An impact analysis for the National guide for wildland-urban-interface fires

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An impact analysis for the National Guide for Wildland-Urban Interface Fires

Prepared for the National Research Council of Canada

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May 2021

National Research Council Canada
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Cover image: 2003 Okanagan Mountain Park Fire, as viewed from Kelowna, BC. Source: Shutterstock.
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Abstract

No Canadian wildfire before 2003 caused more than $10 million in insured loss; since then, five such fires have occurred, costing $5 billion in insured loss and many billions in uninsured damage, among many other negative impacts. Climate change is expected to increase wildfire ignitions 75% during the life of new buildings built today, and more people are choosing to live in areas prone to wildfire. In response, the National Research Council of Canada (NRC) developed the National Guide for Wildland-Urban Interface Fires ("the National WUI Guide" or "the Guide").

The National WUI Guide provides techniques to increase the resilience of buildings and communities in the wildland-urban interface (WUI). It offers optional combinations of building with non-combustible or fire-resistive material and controlling nearby vegetation. The Guide recommends public measures as well, including strategies related to planning, communication, roads, water, and vegetation management around power lines.

Following the Guide's recommendations creates costs and benefits for building owners, home buyers, tenants, residents, local government, and others. This report, sponsored by NRC, provides comprehensive information concerning the Guide's costs and benefits for new buildings, existing buildings, and communities in WUI fire hazard areas across the country.

The project team selected four real houses to represent typical conditions from a statistical sample of 102 houses in nine communities of various sizes in low-, moderate-, and high-hazard locations across Canada. Recent research provides estimates that any given location will experience a wildfire. The project team estimated owners' capital and maintenance costs needed to follow the Guide's options. It used CAL FIRE data to estimate the ignition probability and damage for each house. It estimated property loss, additional living expenses, indirect economic loss, insurance costs, deaths, injuries, instance of post-traumatic stress disorder (PTSD), and some environmental costs.

Given a fire and the probability that the fire occurs, one can estimate future losses where the Guide has and has not been followed. The difference represents the Guide's benefit. The ratio of the benefit to the cost is called the benefit-cost ratio (BCR); if BCR exceeds 1.0, the Guide can be seen as cost-effective. The BCR of the Guide exceeds 1.0 throughout Canada's WUI, with the exception of existing houses in low-hazard areas. Climate change, however, is expected increase fire hazard in the coming decades, including in areas currently defined as low hazard. In the rest of the country, BCRs can exceed 30:1.

Relying on long-term vegetation management rather than fire-resistive materials cuts costs by 3 times and increases the BCR proportionately, though these measures may often require neighbourhood-level cooperation. Table ES-1 summarizes homeowner costs, benefits, and BCRs. Table ES-2 summarizes lifetime community-level costs and benefits for a community that retrofits 9,400 existing houses (mostly using vegetation management) and builds 1,700 new houses in the WUI (mostly relying on non-combustible construction).

Table ES-1. Homeowner costs, benefits, and benefit-cost ratios

	High hazard	Moderate hazard	Low hazard
Existing house			
Benefit	$286,000	$41,000	$2,000
Cost: non-combustible construction	$21,000	$21,000	$28,000
Cost: vegetation control	$9,000	$9,000	$8,000
BCR: non-combustible construction	14	2	0.1
BCR: vegetation control	32	5	0.2
New house			
Benefit	$370,000	$53,000	$5,000
Cost: non-combustible construction	$11,000	$11,000	$1,000
Cost: vegetation control	$4,000	$4,000	$4,000
BCR: non-combustible construction	34	5	5
BCR: vegetation control	93	13	1

Table ES-2. Community-level costs, benefits, and BCRs for a community with 10,000 houses in the WUI

	High hazard	Moderate hazard	Low hazard
Household cost ($ million)	$110	$110	$100
Municipal and utility cost ($ million)	$170	$170	$170
Benefit ($ million)	$4,000	$570	$30
BCR	14	2	0.1
Avoided deaths	20	3	0
Avoided injuries	75	10	0
Avoided PTSD cases	75	10	0
Construction and landscape jobs	50	50	40
GST savings ($ million)	$3	$0.4	$0.0
HST savings ($ million)	$6	$0.9	$0.0

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Abbreviations and notation

BCR	Benefit-cost ratio
CAD	Canadian dollars
CI	Confidence interval
CO_2	Carbon dioxide
DINS	CAL FIRE Damage Inspection Specialists program
DSpace	CAL FIRE Defensible Space database
ea	Each
EAL	Expected annualized loss, that is, long-term average loss per year
EDF	Environmental Defense Fund
ext	Exterior
F	Degrees Fahrenheit
ft	Feet
FEMA	Federal Emergency Management Agency
G	Hazard, or burn rate: average times per year that a location experiences a WUI fire
GB	Gypsum wallboard
GST	Goods and services tax
HST	Harmonized sales tax
ICLR	Institute for Catastrophic Loss Reduction
kg	Kilograms
kV	Kilovolt
kWh	Kilowatt hour
lf	Linear feet
in	Inches
m	Metres
m^2	Square metres
mm	Millimetres
NAICS	North American Industry Classification System
NFPA	National Fire Protection Association
ND	No date, referring to an undated publication
NRC	National Research Council
OR	Odds ratio
PTSD	Post-traumatic stress disorder
SIZ	Structure ignition zone
sq ft	Square feet
USD	United States dollars
WUI	Wildland-urban interface, an area where various structures, usually private homes, and other human developments meet or are intermingled with wildland (vegetative) fuels or can be impacted by the heat transfer mechanisms of a wildfire, including ember transport
x	Fire occurrence, a binary variable: 1 if a location experiences a fire, 0 otherwise
y	Mean damage factor, i.e., loss as a fraction of value exposed to loss

Notes:

Some mixing of US and metric units throughout the paper is unavoidable.

All currency in this report is in 2020 CAD, unless noted otherwise.

Summary of key findings

An Impact Analysis for the National Guide for Wildland-Urban Interface (WUI) Fires

This report estimates the impacts of the National Research Council's National Guide for Wildland-Urban Interface (WUI) Fires ("the National WUI Guide" or "the Guide") through the ratio of the avoided future losses to the capital and maintenance costs (called the benefit-cost ratio, BCR). The National WUI Guide provides direction on how to build and maintain fire-resilient buildings near wildlands. It calls either for structures to be built with non-combustible materials or for surrounding vegetation to be controlled, or both. Satisfying the National WUI Guide's recommendations appears to offer benefits that greatly exceed its costs. The benefits come from avoiding future property and life-safety losses. Ten key findings of our review of the Guide are:

1. **New houses built to satisfy the National WUI Guide recommendations save over 30:1**. Benefits reach 34 times the cost. Costs can be below $5 per square foot, or 2% of construction cost. When neighbours cooperate to control vegetation, costs drop by two-thirds and the BCR triples.

2. **Retrofitting saves up to 14:1**. Modifying existing houses costs more – from $10 to $20 per square foot – but can still be very cost-effective. Neighbourhood cooperation to control vegetation reduces costs by two-thirds and increases BCR three times.

3. **Communities save up to 14:1**, when the costs to homeowners, municipalities, and utilities are accounted for.

4. **Using the Guide nationally saves up to 4:1**, avoiding $500 billion in future losses at a cost of $125 billion. It creates 20,000 long-term jobs, saves 2,300 lives, avoids 17,000 non-fatal injuries and cases of post-traumatic stress disorder, and increases tax revenues by $1 billion.

5. **Nature-based solutions save even more**. Vegetation control needs maintenance and cooperation, but costs only one-third as much as structural measures, producing BCRs as high as 100:1. Indigenous communities have long used fire stewardship to reduce risk.

6. **Stakeholders working together** to follow the National WUI Guide can lower barriers and costs, increasing the nation's benefit.

7. **Climate change makes adaptation more urgent**. Accounting for climate change reveals that benefits increase by 40% as temperatures rise, humidity falls, and the fire season lengthens.

8. **Municipalities and utilities share the cost burden**. Water supply, access, and utility vegetation management matter. Municipalities and utilities bear much of the cost, with benefits affecting wide swaths of the community.

9. **The benefit estimates in this study of the National WUI Guide are conservatively low**. Some real benefits to health, historical and cultural value, peace of mind, pets, mementos, and others can be difficult to quantify and are omitted here.

10. **There's more to do**. To further reduce fire loss, NRC can address the science of climate change, the engineering details to develop the National WUI Guide into a standard, and the social issues in Indigenous and northern communities. The study suggests 12 such topics.

1. Introduction

1.0 Background

The National Research Council of Canada (NRC) developed a National Guide for Wildland-Urban Interface (WUI) Fires, referred hereafter as the National WUI Guide or the Guide. It provides guidance on how to reduce building damage[1] and improve life safety for residents and firefighters impacted by wildfires in the WUI area. In October 2020, NRC contracted the Institute for Catastrophic Loss Reduction (ICLR) to perform an impact analysis of the guide. An impact analysis generally identifies the potential consequences of a change or estimates what needs to be modified to accomplish a change. The present impact analysis measures the consequences of the National WUI Guide with benefit-cost analyses in which the consequences are separated into two categories: 1) costs, which refer to the expected present value of expenditures to satisfy the National WUI Guide's recommendations, and 2) benefits, which refer to the expected present value of future losses that are avoided as a consequence of satisfying the National WUI Guide's recommendations. The impact analysis attempts to quantify all these consequences in monetary terms. Some consequences are expressed both in life-safety impacts (e.g., deaths and non-fatal injuries) and an approximately equivalent monetary value (e.g., accepted regulatory costs to avoid deaths and non-fatal injuries). In some cases, the study could only describe impacts qualitatively.

Following the National WUI Guide reduces the likelihood and severity of WUI fire damage to buildings, reduces the spread of WUI fires, and increases the effectiveness of firefighting and evacuation actions. The National WUI Guide outlines measures that address hazard and exposure factors (such as vegetation, topography, and historical conditions), attributes of the buildings in the WUI, community planning, resources, and outreach (such as access routes, firefighting resources, emergency plans, and evacuation procedures).

1.2 Objectives

The project aims to estimate the costs to retrofit existing buildings and to design new buildings that satisfy the National WUI Guide at the single-building, community, and national levels, distinguishing costs and benefits by hazard level. It aims to estimate benefit-cost ratios at each level and benefits in terms of each of these categories:

1. Reduced future property repair and reconstruction costs
2. Reduced additional living expenses and other costs of residential displacement
3. Reduced future losses associated with direct business interruption, meaning the loss of revenue resulting from damage at a business's facility that prevents it from being used for production, or in the case of transportation infrastructure, the added costs associated with longer travel times
4. Reduced future losses associated with indirect business interruption, meaning the loss of revenue resulting from damage at other facilities
5. Lower insurance costs, specifically the part of insurance premiums associated with overhead and profit, as opposed to the part associated with property repair costs and other claims
6. Impact on maintenance costs

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[1] Several notable firefighting glossaries omit definitions for structure and building. Fire professionals tend to use the word "structure" to mean buildings and other permanent constructions, such as open shelters and water towers. "Building" seems to generally mean a subcategory of enclosed structures with walls and a roof. The present report focuses on a subcategory of buildings in which a few people (one or two families) live and refers to these buildings as houses.

7. Improved public health outcomes, especially related to deaths, non-fatal injuries, and post-traumatic stress disorder (PTSD); public health outcomes are expressed in terms of incidents and are then monetized using the acceptable cost to avoid future statistical deaths and injuries
8. Fewer job losses and some job creation
9. Impact on tax revenues
10. Lower environmental impacts
11. Reduced historical and other cultural impacts
12. Reduced costs for emergency response and loss of service to the community, especially for fire stations and hospitals

The analysis must aggregate from individual buildings that are characteristic of existing and new construction, reflecting Canadian building practices, existing infrastructure, and current preferences for new construction. It must estimate benefits and costs for partially and fully satisfying the National WUI Guide and validate results to the extent practical from recent Canadian and international experience. The report accepts some limitations for purposes of practicality. Also, for practical purposes, it estimates community-level costs for a community that fully satisfies the National WUI Guide, that is, where every existing house within the wildland-urban interface is retrofitted and every new house built within the wildland-urban interface satisfies the National WUI Guide.

1.3 Organization of the report

This chapter has introduced the background and objectives of the study. Chapter 2 presents relevant literature on experience and methods of WUI studies. Chapter 3 describes the methods that the project team employed for the impact analysis. Chapter 4 includes intermediate results, that is, interesting or important quantities calculated during the process of estimating impacts, but that do not qualify by themselves as impacts. Chapter 5 presents conclusions and summarizes the novelties and limitations of this work. Chapter 6 lists the references cited. Appendix A shows how the process of selecting archetype houses used for this analysis seems to satisfy principles recently recommended by the Canadian Home Builders' Association. Appendix B reflects on the impacts of the National WUI Guide on Indigenous communities. Appendix C highlights the National WUI Guide's most cost-effective recommendations.

