	238,364,136	787,303,201	549,981,443	4,312,223	1,909,452	10,000,000

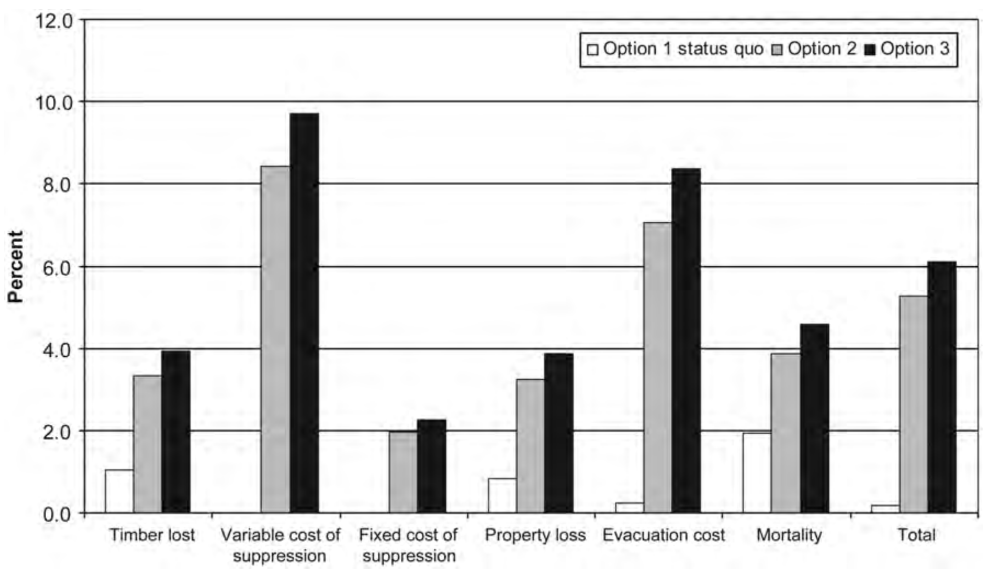

Figure 4 Percentage savings of the present value of social benefits achieved through reduced costs associated with wildland fire impacts.

Table 6 Summary of the investment cost and present value of social benefits, with different discount rates (in millions of 2008 Canadian dollars)

Assumptions	Option 1 (status quo)		Option 2		Option 3	
	0% discount	3% discount	0% discount	3% discount	0% discount	3% discount
Investment cost	**9.8**	**7.5**	**9.0**	**7.6**	**7.1**	**6.4**
Present value of social benefits						
Highest value						
Long research adoption period	254.5	130.1	3,451.7	1,875.1	3,846.8	2,169.1
Medium research adoption period	266.0	137.2	3,594.2	1,975.5	3,973.0	2,266.7
Short research adoption period	300.0	158.6	3,870.8	2,182.3	4,183.4	2,438.9
Lowest value						
Long research adoption period	0.0	0.0	363.1	196.7	410.2	231.9
Medium research adoption period	0.0	0.0	379.2	208.0	425.5	243.8
Short research adoption period	0.0	0.0	410.5	231.3	455.3	268.4
Most likely value						
Long research adoption period	74.1	38.0	2,104.4	1,141.2	2,369.4	1,340.3
Medium research adoption period	77.5	40.1	2,193.6	1,204.0	2,454.2	1,406.2
Short research adoption period	87.7	46.6	2,366.7	1,333.2	2,618.3	1,541.8

Table 7 Net present value (NPV, in millions of 2008 Canadian dollars) and benefit–cost (B/C) ratio, at 3% discount rate

Assumptions	Option 1 (status quo)		Option 2		Option 3	
	NPV	B/C Ratio	NPV	B/C Ratio	NPV	B/C Ratio
Highest value						
Long research adoption period	122.5	17.3	1,867.4	245.4	2,162.7	338.7
Medium research adoption period	129.6	18.2	1,967.9	258.5	2,260.3	353.9
Short research adoption period	151.1	21.0	2,174.7	285.6	2,432.5	380.8
Lowest value						
Long research adoption period	−7.5	0.0	189.1	25.7	225.5	36.2
Medium research adoption period	−7.5	0.0	200.3	27.2	237.4	38.1
Short research adoption period	−7.5	0.0	233.6	30.3	262.0	41.9
Most likely value						
Long research adoption period	30.4	5.0	1,133.6	149.4	1,333.9	209.3
Medium research adoption period	32.6	5.3	1,196.3	157.6	1,399.8	219.6
Short research adoption period	39.0	6.2	1,325.6	174.5	1,535.4	240.7

high levels of economic benefits over the range of expected outcomes and over the range of adoption periods for these outcomes. Specifically, Table 6 indicates that, under Option 1 (status quo), the present value of social benefits ranged from $0 at a minimum to a maximum of $158.6 million (2008 Canadian dollars) assuming a 3% discount rate in return for an investment cost of $9.8 million (2008 Canadian dollars). In comparison, the present value of social benefits under Option 2 and Option 3 ranged from $196.7 million − $2,182.3 million and $231.9 million − $2,438.9 million, respectively (Table 6). Assuming a 3% discount rate the net present value of research to modernize the CFFDRS ranged from $7.5 million to $2,432.5 million (2008 Canadian dollars) under the three options (Table 7).