2. Literature review

2.1 Past fire performance of buildings in the WUI

2.1.1 Sandink's WUI Fire Overview

Sandink et al. (2017) provide a broad overview of WUI fire risk. They recap three costly WUI fires of the 21st century: the 2003 Okanagan Mountain Park fire at Kelowna, BC, the 2011 Flat Top Complex fire at Slave Lake, Alberta, and the 2016 Fort McMurray, Alberta, fire. They offer evidence to support the hypothesis that WUI fire risk has been increasing in recent years, describing three driving factors: (1) development in the WUI, (2) aggressive fire suppression near settlements and in places with valuable timber resources, and (3) climate change driving up temperatures, reducing moisture, and increasing fuel accumulation. They extensively review codes, standards, and tools for WUI fire risk management, many of which are summarized later in this analysis. They warn that codes alone may not suffice to ensure that property owners maintain their yards to control fuel near the house, and they call for study of property owners' behaviours to better understand and promote fuel maintenance. Among many recommendations, the authors call for benefit-cost analyses like the present one.

2.1.2 Canadian Fire Information Database

In the past, the Canadian Association of Fire Chiefs and the Canadian Council of Fire Marshals and Fire Commissioners has made the National Fire Information Database available to researchers (Canadian Association of Fire Chiefs 2016). Its data dictionary (Statistics Canada 2017a) provides detailed information on structural fire incidents (e.g., date, time, location, and resources used in the response), properties affected (e.g., occupancy, construction, values exposed to loss, and fire protection features), property loss, victim information, and other potentially useful data. The impact analysis project team requested access to the database in December 2020 and was informed in January 2021 that the program is currently closed for re-evaluation (A. Therrien, Manager of Membership Services and Special Projects, Canadian Association of Fire Chiefs, written commun., January 27, 2021).

2.1.3 Relevant Evidence from the 2003 Okanagan Mountain Park Fire

Evidence from the Okanagan Mountain Park fire in August and September 2003 might inform the current analysis. The fire occurred mostly in the mountain park that abuts the southern border of the City of Kelowna. In the City of Kelowna Fire Department's (ND) recap of the fire, they report that the fire response included 60 fire departments, 1,000 forestry firefighters, and 1,400 members of the Canadian Armed Forces. British Columbia (2003) reports that the fire damaged or destroyed 238 homes and 14 rail trestles and forced the evacuation of 33,050 people.

The City of Kelowna Planning and Corporate Services Department (ND) reports that in 2001 the city had 40,045 private dwellings (26,735 single-family dwellings, 12,700 housing units in multi-family dwellings, and 605 movable dwellings), which means that the fire damaged or destroyed 0.6% of the city's housing units. Castanet.net (ND) offers a variety of possibly useful imagery: time-lapse AWIS thermal images and an incomplete map of fire-damaged areas in Kelowna (Figure 1A). Satellite imagery of the area indicated by the red rectangle in Figure 1A from December 2004 shows how the fire jumped over some buildings and destroyed others (Figure 1B). Figure 2A shows that houses adjacent to destroyed ones do not necessarily avoid damage completely; note the melted vinyl siding on the house in the background.

Figure 2B shows the same two lots with a new house replacing the destroyed one. The new house appears to have been built with stucco or non-combustible exterior cladding, reflecting a lesson learned.

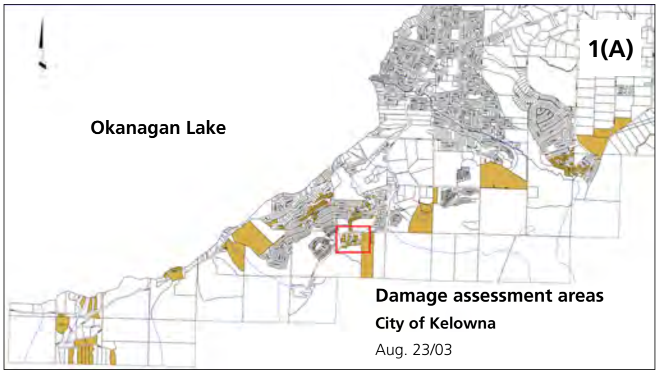


Figure 1. (A) *Incomplete map of fire damage in the City of Kelowna after the 2003 Okanagan Mountain Park fire (Castanet.net, ND).* **(B)** *Satellite image of area indicated by red rectangle in Figure 1A in December 2004 (Google Earth).*

Figure 2. (A) *Street-level photo from immediately after the fire shows that buildings immediately adjacent to destroyed houses are not wholly untouched. Note the melted vinyl siding on the green house.* **(B)** *The same two lots, showing the nearby house repaired and the destroyed one rebuilt. It appears the new house has been rebuilt with non-combustible stucco exterior finish. (A and B: Ottawa Citizen 2013).*

2.1.4 Relevant Evidence from the 2011 Flat Top Complex Wildfire

The Flat Top Complex Wildfire Review Committee (2012) was created to "assess Alberta's wildfire management program with a focus on the department's response to the wildfires that entered the Town of Slave Lake and nearby communities of Poplar Estates, Canyon Creek, and Widewater in May 2011." Two of the three fires that comprise the complex destroyed 610 buildings, including about one-third of the buildings in Slave Lake.

The authors echo others about climate change, longer fire seasons, and "aging coniferous forests dominating more of the landscape" that make "Alberta's forests … likely more flammable than they were even 50 years ago." They note the prior lack of wildfires in Alberta: "Prior to 2011, the last wildfire causing widespread damage to a community was in 1919 when the Town of Lac La Biche was destroyed, and 14 people lost their lives. Since 1919, and prior to the 2011 wildfires in the Slave Lake area, the most significant losses were experienced in 2001 when a wildfire destroyed 10 homes in the hamlet of Chisholm."

Humans caused all three fires of the Flat Top Complex Wildfire, so the authors' recommendations focus on fire prevention and suppression, communication, and business resumption. The report briefly mentions the development of codes and standards. It lacks statistics on construction that might be useful for asset definitions, mitigation measures that apply to the buildings or their lots, or community mitigation costs. Images of Slave Lake from the media show mostly timber-frame and wood-clad buildings and all-or-nothing damage to individual houses, but not all-or-nothing damage to communities, as shown in Figure 3A. The fire also destroyed the Slave Lake Government Centre and Town Library, which appears to have been partly steel-frame construction but with glulam timber gravity frame and a timber roof (Figures 3B–D).

Westhaver (2015) offers a database of 257 buildings damaged by the Flat Top Complex fire (and 188 damaged or destroyed by the Okanagan Mountain Park fire), but only their locations; his focus is on the fire-resistive attributes of the houses that replaced the damaged or destroyed ones as of August 2014. The present project team could find no data that would inform asset definitions, fire vulnerability models (called response functions), costs, or other benefits.

Figure 3. (A) *Destroyed homes in Slave Lake on May 17, 2011 (Ed Kaiser, edmontonjournal.com, use claimed under fair dealing provision).* **(B)** *Slave Lake Government Centre and Town Library (Travel Alberta 2020) before the fire,* **(C)** *burning on May 17, 2011 (CTV, use claimed under fair dealing provision), and* **(D)** *after the fire (Rick MacWilliam, edmontonjournal.com, use claimed under fair dealing provision).*

2.1.5 Relevant Evidence from the 2016 Fort McMurray (Horse River) Fire

The Fort McMurray wildfire in 2016 destroyed about 2,400 structures and caused close to $4 billion in insured losses between about May 1 and May 5, 2016. Westhaver (2016, 2017) addresses the question of why some homes survived the Fort McMurray WUI fire with little or no damage, while others were vulnerable to ignition and were destroyed. He presents statistics on a reconnaissance effort that focuses on 49 houses in five "study cases": adjacent urban homes in which one survived and one did not (case 1), a situation where urban houses received only minor damage despite exposure to fire (case 2), damage pockets within otherwise undamaged urban neighbourhoods (case 3), isolated survivors within largely damaged urban neighbourhoods (case 4), and large lots in rural neighbourhoods (case 5). He attributes the survival of homes that did not burn to compliance with FireSmart guidelines, offering some statistics regarding survival versus degree of compliance with FireSmart and the details of the location (Table 1).

Table 1: Westhaver (2017) summary statistics of homes examined after the 2016 Fort McMurray wildfire

FireSmart Hazard Level for All Homes Assessed in All Situations								
	Low (0-42 points)		Moderate (43-58 points)		High (59-70 points)		Extreme (71+ points)	
	'FireSmart' rated				Not 'FireSmart' rated			
	#	%	#	%	#	%	#	%
Paired Urban Homes – Survived	10	77	2	15	1	8	0	0
Paired Urban Homes – Destroyed	4	31	4	31	1	7	4	31
High Heat Exposure – Survived	3	100	0	0	1	0	1	0
Isolated Urban Ignitions – Destroyed	2	40	1	20	0	0	2	40
Isolated Urban Survivors	2	40	0	0	1	40	0	20
Paired C. R.• Homes– Survived	1	20	3	60	1	20	0	0
Paired C. R.13 Homes – Destroyed	0	0	0	0	2	40	3	60
Surviving Homes by Haz. Level (N = 26)	16	62%	5	19%	4	15%	1	4%
Homes Destroyed by Haz. Level (N = 23)	6	26%	5	22%	3	13%	9	39%

• Country Residential

The summary statistics may help to construct or quantitatively inform a fire vulnerability model, although possibly with difficulty. The sampling strategy appears to be conditioned on (that is, dependent on) outcome, whereas data that relate the probability of burning to FireSmart rating and some measure of intensity (e.g., radiant heat and ember density) would be preferable. It may be practical to use Table 1 to estimate the relative probabilities of ignition in a FireSmart versus non-FireSmart house.

Boutilier (2016, p. 19) provides useful statistics about debris removal. The fire burdened the Regional Municipality of Wood Buffalo with disposing 150,000 metric tons of waste. Some of the debris could potentially be recycled, including 90,000 metric tons of concrete and 2,000 metric tons of scrap metal. But much of the debris included asbestos and other contaminants that the municipality had to place in landfills. Reducing fire damage reduces the burden of debris.

2.1.6 Relevant Evidence from Recent California WUI Fires

Kasler and Reese (2019) present an analysis by McClatchy of CAL FIRE data and Butte County property records suggesting that 2008 additions to the California Building Code (Chapter 7A) effectively reduced damage to compliant homes built after the code went into effect. The database includes all homes in the Camp Fire perimeter and homes within 100 metres of the perimeter – close enough for embers to spark a new fire (e.g., see ESRI 2020).

Syphard and Keeley (2019) analyze building inspectors' reports documenting homeowner mitigation practices for more than 40,000 wildfire-exposed structures from 2013 to 2018. They find that "structural characteristics explained more of a difference between survived and destroyed structures than defensible space distance [structure ignition zone in National WUI Guide nomenclature]. The most consistently important structural characteristics – having enclosed eaves, vent screens, and multi-pane windows – were those that potentially prevented wind-borne ember penetration into structures, although multi-pane windows are also known to protect against radiant heat." Active firefighting sometimes proves crucial, but no single building feature appears to dominate survival. Notably, "while destroyed homes were preferentially included in the study, many 'fire-safe' structures, having > 30 metres defensible space or fire-resistant building materials, were destroyed."

CAL FIRE (2020) provided the project team with a database of 1,065 buildings located within the boundary of the 2018 Camp Fire that had been inspected the year before the fire and immediately afterwards. The database represents a combination of data from CAL FIRE's Damage Inspection Specialists (DINS) and Defensible Space (DSpace) databases. Only one field from the DINS data is included: whether the structure was destroyed or undamaged. Structures with intermediate levels of damage were omitted. The database contains twelve fields for each house from the DSpace databases, including the use of the structure, roof construction, eaves, vent screens, exterior siding, windows, deck and porch construction, patio cover construction, and fence construction. The database does not contain data about fuel near the structure.

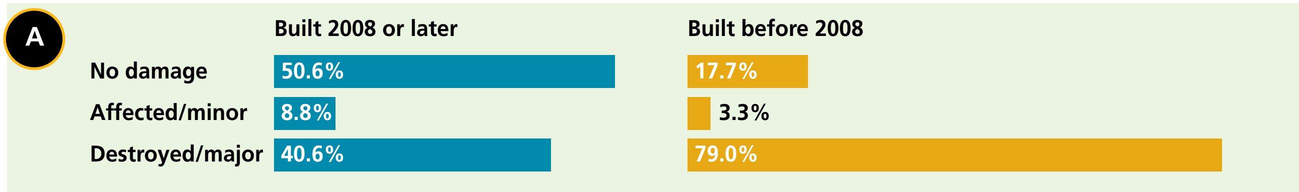
In written and oral communication, Hawks (2020) provided a variety of other valuable information about WUI fires in California between 2013 and 2020. These data are now summarized here. CAL FIRE data shows that 93% of buildings that ignite are destroyed; 5% are affected (meaning repair cost between 1% and 9% of the house replacement cost), and the remaining 2% of buildings experience repair costs that are either minor (10% to 25% of house replacement cost) or major (26% to 50% of house replacement costs) (Steven Hawks, Staff Chief of Wildfire Planning and Engineering Division, CAL FIRE, December 3, 2020, oral commun.).

Figure 4A shows that approximately 51% of the 350 single-family homes built after 2008 within the boundary of the 2018 Camp Fire in Northern California escaped damage. Only 18% of the 12,100 homes built prior to 2008 escaped damage. Manufactured houses burned in nearly equal measure regardless of age.

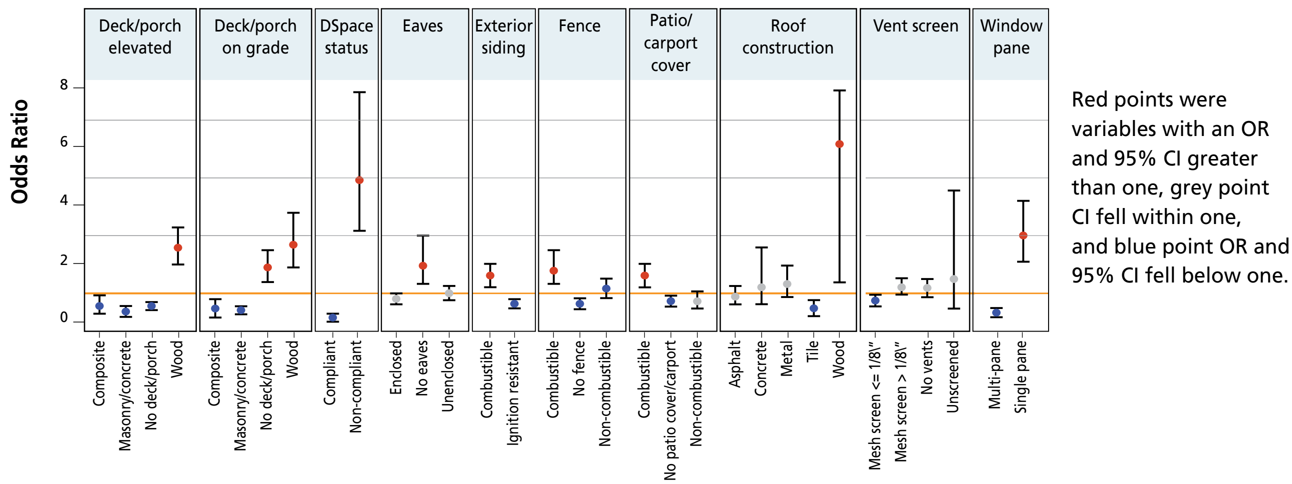
Figure 4B (Hawks 2020) shows odds ratios (OR) attributable to various building features and defensible space (DSpace). Whiskers in the chart show the 95% confidence intervals (CI) for the odds ratios. Figure 4C illustrates how compliance with the 2008 California Building Code appears to reduce the likelihood of ignition and degree of damage in each of seven WUI fires. Figure 4D aggregates the data from the seven fires (Hawks 2020).

Note that the California Building Code's requirements and DSpace data map heavily but still imperfectly resemble recommendations of the National WUI Guide. Especially noteworthy is the absence of information about combustible material immediately adjacent to the house, the area that the National WUI Guide refers to as priority zone 1A. Also note the distinction between damage severity and the probability of ignition. Figure 4E shows damage severity *conditioned* on ignition.

Figure 4: *Some summary statistics from CAL FIRE about damage (A) to pre- and post-2008 buildings and (B) by construction feature, (C) and (D) within and near the 2018 Camp Fire perimeter and seven large fires in 2017–2018, and (E) all permanent structures greater than 120 sq ft within the perimeter of fires from 2014 through 2019. (B–E: Hawks 2020)*

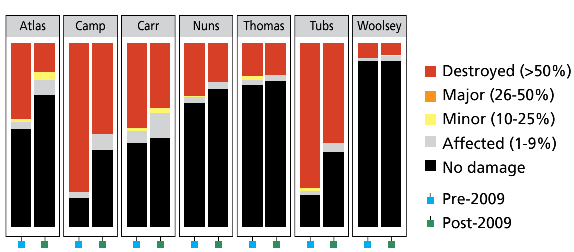


B **Camp Fire Odds Ratio (OR) for each construction feature by sub-material and DSpace status for structures with a corresponding DSpace and DINS point.**



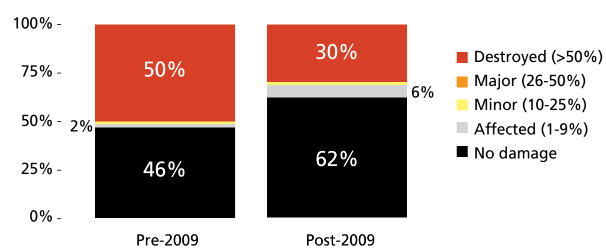
C **CAL FIRE statistics and analysis**

Percentage of structures by damage category inside or within 100 metres of the fire perimeter of the seven largest wildfires in 2017 and 2018



D **CAL FIRE statistics and analysis**

Sum of damage/destroyed percentages to parcels for the seven largest wildfires (Atlas, Camp, Carr, Nuns, Thomas, Tubbs, Woolsey) in 2017 and 2018



E

Category of damage	Structure type						Total	% of residential structures damaged and destroyed	% of all structures damaged and destroyed
	Single-family residences	Multi-family residences	Mixed residential commercial	Non-residential structures	Other minor structures	Infrastructure			
Destroyed (>50%)	27,185	282	16	956	10,329	17	38,785	92.77%	92.60%
Major (26-50%)	149	7	0	26	143	8	333	0.53%	0.80%
Minor (10-25%)	401	13	3	53	178	3	651	1.40%	1.55%
Affected (1-9%)	1,517	55	2	136	395	12	2,117	5.31%	5.05%
Total	29,252	357	21	1,171	11,045	40	41,886	100.00%	100.00%

For example, fire destroyed 93% of the 29,252 single-family dwellings that experienced at least some damage in the fires of 2014–2019, but Figure 4D shows that no more than 54% of houses within fire perimeters of 2017–2018 experienced any damage. Insurers talk about this distinction as frequency (no more than 54% ignition) versus severity (93% total losses conditioned on ignition, 94% expected value of loss conditioned on ignition).

It can help to understand risk through a real-life example. Two personal stories follow that illustrate the value of fire-resistant construction.

Two personal stories from the 2018 camp fire

"I knew we were in the middle of the forest. Why wouldn't you do everything you could to make it last?"

In November 2018, the deadliest and most destructive wildfire in California's history ravaged Butte County, California. The Camp Fire burned the densely populated town of Paradise on November 8, leaving at least 85 dead and eventually spanning 240 square miles. It took 17 days to fully contain. CAL FIRE reports that the fire ultimately cost $16.5 billion and destroyed 18,793 structures. By December 12, 2018, FEMA approved $180 million in grants and loans for survivors. Federal and state agencies provided over $27.7 million in grants for home repair, replacement, and rental expenses. The Small Business Administration approved over $140 million in disaster loans for homeowners and businesses.

In an interview with the *Sacramento Bee*, two Paradise families reported having returned to their homes to find them almost untouched by the fire (Figure 5). Sean and Dawn Herr marvelled at their fortune, visiting their home in March 2019 to find it still standing (Figure 5A, B). They credit its survival to the gravel skirt encircling the house. Built in 2010, their home adheres to the 2008 California Building Code, whose provisions resemble the National WUI Guide in many ways, including fire-resistant roofing, siding, and other features. The code protected 51% of the 350 single-family homes built after 2008 in the Camp Fire's path, while only 18% of the 12,100 homes constructed prior to the code's enforcement survived.


5(A)


5(B)

The home of the Carrells, Paradise residents who fled to escape the Camp Fire, also complied with 2008 California Building Code requirements for houses in the wildland-urban interface and survived the fire. "I thought, 'Oh, well, the house is done,'" said Oney Carrell (Figure 5C). "I knew we were in the middle of the forest. Why wouldn't you do everything you could to make it last?'"


5(C)

Figure 5. *Two houses in Paradise, California, built to comply with fire-resistive standards of the 2008 California Building Code, survived the 2018 Camp Fire, while nearby houses burned down at a much higher rate. (A, B) The home of Sean and Dawn Herr, surrounded by its gravel apron. (C) The home of Oney and Donna Carrell. (Hector America, the* Sacramento Bee *via the Associated Press, reprinted with permission)*

2.2 WUI guides, standards, and model codes

The California Building Code (California Building Standards Commission 2019a) Chapter 7A regulates materials and construction methods for exterior wildfire exposure. Leading requirements introduced in the 2008 edition of the code include:

1. Roofing material is fire-resistant: non-combustible or made of fire-retardant–treated wood, or made of fire-retardant–treated wood shingles and shakes (Sec 705A).
2. Gutters prevent accumulation of leaves and debris (Sec 705A4).
3. Fine mesh covers attic ventilation openings (Sec 706A).
4. Exterior cladding must be non-combustible, or ignition-resistant, or tested for 10-minute direct flame contact, or backed by ⅝-inch Type-X gypsum sheathing on the exterior side of the framing, or have a one-hour fire rating on the exterior side of the framing (Sec 707A).
5. Glazing must be multi-pane with one tempered pane, or glass block, or have 20-minute fire rating, or tested for 10-minute direct flame contact with Sec 12-7A (Sec 708A.2).
6. Doors must have an exterior surface that is non-combustible or ignition-resistant, or be solid core, or have a 20-minute fire rating, or tested for 10-minute direct flame contact with Sec 12-7A (Sec 708A.3).
7. Decks, porches, balconies, and stairs must have walking surfaces that are constructed of ignition-resistant material, or exterior fire-retardant–treated wood, or are non-combustible, or resistant to three-minute direct flame and burning brand tests (Sec 709A).

Enforcement varies by jurisdiction. CAL FIRE oversees fire protection mostly in rural areas and enforces Chapter 7A in any region that it designates as a "severity zone" – with moderate, high, or very high hazard level. Cities and other jurisdictions with their own fire departments generally only use Chapter 7A where CAL FIRE says the threat is very high. Local governments can reject the CAL FIRE designation.

Two other relevant existing WUI building codes include International Code Council (2018), a model code to regulate the construction, alteration, movement, repair, maintenance, and use of buildings and non-building structures in the wildland-urban interface, and the National Fire Protection Association (NFPA 2018) standard for reducing structure ignition hazards from wildland fire.

FireSmart Canada (2018) offers guidance for homeowners on how wildfires grow, spread, and burn homes. It explains non-combustible construction and how to maintain Home Ignition Zones 1 through 3. It does not represent a code or standard.

Some communities have adopted local ordinances to reduce fire risk in existing buildings. The City of Big Bear Lake (2008), a community of 5,200 in Southern California, passed an ordinance declaring wood shake shingle roofs "a severe fire hazard and danger," ordered homeowners to replace them by 2012, and offered cash incentives of up to USD $4,500 for new roofs.

Standards Australia (2009) offers Australian Standard AS-3959, Construction of Buildings in Bushfire-Prone Areas. In locations subject to WUI fire, the standard requires non-combustible roofing. Requirements vary by hazard, as defined by a parameter called bushfire attack level. Sample requirements for relatively low hazard include:

- The bottom 400 mm of walls must be non-combustible or fire-resistant.
- Windows can be fitted with non-combustible shutters, fine (< 2 mm) metal mesh screens, be made of safety glass, or be at least 400 mm above the bottom of the wall.
- Exit doors can be protected by shutters, fine metal mesh screens, or be made of non-combustible material or fire-resistant timber. Garage doors have similar requirements.
- Deck material must be non-combustible or fire-resistant timber if it is near windows (300 mm to 400 mm, depending on direction).

Requirements grow stricter at higher bushfire attack levels.

Intini et al. (2017) review WUI design standards and guidelines, along with construction, hazard, fire protection, and other issues, for Canada, California and the United States, Australia, New Zealand, Europe, France, and Italy. They do not address the quantification of benefits or costs.

2.3 Retrofit and new design costs, benefits, and benefit-cost analysis

The Multi-Hazard Mitigation Council (2019) presents benefit-cost analyses of compliance with the 2015 International Wildland-Urban Interface Code, both for new construction and for retrofitting existing buildings to comply with the code. It estimates retrofit costs as high as $70,000 and benefit-cost ratios that can exceed 4:1 in high-hazard areas for retrofit and over 6:1 in high-hazard areas for new design. It estimates the costs for vegetation management to be $150 per year.

The Institute for Catastrophic Loss Reduction (2019) explains to insurers the incremental costs of satisfying the recommendations of the National WUI Guide. It explains the features of a fire-resistant house, such as non-combustible roof, cladding, and doors, explains recommendations for structure ignition zones, and estimates the costs of satisfying the National WUI Guide to various degrees. The authors estimate that to retrofit an existing home to satisfy the National WUI Guide would cost up to $15,000.

Hanscombe Ltd. and the Institute for Catastrophic Loss Reduction (2019) offer a cost-estimation spreadsheet tailored to various changes to make houses more resistant to wildfire.

RSMeans (2019a, b, and c) offers costs for residential, commercial, and industrial construction, including square foot costs for several categories of residential buildings, plus costs by RSMeans components, ASTM UNIFORMAT II assembly, and the classification system. RSMeans (2019d) provides costs for residential repair and remodelling tasks, such as demolishing and replacing exterior siding, replacing windows and doors, and other tasks likely to be relevant to retrofit existing dwellings. All four documents include location adjustment factors to account for costs in Canada.