Triangular probability functions were used to account for uncertainty about the benefits of research. The cumulative distribution functions for the CBA of the various research options and adoption lag times are shown in Figures 5 and 6. There is an approximately 70% chance that the current research effort (status quo) will yield a present value of social benefits of $38 million with a long research lag time of 6 years after the project is completed (Figure 5a). There is a slim chance that the current research effort (status quo) will yield $130 million present value of social benefits whereas under Option 3, there is a slim chance that the present value of social benefits will be less than $200 million (Figure 5a). The mean annual present values of the social benefits of research, at a 3% discount rate, were $65.80 million and $75.52 million for research investments of $0.85 million/year (Option 2 scenario) and $1.17 million/year (Option 3 scenario), respectively, with research adoption continuing for 4 years after the completion of the project.

The benefits to wildland fire management agencies will depend on the uptake of research outputs and the associated time lag (Figure 6). The cumulative distribution functions indicate that the probability of a present value of social benefits of $1 billion is about 40% from an 11-year research adoption program compared to a present value of social benefits of $1.18 billion in a five-year research adoption program for research Option 2 presented in Figure 6b.

The cumulative distribution functions (Figure 6) are different for the different research adoption options, but there is generally a higher probability of larger economic benefits if the research

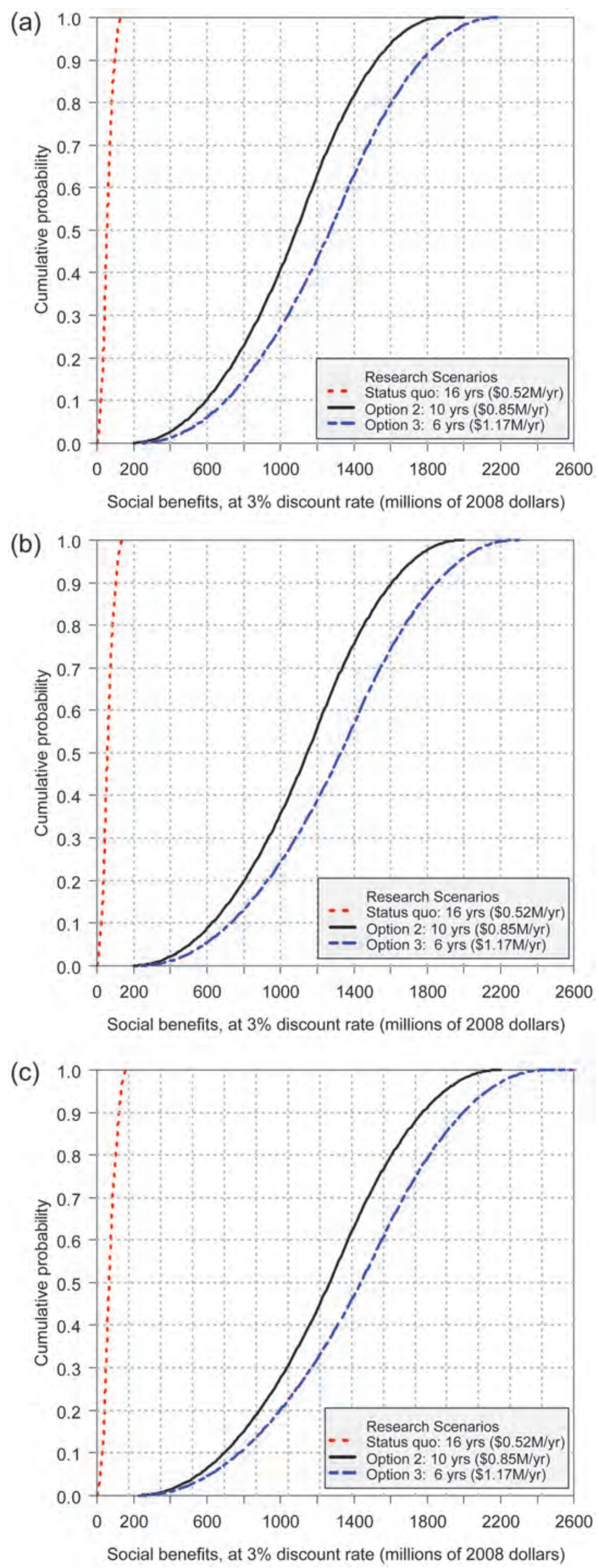

Figure 5 Cumulative distribution functions for the present value of social benefits of three research adoption scenarios for wildland fire research leading to development of the next generation of the Canadian Forest Fire Danger Rating System.