Headwaters Economics (2018), in partnership with the Insurance Institute for Business and Home Safety (IBHS), finds that a new home can be built to wildfire-resistant codes for approximately the same cost as a typical home. The authors estimate the typical construction cost of a three-bedroom, single-storey, 2,500-square foot single-family dwelling in Park County, Montana, and then estimate the cost with wildfire-resistant detailing. They estimate the total construction cost to be $525,000, of which approximately $120,000 comprises the roof, exterior walls, deck, and managing the structure ignition zone. Note that some elements of the non-compliant version differ significantly from some common Canadian construction, especially the use of cedar plank siding. Substituting fibre cement cladding for cedar plank siding saves an estimated $26,000. If typical construction starts with less expensive cladding, such as vinyl, the wildfire-resistant house would be somewhat more expensive than the typical one by about $10 per square foot. Flavelle (2018) summarizes the same study.

The Multi-Hazard Mitigation Council (2005) offers an example of nationwide benefit-cost analysis for several natural hazards (flood, hurricane, and earthquake), mostly for physical changes to existing buildings, utilities, and transportation infrastructure, and Li and Kovacs (2020) provide a recent review of benefit-cost analysis for natural hazards. The US Federal Emergency Management Agency (2009) offers a benefit-cost analysis toolkit that automates many aspects of benefit-cost analysis, including wildland-urban interface fires. For general methods of engineering economics, including benefit-cost analysis, see Newnan et al. (2006) and similar textbooks.

2.4 House and community data

Statistics Canada provides a variety of relevant data, two of which are the average household size and definitions of small, medium, and large population centres. Statistics Canada (2020a) reports the average household size at 2.4 people. Statistics Canada (2012) groups population centres by size: small (1,000 to 29,999 residents), medium (30,000 to 99,999), and large (100,000 or larger).

Zillow.com provides real estate market information about houses for sale and rent, usually including many of the following details: location, asking price, past sales prices, number of bedrooms, number of bathrooms, square footage, year built, heating and cooling methods, parking availability, a general text description, and photographs.

Statistics Canada (2016) provides a variety of information about Canadian housing. For example, its data product table 98-400-X2016222 provides estimates of the quantity of housing units by geographic aggregation, era of construction, type of dwelling, and type of occupant. For example, it shows that, as of 2016, 75% of single detached houses were built after 1945, the average single detached house in Canada was built in 1975, and 25% were built after 1995.

2.5 WUI hazard

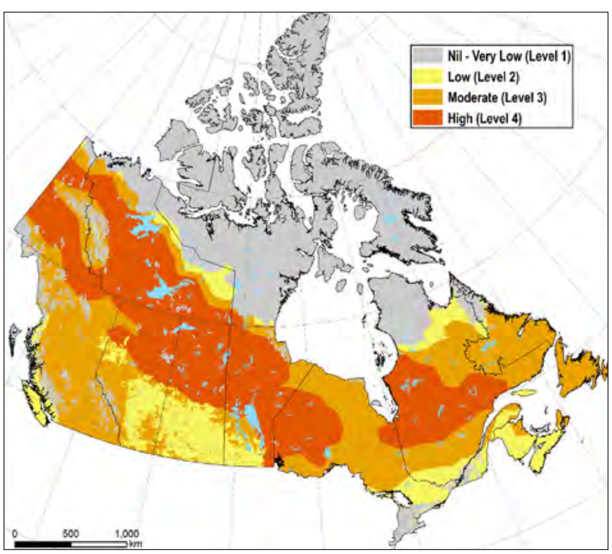
Johnston (2016) found that “Canada has 32.3 million hectares (ha) of WUI (3.8% of total national land area), 10.5 million ha of wildland-industrial interface (1.2%), and 109.8 million ha of infrastructure interface (13.0%) ... 60% of all cities, towns, settlements, and reservations across Canada were found to have a significant amount of WUI (defined as those with more than 500 ha of WUI within a 5 km radius ...) and therefore may have the potential for interface fire issues.”

Johnston and Flannigan (2018) offer what they consider to be the first national map of the wildland-urban interface in Canada. They use a map of actual structure locations (as opposed to census data) from Natural Resources Canada, rasterizing the data to 30-metre pixels. They map wildland fuels in terms of difficulty of suppression and spatial connectivity from another Natural Resources Canada dataset. They define the interface as the “area of wildland fuels surrounding any potentially vulnerable structure, i.e., a fuels-focused, not a structure-focused definition.” The authors believe that without building footprints, one cannot estimate “the number of homes or how much of the human population is living within interface areas….”

The National Research Council Canada's National WUI Guide (2020 draft) provides a map of historical wildfire hazard: its Figure 6 is reproduced here in Figure 6A. The map offers four hazard levels: 1) nil to very low, 2) low, 3) moderate, or 4) high. Erni et al. (2020) offer corresponding maps of burn rates. S. Taylor (Canadian Forest Service, written commun., October 7, 2020) explains the map origin and the quantitative meaning of the hazard levels:

> The map [in the National WUI Guide] is largely based on an as-yet unpublished map of national burn probability that is the major outcome of a project we had funded through the Canadian Safety and Security Program. It is the outcome of a fire simulation process. Fuels, topography, and probability of ignition are defined at a 250-metre scale across Canada. Millions, tens of millions of fires are simulated where daily weather is drawn from a historical distribution, in a Monte Carlo process. The burn probability is the empirical frequency that a cell is burned in usually more than 10,000 simulated fire years. This is very similar to the use of the FSim model to map hazard in the US … At the end of the day, the burn probability value aims to be an estimate of the annual probability of a 250-metre cell burning. There is at least a 10-fold difference in burn probability between different regions.
>
> For the purposes of this guideline, we upscaled the 250-metre resolution map to 10 km. The classes are some modification of quartiles. The low, medium, and high map classes are nominally > 7600-, 450–7600- and < 450-year fire return intervals, which we define here as the inverse of annual burn probability… The prairies and the developed portion of southern Ontario were not included in the simulation because they have very low historical fire incidence. There are very sharp transitions in fire occurrence in some parts of Canada, particularly [British Columbia], that are not captured in the modelling process. Thus, we assigned Queen Charlotte Islands/Haida Gwaii, Prince Edward Island, the very outer coast of [British Columbia] in the so-called fog zone, and agricultural land to the nil/very low class, and natural grasslands (surrounded by farmland) in the prairies to low.

Later, Taylor (written commun., February 12, 2021) advised that median annual burn probabilities are as follows: median annual low hazard burn probability is 0.0068%, moderate is 0.086%, and high is 0.61%.



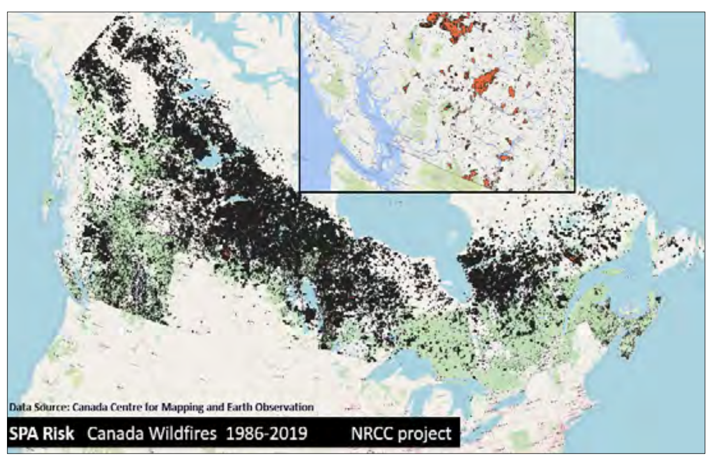


Figure 6. (A) *Wildfire hazard mapped from spatial burn probability outputs based on wildfire growth simulations driven by historical weather and wildfire locations.* **(B)** *Canadian wildfires 1986–2019.*

Natural Resources Canada (ND) offers the Canadian National Fire Database (CNFDB), a database of wildfire perimeters compiled from provinces, territories, and Parks Canada.

Canada Wildfire (2020) offers a variety of potentially useful data and tools. Among these are Burn-P3, a "spatial fire simulation model that is used for land-management planning and wildland fire research." It simulates fire ignition and spread, accounting for fuel, topography, weather, and ignition patterns, as well as estimates fire probabilities.

Gaur et al. (2021) project changes in wildfires near 11 Canadian cities associated with 2 °C to 3.5 °C of global warming. The authors estimate the fire season lengthening by two to eight weeks relative to the period 1989 to 2019. They also find statistically significant evidence of more frequent weather conducive for wildfires around the cities and more intense wildfires near all the cities.

Wotten et al. (2005) estimate that in Ontario "overall, the total amount of fire activity in Ontario's fire management area is expected to increase 15% by 2040 and 50% by 2100." Wotton et al. (2010) estimate a nationwide increase in fire occurrence of 25% by 2030 and 75% by the end of the 21st century.

It is sometimes valuable to know the proportion of WUI fires that originate within houses. The Canadian Forest Service (2013) represents one of several potentially useful geographic datasets of Canadian fire history. Its Large Fire Database fire point dataset distinguishes between lightning and human ignition sources. Among 11,231 large fires from 1959 to 1999, lightning caused about 72%, people caused 25%, and unknown causes account for the rest.

Prestemon et al. (2013) offer statistics about ignition sources of US wildfires with more categories. They tabulate ignitions between 2000 and 2008 on US Forest Service land. Fires that begin inside buildings do not appear among the top eight causes. (Sources representing at least 5% are, in decreasing order, lightning, campfires, arson, and burning debris.) Keeley and Syphard (2018) report statistics from CAL FIRE for the ignitions within CAL FIRE's jurisdiction (generally unincorporated portions of California) from 1919 to 2016. Fires that begin within houses do not appear among the top 11 ignition sources. (Sources representing at least 5% are, in decreasing order, equipment [26%], arson [13%], debris [13%], smoking [11%], vehicles [10%], playing [9%], and lumber [6%].)

2.6 WUI fire vulnerability models

The vulnerability of buildings to fire damage is commonly referred to as a response function. Data already presented in Section 2.1 provide crucial information for estimating the vulnerability of buildings to wildfire damage. This section supplements those resources with a few other references.

Cohen (1995) offers a Structure Ignition Assessment Model (SIAM) that describes the time to ignite buildings through their windows as a function of the number of panes in windows, glass type, and distance from burning vegetation. Later development of SIAM (Cohen 1999) added a model of the time to ignite wood cladding versus flame distance and radiant heat flux.

The Federal Emergency Management Agency's (2003) benefit-cost analysis toolkit for WUI fires offers general principles of benefit-cost analysis, but it is of limited use for the present project. It does not offer guidance on how to quantify the replacement cost of a house or how to parameterize its fire-resistive features. It offers no data on the probability that a house ignites when it is within or near a wildfire, nor of the degree of damage or loss if the house does ignite.

Caton et al. (2017) discuss experimental and fire-experience evidence quantifying fundamental exposure conditions contributing to ignition and fire spread, especially firebrand production, dimensions, mass, temperature, and fuel bed ignition. They also provide various historical fire statistics for the United States.

Hakes et al. (2017) complement Caton et al.'s review by quantifying the response of various building components and systems such as roofing, gutters, eaves, vents, siding, windows, glazing, decks, porches, patios, fences, mulches, and debris. The data may ultimately contribute to a future physics-based model of fire transmission, damage, and property loss.

Manzello (2014) describes an experimental program by the US National Institute of Standards and Technology to understand structure vulnerabilities to wind-driven firebrand showers in wildland-urban interface fires. It does not offer quantitative relationships between attributes of the WUI fire and ignition probability or degree of damage.

2.7 Deaths, non-fatal injuries, and post-traumatic stress disorder

Ahrens and Evarts (2020) summarize fire death statistics in the United States in 2019. Their Table 1 shows that the US experienced 264,500 fires in one- and two-family homes, including manufactured homes, resulting in 2,390 civilian deaths and 8,800 non-fatal civil injuries, meaning 0.0090 deaths per house fire and 0.0333 non-fatal injuries per house fire.

CAL FIRE data suggest lower fatality rates in WUI fires. In California's 20 most destructive wildfires, 207 people died and 51,745 structures were destroyed, suggesting a fatality rate of 0.0040 deaths per destroyed structure. Since destroyed structures represent about 93% of building ignitions, the fatality rate equates with about 0.0037 deaths per ignition. If non-fatal injuries occur in proportion to deaths, these data suggest 0.0138 non-fatal injuries per ignition.

There is some uncertainty about fatality numbers, however. Von Kaenel (2020) suggests that the Camp Fire killed about 140 people, rather than the official tally of 85 (CAL FIRE 2019), and the number may be even higher. Survivors claim that many people died after the fire because of respiratory conditions, stress, and other problems that are hard to directly causally connect to the fire. Prime Clerk (2020) provides a database of claims against Pacific Gas and Electric Company (PG&E) resulting from the Camp Fire (among others). It includes approximately 270 unique names of people in wrongful death claims. Using 140 to 270 deaths as the likely range of actual deaths and 14,343 housing units damaged or destroyed, the fatality rate appears to range between 0.0098 and 0.019 deaths per ignition, or approximately one to two times the nationwide average from all structure fires suggested by Ahrens and Evarts (2020).