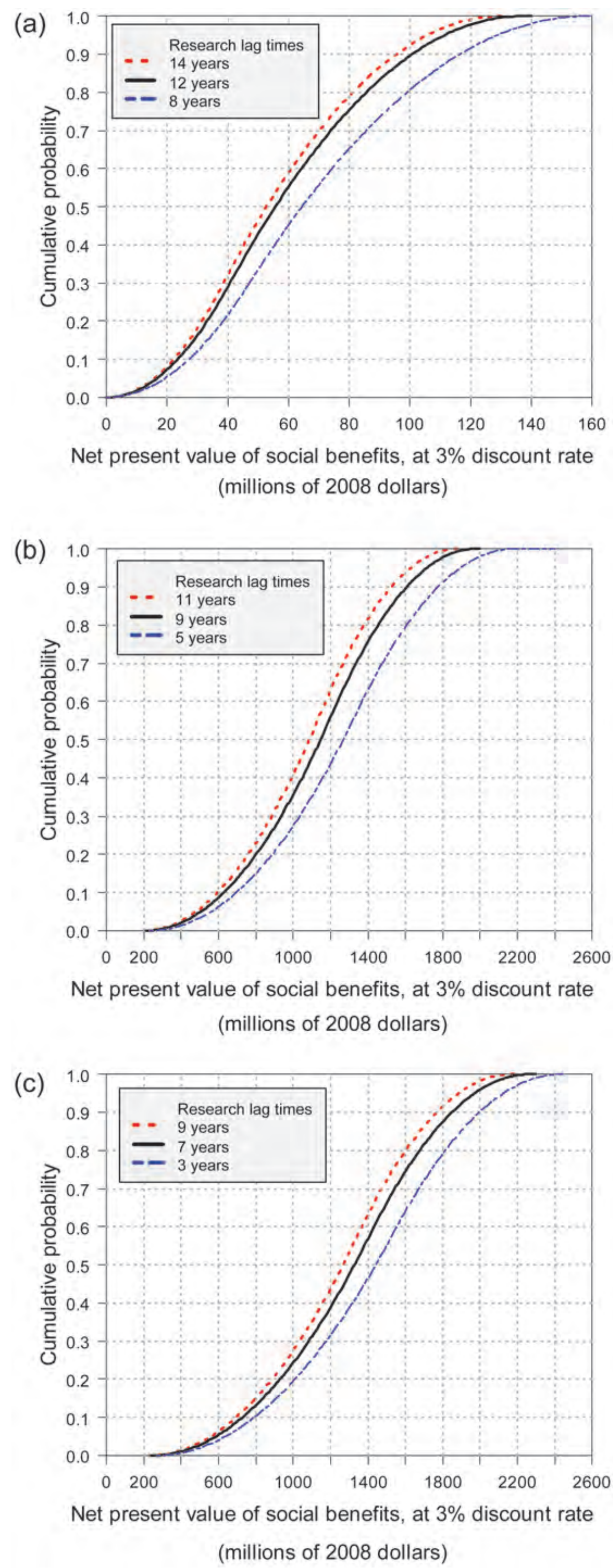

Figure 6 Cumulative distribution functions for the present value of social benefits of three research effort options leading to development of the next generation of the Canadian Forest Fire Danger Rating System.

adoption period is shorter and the process of adoption is completed during the life of the project. This assumption is impractical, but the analysis highlights the importance of technology transfer as a component of the research program and the need to initiate technology transfer early in the project, rather than towards the end.

Conclusion

Over the past 40 years, since the initial development of the CFFDRS, a wide range of changes and advances have occurred in areas relevant to the system, including information resolution, satellite technology, identification of new fuel types, climate change, forest disturbances, and scientific knowledge. Recognizing these changes, the CFS is embarking on a research program to develop models and modules to enhance data resolution in a systematic and scientifically sound fashion for the next generation of the CFFDRS. The aim of this study is to improve understanding about fire danger and fire behaviour to allow development of better prevention and control methods. There is a strong need to develop better public warnings and to improve public preparedness and thus to minimize the effect of wildland fires on the health and safety of Canadians. In this study, we have presented a framework for assessing estimates of the social benefits of wildland fire S & T in developing the next generation of the CFFDRS. This framework is transferable to other issues of public policy within forestry (e.g., pest management) and beyond.

The probabilities associated with various expected outcomes from wildland fire S & T projects can be considered as measures of risk and uncertainty in research investment. Presenting the cumulative distribution functions for different research scenarios in a manner similar to that shown in Figures 4 and 5 of this article will allow researchers and managers to compare the risks associated with each of the scenarios and to compare these risks with their expectations of research outcomes.

Finally, these results are subject to various assumptions, as described above. Estimates of expected outcomes or changes in economic and social benefits have often been derived on the basis of important parameters such as research adoption or the high cost of fire management. In this study, the use of different research scenarios and research adoption programs reflects the uncertainty that surrounds the outcomes. This uncertainty was addressed by using triangular probability distributions of expected outcomes and adoption of fire danger research, a more rigorous means of recognizing that both the outcomes and the benefits of research are subject to uncertainty than has previously been employed.

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