Prime Clerk's (2020) database lists approximately 28,475 personal injury claims against PG&E resulting from the Camp Fire, judging each unique address associated with a personal injury claim from the Camp Fire as one injury. Approximately 52,000 people were evacuated because of the Camp Fire, so 28,000 injuries seem implausible, especially since most of the claimant addresses are in Butte County, as opposed to people in distant downwind counties who might have suffered respiratory problems because of smoke. Still, even if only 10% of injury claims were legitimate, the implication is that WUI fire injuries outnumber deaths by 10 to 1, as opposed to 3 to 1 as suggested by Ahrens and Evarts (2020).

Regardless of the fraction of personal injury claims that are legitimate, the actual cost to PG&E may average over $52,000 per claim (Personal Injury San Diego 2020; median, factored by 1.35 for inflation and 1.25 for currency exchange). With 100 times as many personal injuries as wrongful death claims, the implication is that PG&E may ultimately pay $1.5 billion for 28,000 personal injury claims because of 14,343 housing units damaged or destroyed, or two personal injury claims and $105,000 in personal injury payments per housing-unit ignition. The figure of $1.5 billion represents about 9% of PG&E's total $20 billion budgeted for its fire victim trust fund for victims of the 2015 Butte, 2017 North Bay, and 2018 Camp Fires, of which the Camp Fire represents 63% of total claims.

The *Chico Enterprise-Record* (2018) used data provided by Butte County to map the locations where 53 positively identified victims of the Camp Fire died. Of the 53 victims, 32 died inside a residence, 11 outside a residence, eight in vehicles, one under a vehicle and one at a Sacramento hospital. All but the last death occurred inside the fire perimeter, suggesting that they died because they failed to evacuate. The Butte County Sheriff's Office provided a large, but still partial, list of 84 Camp Fire deaths (Brekke 2019). The victims' ages seem noteworthy. None were younger than 20 years old, six were aged 20 to 49, and six were aged 50 to 59. The median age of victims was 72, about twice the median age of Butte County residents. Butte County Social Services attributes many of the deaths to the speed of the fire, residents' ages, demographics, disabilities (residents tend to have a higher chance of having one or more disabilities), and possibly inadequate communication planning and implementation (Bizjak et al. 2019).

The Multi-Hazard Mitigation Council (2019) uses the number of severe non-fatal injuries as a proxy for the instances of post-traumatic stress disorder (PTSD), drawing on Sutley et al. (2017a, b). The Multi-Hazard Mitigation Council (2019) also suggests the following acceptable costs: $13,000,000 to avoid statistical deaths, $5,100,000 for injuries, and $125,000 for instances of post-traumatic stress. These values are taken from the Multi-Hazard Mitigation Council (2019, Table 4-35), inflated at 2% per year and converted to Canadian dollars with a 1.25 CAD/USD currency conversion factor.

Matz et al. (2020) examine health impacts from fire particulate matter in Canada's wildfire smoke from 2013 to 2018. They estimate annual premature mortalities of approximately 100 deaths attributable to short-term exposure and 1,000 deaths attributable to long-term exposure, as well as many non-fatal cardiorespiratory health outcomes. They do not attempt to distinguish the effects of fine particulates from burning vegetation versus those produced by burning houses. It seems likely that the houses account for less than 1% of the particulates, possibly 0.1% or less. This is important because the National WUI Guide would probably affect the amount of fine particulates produced by burning houses, but not by burning vegetation.

2.8 Additional living expenses and business interruption losses

Insurers commonly estimate the value of additional living expenses for fire insurance of homes to be 10% of the building replacement cost. Alternatively, the Multi-Hazard Mitigation Council (2019) estimates the cost of additional living expenses to be approximately $110 per household per day. The two values agree if a household in a house with a $500,000 replacement cost is displaced for 12 to 18 months, which seems plausible. Indirect business interruption was taken as $0.47 per $1.00 of direct time-element loss, i.e., $52 per household per day.

2.9 Insurance savings

The Multi-Hazard Mitigation Council (2019, p. 300) divides insurance premiums into two parts: pure premium (the expected value of losses per year), and overhead and profit, which in the United States is about 42% of pure premium. In that work, the authors assume that insurance premiums eventually adjust to reflect the true risk, perhaps under regulatory pressure. Thus, when one undertakes a mitigation measure, the pure premium drops in proportion to the savings from the mitigation measure cost. The authors also assume that regulatory pressure causes overhead and profit to similarly adjust, remaining at the same multiple of pure premium.

2.10 Wildfires and job impacts

Stinchcomb (2018) quantifies the impact of the 2017 Tubbs and Thomas fires in California on job postings and, by extension, employment in their respective regions. He finds no apparent impact of the Thomas Fire on employment, attributing the lack of effect on the diverse economy and the fire's greater damage to residential neighbourhoods. However, he sees a significant decline in job postings after the Tubbs Fire and blames the dip on damage to wineries, the region's economic focus. He does not appear to believe that one can predict job impacts before a disaster, although by using job postings, "one can gain some insight in real-time, even as the event is occurring, on what kind of impact the event may have on a local economy by seeing the immediate impact on job postings volume."

The Bureau of Labor Statistics (2020) examines the 12-month change in employment near the 2017 Tubbs Fire and 2018 Camp Fire. The authors find that "while the fires destroyed infrastructure and dwellings and spread smoke and ash throughout the region, local employment quickly recovered following both of the fires. One year after each fire, construction employment had increased and has remained at higher levels as the rebuilding continues in Sonoma, Napa, and Butte counties." However, the construction job gains were temporary, with construction employment returning to pre-fire levels after a year and no strong signal in total employment apparent after either fire.

Despite the lack of a signal in the local construction industry from these three fires, the National WUI Guide may create long-term jobs in the domestic construction industry as buildings are retrofitted. Approximately half of the retrofit cost is spent on labour and half on materials. Labour costs construction contractors approximately $50 to $75 per labour hour. Thus, every $1 million per year spent on retrofitting involves spending $500,000 on labour, which is equal to 8,000 labour hours, or four full-time equivalent jobs. Part of the material costs could also generate jobs, to the extent that tempered glass and non-combustible siding and decking are manufactured in Canada.

2.11 Wildfires and environmental harm

McNamee et al. (2020) review the state of knowledge about the environmental impact of fires for the National Fire Protection Association (NFPA). Most fires occurring in the built environment "contribute to air contamination from the fire plume, contamination from water runoff containing toxic products, and other environmental discharges or releases from burned materials." The authors find, "With respect to the cost of environmental impact resulting specifically from fire, the literature is sparse."

McNamee et al. (2020) point to a study by NIST's Applied Economics Office Engineering Laboratory (Thomas et al. 2017) that attempts to quantify the costs and losses of wildfires. Thomas et al. (2017) recap literature on the economic losses associated with wildfire environmental impacts but offer no insight into environmental losses specifically associated with burned buildings.

Andersson et al. (2004) suggest one approach to estimating the environmental costs of building fires, with a catalogue of the mass of six burnable materials in an average dwelling. Correcting for the relatively small size of their average dwelling, one can estimate that the average Canadian dwelling contains about 12 tons of wood, paper, textiles, polyvinyl chloride, polyurethane, and polyethylene, with wood, paper, and textiles dominating. Burning a ton of wood or paper produces about 0.75 tons of CO_2. Holder et al. (2020) offer quantities of 21 categories of toxic emissions from WUI fires. But it is not clear how to assign a monetary value to the environmental cost of each ton of these products burned and deposited elsewhere by the plume or runoff.

Wang et al. (1994) suggest two methods: 1) value the pollutants by the monetary value of their health impacts (the "damage method") or 2) value the costs to control them under emissions standards (the "cost method"). The cost method seems practical, but it involves an important assumption about revealed preferences. It assumes that emissions standards are ideal, meaning they are set so that the marginal damage of air pollution just equals the marginal control cost. The authors use their methods to assign economic values to five classes of pollutants in dollars per ton. The costs generally range from \$6,000 to \$30,000 per ton. None of the pollutants map clearly to the materials in the Andersson et al. (2004) catalogue, and none of them were CO_2, the principal pollutant from burning paper and wood. The Environmental Defense Fund (2020) estimates the true social cost of carbon between \$75 and \$200 per ton of CO_2.

In a recent development related to wildfires and environmental harm, Proctor et al. (2020) and San Lorenzo Valley Water District (2020) report volatile organic compound contamination in water distribution systems following three California wildfires. The latter found benzene concentrations three times the state's health-based maximum contaminant level. The authors speculate that the wildfires heated plastic pipes, which released the contaminants. Isaacson et al. (2020) conducted tests that support the hypothesis: 10 out of 11 pipe materials, when heated to between 300 °F and 400 °F, leached various volatile organic compounds into the water. One could apply the cost method that Wang et al. (1994) suggest, since water agencies can estimate the cost to clean up contaminants in a burned distribution system. But to contaminate the water supply, the distribution pipes, rather than lateral service connections to the houses, must produce the contaminants. Making houses less vulnerable to wildfire would reduce water contamination only insofar as doing so reduces the temperature or extent of the fire in city streets. Burned houses contribute little, if any, to the environmental cost of water supply contamination by volatile organic compounds.

2.12 Community costs for planning and resources

Maranghides et al. (2015) provide an event timeline and review of firefighting actions in response to the 2012 Waldo Canyon Fire near Colorado Springs, Colorado. Among several dozen findings that are relevant here, the authors find that "pre-fire planning is essential to enabling safe, effective, and rapid deployment of firefighting resources in WUI fires. Effective pre-fire planning demands a better understanding of exposure and vulnerabilities. This is necessary because of the very rapid development of WUI fires." Maranghides et al. (2015) mention several kinds of plans and other resources:

- Mapping: "Mapping of hazards within and around a community, together with preplanning for rapid and targeted deployment [of firefighters] within the community"
- Standard operating procedures: address "staging of resources and the identification and prioritization of hazards"
- Exercises: rehearsed deployment with mutual aid providers
- Ground apparatus and personnel: "Engines, rush trucks, hot shot crews, etc."
- Aerial fire suppression resources: aircraft and personnel
- Water distribution
- Handheld radios with additional batteries
- Situational awareness: "Data to enhance situational awareness assessment"

Planning. Many of these cost items are related to planning. It may be useful to know how much one full-time equivalent planner costs. In Canada, the US, and Mexico, the North American Industry Classification System (NAICS) sector 541320 (landscape architectural services) comprises establishments primarily engaged in planning and designing the development of land areas for projects, including subdivisions and public buildings (Classcodes.com 2017, p. 466). In Canada, planners and urban planners earn approximately $86,000 per year (Brasuell 2016, Neuvoo 2021a). In Canada, 12,655 planners are employed, which equals 0.068% of 18.5 million employees and 0.034% of the population (Statistics Canada 2019).

Access and egress routes. The National WUI Guide specifies recommendations for access and egress routes by referring to NFPA 1141 (National Fire Protection Association 2017). That standard specifies the number of access routes and a multitude of road design features, including a hard surface finish (paving), road widths, curvature, clearances, slope, sight distances, and accessories such as speed bumps and traffic calming devices. The present work cannot attempt to quantify all these costs even for a single community. We can, however, provide information about some of the likely leading cost items.

Paving unpaved roads. For some rural communities, the leading cost item for access routes may be hard, all-weather surface paving. The cost for asphalt concrete pavement on top of the roadbed adds about $444,000 per mile of undivided two-lane rural road. That figure is about 15% of the total construction cost of $2.5 million to $4 million per mile for a paved two-lane rural road (Florida Department of Transportation 2020). That paving figure is somewhat lower than RSMeans (2019e, p. 310), which estimates the cost to add an asphalt 2.5-inch wearing course at $18 per square yard, or $250,000 per mile of undivided two-lane road that is 24 feet wide. A community might opt to add curbs, gutters, and sidewalks. Curbs and gutters add about $12.50 per linear foot, or about $132,000 per mile for both sides (RSMeans 2019e, p. 318). Cast-in-place four-foot sidewalks with wire mesh reinforcement on both sides add $275,000, bringing the total to pave existing unpaved road and to add curbs, gutters, and sidewalks to $660,000 per mile. Hereafter, only the $250,000 per mile paving costs (without curb, gutter, and sidewalk) are used to estimate community costs of following the National WUI Guide's recommendations for paving. The project team performed a small sample of communities with unpaved roads and found lots averaging 200 feet wide, suggesting about 50 households per mile of unpaved road, equating with a paving cost on the order of $5,000 per household on unpaved roads.

Access routes. The Altus Group (2018, p. 12) estimates the cost of a new, eight-metre wide local road at $2,600 to $3,900 per metre, or $5.2 million per mile, at the high end of the $3 million to $5 million estimate from the Florida Department of Transportation (2020). The cost to add a paved 500-foot access route is, therefore, about $500,000 using the Altus Group figure.

Bridges. Another leading cost item for rural communities may be bridges sufficient to carry firefighting apparatus. An average pumper weighs about 35,000 pounds and can carry 15,000 pounds of water (Fire Apparatus Manufacturers Association 2018), a live load that may exceed the capacity of older roadway bridges. To build a low-volume creek crossing costs about $2,600 per square metre (British Columbia Ministry of Transportation and Infrastructure 2012), or about $200,000 for a two-lane bridge spanning about nine metres. However, in a brief search of Google Earth Street View images of several bridges near sample houses, we found no bridge capacity postings.

Water distribution. The National WUI Guide recommends water supply by referring to NFPA 1141 (National Fire Protection Association 2017). Communities that rely on wells for drinking water could have insufficient flow for firefighting purposes. The largest cost item in a water supply system tends to be the distribution network: the system of six-inch buried pipelines and hydrants that cost approximately $1 to $2 million per mile (Zhao and Rajani 2002), including hydrants and service connections. With rural households spaced on either side of a road and 200-foot wide lots, a new water supply system can cost $30,000 per household. Water mains tend to last about 100 years before requiring replacement (Ductile Iron Pipe Research Association 2021).

Power lines, poles, and vegetation management. The Multi-Hazard Mitigation Council (2019, p. 410) studied two projects to underground high-voltage electric transmission lines along a mostly rural alignment: 5.25 miles of 46 kV transmission line and 26 miles of 34.5 kV, at a total cost of $4.6 million, or $150,000 per mile. In research for Edison Electric Institute, Hall (2013 p. 32) estimates that converting electric distribution lines to underground costs between $500,000 and $2.2 million per mile. At about 20 to 25 households per mile of electric transmission and distribution line (Weeks 2010), converting to underground distribution costs at least $30,000 per household. Replacing wooden overhead poles with steel costs $2,500 to $5,000 in British Columbia (Wilson 2019), about the same as in Colorado (Colorado Springs Utilities 2020) and average for North America (RSMeans 2019e, p. 404). BC Hydro has about 900,000 wooden power poles (Wilson 2019), 1.8 million customers (1.65 million residential), and 58,000 km of distribution lines (BC Hydro 2010), suggesting about 25 poles per mile, costing $93,000 per mile and 0.5 poles per household. The Utility Partners of America (2020) estimate there are about 170 million wooden utility poles in the United States, or about 1.5 poles per household. Thus, replacing wooden poles with non-combustible ones costs between $2,000 and $6,000 per household. Haller and Smith (2006) describe methods used by three utilities to control vegetation around power lines with a combination of tree trimming and herbicides at an annual cost of about $3,000 per mile, or $60 per household per year.

Firefighter response planning and resources. Fire service also adds to the cost of fire protection and planning. The National Fire Protection Association (Zhuang et al. 2017) estimates that in 2014, the United States spent about $135 billion on fire services, or about $1,000 per household per year, about half of which was directly spent on professional firefighters, and the other half representing the value of volunteer firefighters. Canada employs about 145,000 career and volunteer firefighters (25,000 and 120,000, respectively). Career firefighters earn approximately $90,000 per year (Living in Canada ND), and the average fire chief earns $126,000 per year (Neuvoo 2021b).

Public education. As described elsewhere in this chapter, a growing body of literature intended for the public explains the nature of the wildland-urban interface, its fire risk, and the nature of fire-resistant construction. However, public education also involves efforts to make the public aware of that literature and perhaps to better understand what to expect in an emergency. After the Waldo Canyon Fire near Colorado Springs, Colorado, the Colorado Springs Fire Department began a stewardship program with its 112 homeowner associations. They prepared and distributed "packets with information on tax benefits, tree service providers, evacuation planning, emergency planning, and outdoor burning. Everything a homeowner would have a question about is in that packet." They "raffle off an evacuation kit to get them thinking about what [homeowners] should put into their kits" (Markley 2017).

Emergency communication resources. Canadian emergency managers can use the National Public Alerting System (Public Safety Canada 2020), Wireless Public Alerting Service (Government of Canada 2016), social media platforms such as Twitter and Facebook, and perhaps other communication systems. People also rely on each other for information, as was evident in the Camp Fire (Sabalow et al. 2018), Waldo Canyon Fire (Markley 2017), and others, where people were contacted by neighbours, friends, and family.

2.13 Cultural and other intangible non-monetary issues

The present analysis focuses on quantifying tangible benefits at the house, community, and national levels, especially monetary costs, casualties, and, to a limited extent, environmental impacts. But disasters affect different populations differently, partly because infrastructure improvements differ by economic and other demographic status, partly because people's ability to withstand a disaster differs under the same stress from infrastructure impacts, and partly because cultural factors matter regardless of infrastructure and vulnerability status.

While the present study does not address these issues in serious depth, it seems worthwhile to at least mention some of the literature that shows how they might matter and to a limited extent how they can be treated.

Davis et al. (2012) recommends treating the issue by combining medical and functional methods. Under such a paired approach, one identifies high-risk, high-vulnerability populations, accounts for how overlapping population characteristics may increase or decrease the vulnerability of an individual in a disaster, considers the effects of stakeholder involvement, and identifies systemic levels where medical intervention can reduce vulnerability.

Fire has important cultural significance for Indigenous people. FireSmart Canada (2020, p. 8) distinguishes between good and bad fires. Good fires have various long-term benefits, “with limited negative effects on livelihoods and communities… [while] bad fires are unwanted, out-of-control fires that can threaten lives, livelihoods, and damage properties or communities.” As far as the project team can tell, the present work only relates to the costs and benefits of preventing or mitigating the effects of bad fires.

The project team is aware only of highly approximate methods to quantify cultural benefits. For example, the Multi-Hazard Mitigation Council (2005 and 2019) attempts to express cultural benefits that result from preventing damage to museums and historical buildings via visitor revenue. The money that people spend to visit a museum, cultural institution, or historical site crudely estimates the monetary value that society places on the building, the institution, cultural artifacts, or cultural practices enacted at the site.

2.14 General statistical methods

Ang and Tang (1975), Benjamin and Cornell (1970), and other standard textbooks on probability and statistics offer general guidance on sampling, stratified samples, and the theorem of total probability. Law and Kelton (1991) and similar textbooks offer guidance on validating models of real-world systems.

2.15 Housing affordability

The National Association of Home Builders (Zhao 2020) estimates that “a $1,000 [USD, or $1,250 CAD] increase in the median new home price ($344,652) would price 158,857 US households out of the market. In other words, 158,857 households would qualify for the new home mortgage before the change, but not afterwards.” For scale, in 2020, there were 128.45 million households in the United States, so 159,000 households represent about 0.1% of households. A $1,000 increase represents about 0.3% of the price of a median new home.

Other market evidence might counterbalance Zhao’s findings. For example, Simmons and Kovacs (2017) find that a local wind safety ordinance enacted in Moore, Oklahoma, that raised construction costs by about 2% (six times the increment considered by Zhao) had “no effect on price per square foot, home sales, or new building permits” in that city in the three or so years after the ordinance was enacted.

2.16 Demand surge

Wildfires can destroy thousands of buildings at once – potentially representing years of construction by the local industry. Therefore, reconstruction after such catastrophes can place a sudden, extreme demand on the local construction industry, temporarily (for up to a few years) increasing costs; insurers tend to refer to the phenomenon as demand surge. Olsen and Porter (2011) trace demand surge primarily to increased wages as labourers demand higher wages. Material prices do not seem to play a role in demand surge, which agrees with the economic concept for commodities called the law of one price. The authors observed the upper bound in a single large disaster to be about a 50% increase in construction costs after Cyclone Larry in 2006, which destroyed most of the houses in an isolated Australian community. The remoteness of the catastrophe seems to have played a role in producing such a high level of demand surge. In more common situations, demand surge can reach about 20%, according to Olsen and Porter (2011, p. 8).

2.17 Exchange rate

Some cost data referred to here (e.g., RSMeans 2019a, b, c, d) are published in US dollars (USD) and must be converted to Canadian dollars (CAD) for use. The exchange rate between USD to CAD has fluctuated in the last 10 years between about $0.95 CAD per USD (September 2017) and $1.45 CAD per USD (March 2020). It seems reasonable to use the average over the last 10 years to project costs over the next 10 years, about $1.25 CAD/USD.

Figure 7. Exchange rate fluctuations March 2011 through March 2021

3. Methodology

3.1 General methodology

This study estimates the value of protecting homes in the wildland-urban interface (WUI). The WUI is defined as "an area where various structures, usually private homes, and other human developments meet or are intermingled with wildland (vegetative) fuels or can be impacted by the heat transfer mechanisms of a wildfire, including ember transport," according to the National Guide for Wildland-Urban Interface (WUI) Fires (National Research Council of Canada 2020 draft).

The project team applies an engineering approach to estimate the benefits and costs of the National WUI Guide. An engineering approach means applying engineering principles to estimate the future probabilistic fire performance of idealized models of real buildings. Briefly, the analysis proceeds as follows and as illustrated in Figure 8. Details are presented below, under principal tasks.

1. **Define the assets at risk**. We collect a stratified sample of important attributes of the assets (i.e., homes) to be analyzed: square footage, number of storeys, cladding material, roof material, etc. Average or median values of the attributes are used to define idealized models, referred to here as archetypes. Several archetypes are used here, both under as-is and what-if conditions (i.e., homes that partially or fully follow the National WUI Guide recommendations). We select one or more sample geographic locations at which to perform the analysis, such as a characteristic geographical location for each of several hazard levels (which here means burn rate – the frequency with which fires occur at a specific location, as qualitatively shown in Figure 6 and quantitatively in Erni et al. 2020). We use construction cost estimation principles to estimate the replacement cost (new) of each archetype, or in the case of retrofit, the cost to perform the retrofit. These are exemplified by applying RSMeans' square foot, assemblies, and construction cost manuals, as opposed to other real estate valuation techniques, such as sales comparisons.

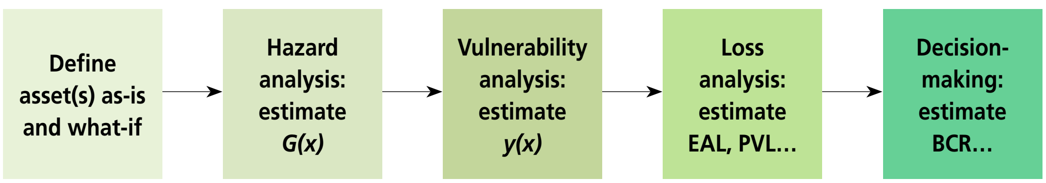
2. **Hazard analysis**. We estimate the frequency with which fires occur at each sample geographical location. This is generally performed by empirically analyzing past fire occurrence rates, possibly enhanced by projection into the future to account for climate change. One can analyze fire footprints from the past 30 years to calculate the historical probability that any given location will experience a WUI fire in a one-year period. Alternatively, one can select sample communities in each mapped hazard level and take their burn probabilities from an authoritative resource such as Erni et al. (2020). In Figure 8, x denotes the binary variable that a fire occurs at the sample location and $G(x)$ denotes the burn rate, meaning the average frequency with which a fire occurs at the location(s) of interest. (In other contexts, x can take on scalar values such as the degree of shaking in an earthquake.)

3. **Vulnerability analysis**. We estimate the vulnerability of each asset (as-is and what-if) to WUI fire, usually with a relationship called a response function. Both vulnerability and response function refer to a relationship between loss (e.g., repair cost) and degree of hazard, which here refers only to the occurrence of a fire at the sample location. Vulnerability estimation may be empirical (from past WUI fire experience or laboratory tests), analytical (using engineering first principles), and sometimes a hybrid of the two through applying engineering judgment. Vulnerability is estimated for each benefit category: building repair cost, content loss, life-safety impacts, etc. In Figure 8, $y(x)$ denotes the expected value of loss (e.g., building repair cost) as a fraction of value exposed, conditioned on the value of x.

4. **Loss analysis**. We integrate value, hazard, and vulnerability to estimate expected annualized loss (EAL in Figure 8) under as-is and what-if conditions. Then we calculate the present value of future losses (denoted by PVL in Figure 8) under as-is and what-if conditions. The difference between the two is taken as the benefit (B) of the mitigation measure, here meaning the application of the National WUI Guide. Benefits are aggregated from the level of per-house, per-benefit category to the house, community, and national levels, using estimated quantities of houses and people in each mapped hazard level.

5. **Decision-making**. We use the results of the asset analysis and loss analysis to present decision-making information in convenient, meaningful formats, such as benefit-cost ratios (BCR in Figure 8) by archetype, hazard level, community, and nation. One can also present other meaningful quantities, such as jobs created, number of houses lost per year, and number of avoided deaths, non-fatal injuries, and instances of PTSD.

Figure 8. General engineering approach to benefit-cost analysis



3.2 Select archetypes

This is a modest but pivotal task. Mischief and error creep into studies like this from relying solely on judgment or published sources such as RSMeans to select a single specimen to represent a class. The present project develops cost estimates of a new WUI-resilient home and costs to retrofit an existing home. Archetypes might differ for building new versus retrofitting an existing home.

Archetypes are selected as follows. A few sample communities are selected from each hazard level (e.g., as shown in Figure 6). Ideally the sample communities also span the country geographically (in Canada, at least east to west), and in community size according to some authoritative nomenclature. Within each community, one selects sample assets without regard to their size, location, or other attribute, other than requiring that they belong to the asset class in question, which here means single-family dwellings. One identifies attributes that are most likely to strongly influence cost, benefit, or both. In the present case, the project team collects the data listed in Table 2 for each house.

Table 2: Sample house data fields

Field	Example	Meaning
ID	1	A unique index
Community	Wells, MB	Community, province
Address	123 Main St	Street address
Storeys	2	Number of storeys above grade
Basement	0	Storeys below grade
Bd	4	Number of bedrooms
Ba	3	Number of bathrooms
Sq ft	2,184	Living area in square feet by real estate listing standards
Year built	2017	Year built
Year built est	FALSE	Is "year built" an estimate based on data collector's judgment of its architectural style?
Plan aspect ratio	1.3	Approximate ratio of longer plan dimension to shorter, for estimating exterior wall perimeter as a function of plan area
Exterior wall area	2,666	Exterior cladding area in square feet, estimated using sq ft, storeys, plan aspect ratio, and estimated storey height
Roof matl	Comp	Roof material
Roof matl est	FALSE	"Roof material" is an estimate from a photo
Ext wall cladding	Stone	Exterior wall cladding material
Ext wall cladding est	FALSE	Exterior wall cladding material is an estimate from a photo
Foundation and deck enclosed or treated	TRUE	Is the deck either enclosed or treated for fire resistance
Glazing surface area	0.3	Fraction of exterior wall area that is glazed
Homes in neighbourhood	< 100	Number of homes in the neighbourhood
Access routes	1	Number of access routes per Chapter 4
Enough access	TRUE	Do the number of access routes satisfy recommendations?
Access route length		If another access route were added, what would its shortest practical length in feet be?
Fuel 0–100 m	F3	Fuel type according to National WUI Guide Table 2, within 100 m of the sample building
Fuel 100–500 m		As above, but 100 m to 500 m from the sample building
Hazard	High	Hazard level according to Figure 6 in the National WUI Guide
Exposure	High	Exposure level according to simplified method of National WUI Guide Section 2.6.3.1
Paved	TRUE	Is the road in front of the sample house paved?
UG elec	FALSE	Is the electricity distribution system at the sample house underground?
Wood poles	TRUE	If the electricity distribution is on above-ground poles, are they made of wood?
> 5 m clear wires	FALSE	If electric distribution is on above-ground poles, is there at least 5 m clearance between the wires and vegetation?
Hydrants	FALSE	Are there fire hydrants within ~500 feet of the sample house?

One then groups the records by hazard level. Within each hazard level subset, one calculates median values of parameters that seem to matter most to cost and benefit, such as storeys, square footage, cladding material, and roof material. One then chooses a sample from each subset that comes close to the median attributes. That sample is then used as the archetype existing building for that hazard level.

To select an archetype to represent new buildings, one limits the samples in each hazard level to recently built houses, for example, built in the last 10 to 20 years. One calculates medians in these subsets and again selects a sample from the subset that comes closest to the median; that sample is used as the archetype for new houses in that hazard level.

The project team selects archetypes from real houses to avoid unnecessary recourse to judgment. Real houses offer some advantages over idealized ones with the desired same sample attributes. Real houses offer greater credibility: one can show photographs of them, imagine them more clearly, and estimate important quantities more defensibly. People can relate to images of a real, existing house and compare it to their own. While judgment can be used to check archetypes, an archetype cannot be reliably selected by judgment. The project team has seen more than one study deeply undermined by designing so-called index buildings using judgment or to take advantage of convenient pre-existing models. In one case, this approach resulted in costly experiments that were essentially representative of two-storey homes, while most homes that the study addressed were single storey.

In the present study, existing homes in high-hazard, moderate-hazard, and low-hazard areas may differ in size, height, and other important attributes because WUI hazard might correlate with other economic factors and regional preferences. And since home construction economics and architectural styles change over time, new houses may be larger than older ones.

The project team selects a stratified sample of 102 existing homes at random in the high, moderate, and low WUI hazard as defined in Figure 6 of the National WUI Guide. Here, "stratified" means 34 homes in each hazard stratum, deliberately selecting locations to include several samples from each province that have significant land area in the hazard stratum.

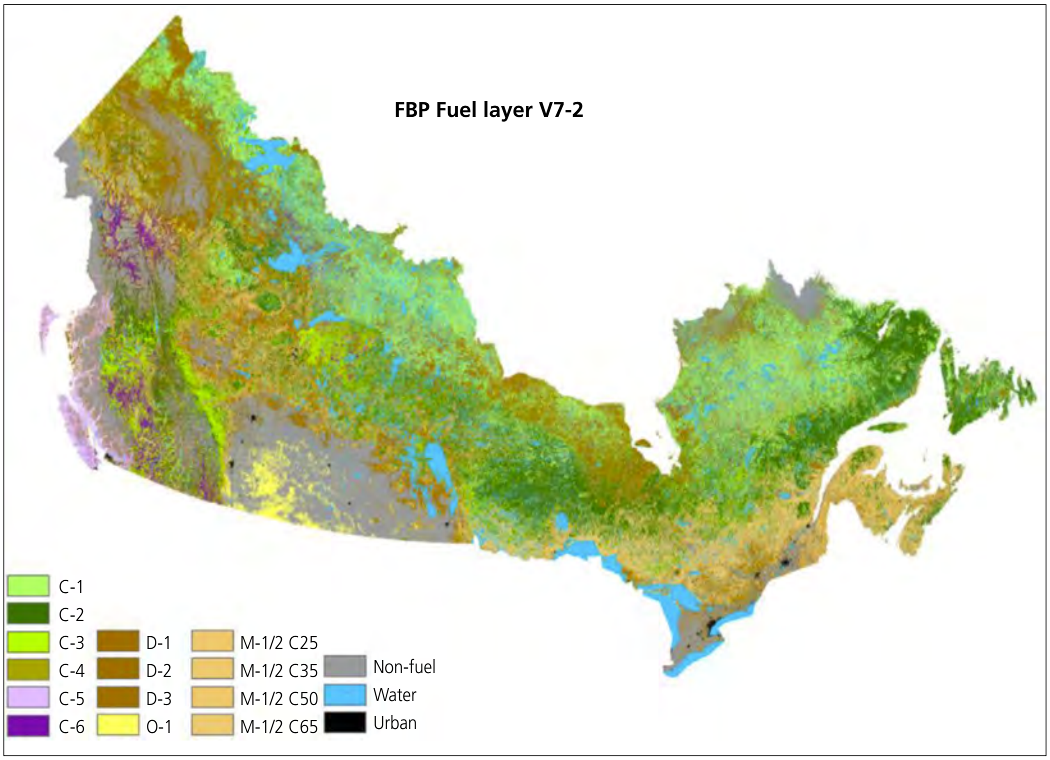
The project team estimates quantities for each house using Zillow.com (for most attributes) and Google Earth (for perimeter and footprint area). For example, an existing home for sale in Thunder Bay, Ontario (Figure 9), has the following attributes (not all attributes from Table 2 are shown here).

Note that this archetype selection process generally satisfies the principles proposed by the Canadian Home Builders' Association (2020), as detailed in Appendix A.

Figure 9. Example of an existing home in high WUI hazard

Location: (address omitted for owners' privacy)
Thunder Bay, ON
Year built: 1975 (est.)
WUI hazard level: High (National WUI Guide Figure 6)
Fuel type: F2 within 100 m (see Figure 10 for FBP system fuel type M1. Figure 4 and nearby images from Google Earth suggest at least 25% conifers. By the National WUI Guide Table 2, these attributes imply field type F2.)
Exposure level: Moderate (National WUI Guide Table 3)
Storeys: 1
Square footage (sq ft): 1,280
Bedrooms, baths: 3, 1
Exterior wall area (sq ft): 1,900 (est.)
Roof: Composition
Exterior cladding: Vinyl
Basement: No

Figure 10. Forest Fire Behaviour Prediction System (FBP) fuel types (National WUI Guide, Figure 16, after Beaudoin et al. 2014).



In some cases, some vulnerability attributes may not be visible at the house location. Zillow provides photos of sample houses, enough to observe most attributes of the house itself. One can observe the number of access routes from Google Earth satellite view. Google Earth Street View provides most or all of the other attributes (fuel type, paving, electricity, and hydrants). In some cases, Google Earth Street View is not available at the house address. In those cases, the project team observes the missing attributes from the nearest accessible location on Google Earth Street View. The nearest accessible location is usually less than a mile away, so fuel type is reasonably accurate. Paving may be observable from the nearest intersection, where one can see whether the street leading to the house is paved. Electricity and hydrant features at the nearest point are probably reasonable estimates of the conditions at the house, or possibly conservative, meaning that the farther one is from a place that is accessible from Google Earth Street View, the more likely that features like paving and vegetation control are to be poorer than at the point of observation. However, for present purposes – statistical estimates of houses in general rather than well-documented features of specific houses – the approximations used here seem reasonable.

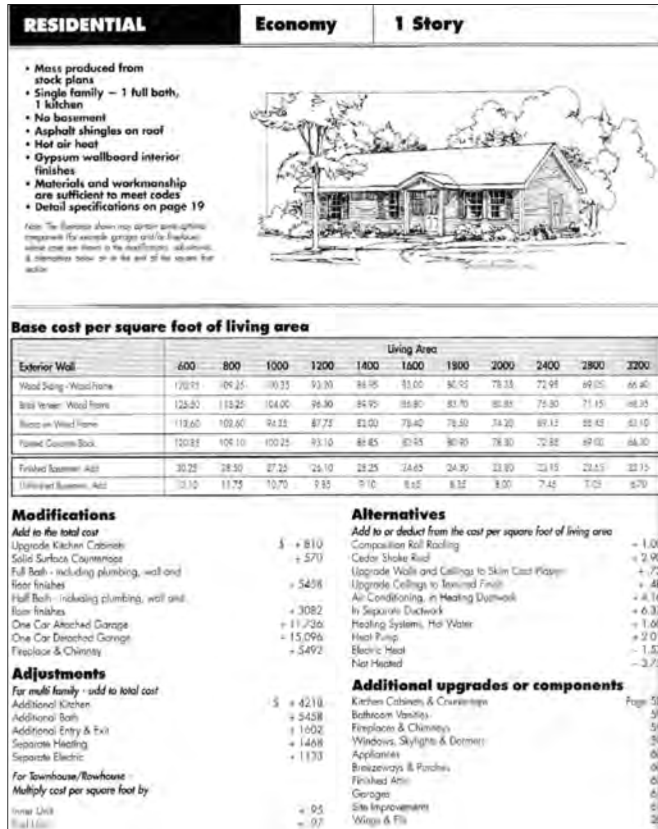
3.3 Compare costs of WUI mitigation for selected archetypes

The project team uses RSMeans data to estimate the following items:

1. The replacement cost (new) of the new home archetype
2. The change in replacement cost (new) of the same home designed to satisfy the National WUI Guide
3. Renovation cost of existing home archetype to fully satisfy the National WUI Guide
4. Renovation cost of existing home archetype to partially satisfy the National WUI Guide, ignoring modifications that seem impractical or not cost-effective

The project team estimates costs by selecting the most similar RSMeans square foot model and using RSMeans' location factor, modifications, adjustments, alternatives, and additional upgrades to refine the base cost. Costs for modifications to satisfy the National WUI Guide eventually call for reference to RSMeans' square foot cost data, assemblies cost data, repair and remodelling cost data, and several other resources.

Figure 11. RSMeans square foot costs data for new construction of a one-storey home



To illustrate items 1 and 2, the average attributes of the 34 new high-hazard houses resemble the sample house depicted in Figure 9. The closest RSMeans model would be the residential economy one-storey home shown in Figure 11.

The project team estimates the construction cost (new) under typical new construction practices using RSMeans (2019c) square foot costs for overall costs, e.g., as illustrated in Table 3. Figures in the table are purely illustrative.

Table 3. Method to estimate construction cost (new) of archetype houses

Item	Quantity
Base cost (1,100 sq ft main house)	$90
Wing (180 sq ft)	$130
Total (USD)	$122,400
Porch, economy, open (USD)	$7,100
Location factor (Thunder Bay, ON)	1.11
Currency (CAD/USD)	1.25
Construction cost new (CAD)	$180,000

The project team uses RSMeans assemblies and construction cost manuals (RSMeans 2019b and c) to estimate the change in construction cost to fully satisfy the National WUI Guide. Table 4 illustrates the method for an example building. Figures in the table are purely illustrative. Costs are compared with related prior work, e.g., Flavelle (2018).

Table 4. Method to estimate cost to satisfy the National WUI Guide for new construction

Item	Quantity
Fire-resistant roof covering (no change)	$0
Remove vinyl or T1-11 siding ($10.25/sq ft) x 1,900 sq ft	($19,475)
Front door birch solid core (no change)	$0
Sliding door aluminum (no change)	$0
Remove 8 windows vinyl dual-pane insulated glass 3 x 5–6	($5,250)
Remove pressure-treated DF deck 225 sq ft	($884)
Add HardiePlank siding $9.75/sq ft x 1,900 sq ft	$18,525
Add 8 windows steel dual-pane temp glass	$14,807
Add HardieDeck 225 sq ft	$2,750
Add 75-year maintenance of fuels, priority zones 1–3	$9,700
Location factor (already included)	1.0
Currency (CAD/USD)	1.25
Change in construction cost new (CAD)	$25,216 (illustrative only)

Quantities in red and parentheses are negative.

3.4 Extrapolate cost comparisons to other Canadian WUI areas

In principle, one could vary construction costs geographically by applying RSMeans' location factors. Doing so would probably produce only illusory accuracy, for at least two reasons. First, the variability between actual applications and the archetype houses probably swamps the location factor. Second, repair costs vary geographically as well, just like initial costs. If both benefits and costs scale by the same factor, the benefit-cost ratio remains constant.

3.5 Aggregate results at the community level

The project team estimates the hazard for a middle-sized community in each hazard level.

Using the average number of people per household estimates the number of archetype t houses by hazard level h in the sample community, represented by $N(h,t)$. Let $C(h,t)$ denote the estimated retrofit cost for that hazard level and archetype. The community cost to retrofit existing buildings to satisfy the National WUI Guide can be calculated as follows:

$$C = \Sigma_h \Sigma_t N(h,t)\ C(h,t) \qquad (1)$$

The calculation is performed for full retrofit of existing houses in the WUI and for new houses that will be built during a planning period. Let $N'(h,t)$ denote the number of new homes added to the sample community per year going forward, and $C'(h,t)$ denote the incremental cost to satisfy the National WUI Guide for new construction, for hazard level h and new home archetype t. Then the annual marginal cost per year at the community level for new construction can be estimated as:

$$C = \Sigma_h \Sigma_t N'(h,t)\ C'(h,t) \qquad (2)$$

3.6 Community costs for National WUI Guide Chapters 4 and 5

The community may also incur costs to satisfy the National WUI Guide because it calls for considering WUI hazard in land-use planning. Doing so entails evaluation costs and possibly changes to development patterns that could raise or lower tax revenues, costs or savings from vegetation management, and costs for water supply, access and egress route construction and maintenance, developing and maintaining areas of refuge, fire protection services, power transmission and distribution, and intangibles such as the preservation and access to wildland spaces. The National WUI Guide provides a wide variety of guidance with many possible cost categories. The leading ones appear to include:

1. Planning: policy analysis and development plans (Sec 4.2.1)
2. Tax consequences from land-use constraints (Sec 4.2.2)
3. Enhanced access and egress routes and planned areas of refuge (Sec 4.2.3)
4. Enhanced water supply for firefighting (Sec 4.3.1)
5. Undergrounding power lines and non-combustible poles (Sec 4.3.1)
6. Buses, watercraft, and emergency communication (Sec 4.3.2)
7. Firefighting response planning (Sec 4.3.3.2)
8. Evacuation planning and resourcing (Sec 5.2.1)
9. Emergency communication equipment, planning, and training (Sec 5.2.2)
10. Public education development and implementation (Sec 5.3)

Planning. Some of these cost categories cannot be estimated. The National WUI Guide's recommendations for policy analysis and development planning do not seem to explain clearly enough for cost estimation purposes the planning products that municipalities, Indigenous, provincial, and territorial governments would implement to follow the Guide. For this cost category, the project team estimates order-of-magnitude costs considering WUI planning as a reasonable fraction of overall planning. See Chapter 4 of this report for our rationale and findings on this and all subsequent items.

Taxes. Tax consequences are estimated considering the possibility that the National WUI Guide will affect construction prices, hinder or promote development, and thereby reduce or increase tax revenues in proportion to the change in development expenditures. See Chapter 4 for our rationale and findings.

Access and egress routes. Costs of paving unpaved neighbourhoods and of adding access and egress routes probably dominate item 3. Costs are taken from the available literature on a per-route or per-household basis, rather than attempting to estimate quantities for every community or for sample communities. The project team observes pavements and sufficiency of access routes for each sample building and draws statistical information from those observations on the likelihood that a community will have to pave or improve access.

Water supply. The project team quotes available literature on the cost of water supply on a per-household basis for neighbourhoods that currently rely on well water or that otherwise have insufficient flow for firefighting purposes. The team estimates the cost to install a municipal water supply system of buried water mains and common pipe material and diameters. The project team observes the presence of hydrants near each sample building and draws statistical information from those observations of the likelihood that a community will have to improve water supply.

Power lines, poles, and vegetation management. The project team quotes the literature in Chapter 2 on costs to underground power lines, replace combustible power poles with non-combustible poles, and control vegetation on a per-household basis. The project team observes near each sample house whether power is underground, and if not, whether utility poles are wood and have more than 5 metres of clearance to vegetation. It draws statistical information from those observations on the likelihood that a community will have to pave or improve these features.

Buses, watercraft, and communication. The project team estimates planning for buses, watercraft, and emergency communication based on adding two hours to an annual exercise with 15 people (one for each emergency support function), doubled to account for the planning to design that part of the exercise.

Firefighter response planning. The costs for firefighting response planning and evacuation planning and resourcing are estimated as approximately equal to the cost of the plan for buses, watercraft, and emergency communication, plus a modest cost to secure a mutual aid commitment from a busing company.

Emergency communication. The project team quotes the literature in Chapter 2 that suggests Canada has already built the emergency communication systems it needs and includes the effort to plan emergency communication with the prior item.

Public education. The cost of public education development and implementation is estimated based on an estimate of the firefighter labour to communicate with neighbourhoods and neighbourhood associations.

It is impractical to quantify all costs; some are described only qualitatively. We identify some important data gaps and assumptions.

3.7 Benefits analysis methodology

3.7.1 Benefits Analysis General Methodology

The project estimates the economic and life-safety benefits of satisfying the National WUI Guide for (a) new construction, (b) full retrofit, and (c) partial retrofit to a limited extent, as shown in Appendix C, for each hazard level. Mathematically, benefits for a single asset (a single house) can be calculated as follows: One first estimates the expected annualized loss (*EAL*) under as-is conditions, using equation 3a or 3b, and repeats for what-if conditions, *EAL'*. Benefit is then calculated using equation 4.

$$EAL = V \cdot \int_0^\infty y(x) \left| \frac{dG(x)}{dx} \right| dx \quad (3a)$$

$$EAL = V \cdot y(x) \cdot G(x) \quad (3b)$$

$$B = (EAL - EAL') \frac{(1 - \exp(-r \cdot t))}{r} \quad (4)$$

where

EAL = expected annualized loss of the asset (the house) under as-is conditions, i.e., the expected value of the loss in one year, accounting for the probability of one or more hazardous events (here, fires).

V = value exposed to loss. In the case of property repair costs, *V* refers to the replacement cost (new) of built property – the house, appurtenant structures such as sheds and fences, and contents. In the case of deaths, non-fatal injuries, and instances of PTSD, *V* refers to the number of occupants. In the case of time-element losses (additional living expenses or direct business interruption), it refers to the value of additional living expenses or direct business interruption in the case of full loss of the asset, e.g., the house burns down.

x = degree of environmental excitation. Here, *x* is taken as a binary variable (1 if a house is within a fire perimeter, 0 otherwise), then the integral is not needed, as in equation 3b.

y(x) = expected fraction of value *V* lost conditioned on environmental excitation x. This is often called the vulnerability function. It can be developed from empirical observation (either in actual fires or in the laboratory), analytically from engineering first principles, or from model components that draw on empirical observation (see for example, Caton et al. 2017, Hakes et al. 2017), or through a judgment-informed process. In the simpler formulation of equation 3b, *y(x)* can only take on two values: if $y(0) = 0$, $y(1)$ = the expected value of loss as a fraction of value exposed to loss conditioned on the asset being affected by the environmental excitation, e.g., it stands within 100 m of a fire perimeter. In either case, *y(x)* depends on building attributes, with a potentially different quantity for each category of assets.

G(x) = expected value of exceedance frequency of environmental excitation *x*. In the present case, *G(x)* represents the estimated number of times per year that a location would be inside a WUI fire perimeter. Conceivably, one could model non-stationary hazard *G(x)*, accounting for the effects of climate change, considering projections of temperature, precipitation, drought severity, and others, as suggested by Littell et al. (2009) and Wotton et al. (2010); see also Tedim et al. (2019) and perhaps Marlon et al. (2009). We account for non-stationary hazard in a subsequent section of this report.

EAL′ = like *EAL*, except under what-if (mitigated) conditions, which here means either (a) new house that satisfies the National WUI Guide, (b) existing house that fully satisfies the Guide, or (c) existing house that partially satisfies the Guide. It is calculated using *V′*, *y′(x)* and *G′(x)*, analogs to *V*, *y(x)*, and *G(x)* but under what-if conditions.

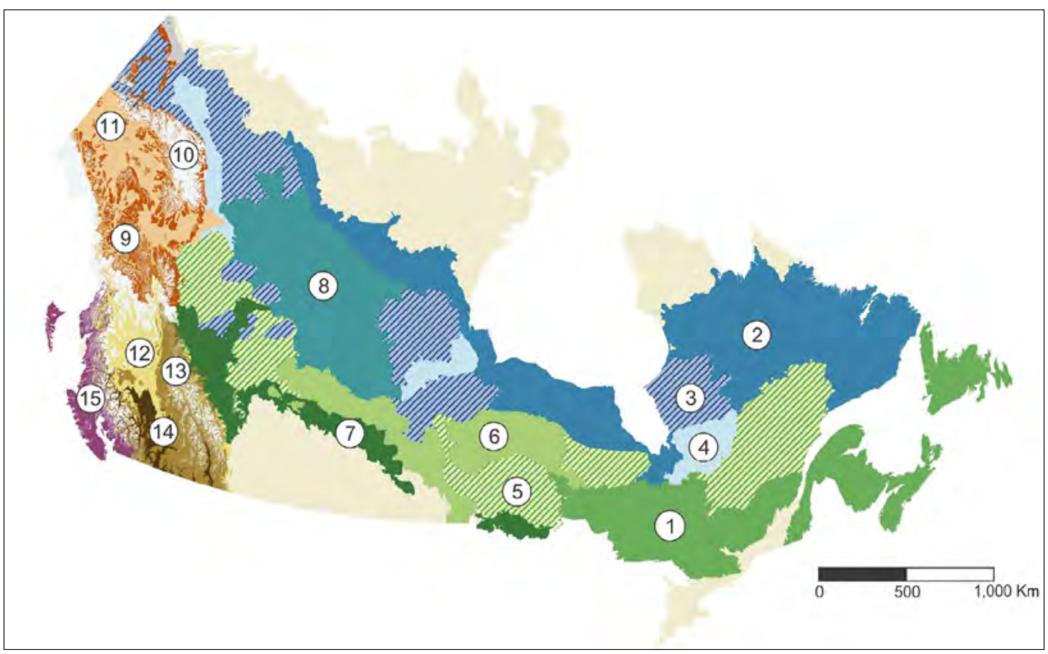
r = discount rate. In the case of monetary losses, *r* is often taken as the real cost of borrowing, i.e., either the current or long-term prevalent commercial or personal mortgage interest rate minus inflation. In the case of life-safety impacts (deaths, non-fatal injuries, and instances of PTSD), *r* is taken as zero.

t = expected remaining useful life of the mitigation measure, taken here as 75 years for a new house, and somewhat less, 50 years, for an existing house.

3.7.2 Hazard G(x)

For consistency and simplicity, the project team quantifies the fire hazard using burn rates taken from Erni et al. (2020). Erni et al. (2020) do not offer weighted average burn rates by hazard level, so the project team selects three sample communities in each hazard level and draws their burn rates from Erni et al.'s (2020) map of fire regime types (Figure 12) and a related table with burn rate (%/year; Erni et al. 2020, Table A2). The project team calculates a sample weighted average, using community population as the weight. The project team attempts to select sample communities to span geography (within each southern province) and community size (small, fewer than 30,000 people; medium, 30,000 to 100,000 people; and large, more than 100,000 people). The Erni et al. (2020) burn rates are based on historical (1970–2016) fires, so they do not account for climate change.

Figure 12. Fire regime types by Erni et al. (2020), each with an estimated burn rate



3.7.3 Property Vulnerability y(x)

At least three options are available to estimate vulnerability:

1. Two functions: one for buildings that meet the recommendations of the National WUI Guide, one for buildings that do not. The function is the product of ignition probability and the expected value of loss as a fraction of value exposed. Both can differ between the buildings that meet and do not meet the recommendations. The advantages of this approach include great simplicity and a strong empirical basis. Its disadvantages include lumping all houses that do not meet the Guide's recommendations into one group: the best and the worst are treated the same, the details make no difference in the benefit-cost analysis, and we cannot tell which deficiencies really matter. The vulnerability function for option 1 looks like equation 5. In the equation, x is a binary variable for ignition, p_c denotes the ignition probability for a house that meets the Guide's recommendations, given presence within 100 meters of the fire perimeter, v_c is the expected value of repair cost as a fraction of replacement cost new for such a house that experiences an ignition, and n_c denotes similar variables for a house that does not meet the recommendations. From Figure 4D, one can estimate $p_c = 0.38$ and $p_{nc} = 0.54$. From the column for single-family dwellings in Figure 4E, $v_{nc} = 0.94$. From Figure 4D, one can also estimate that $v_c = 0.74$.

   $y_c(x) = x \cdot p_c \cdot v_c = 0.281x$ Meets recommendations (5a)

   $y_{nc}(x) = x \cdot p_{nc} \cdot v_{nc} = 0.508x$ Does not meet recommendations (5b)

2. A function reflecting all of the applicable modifiers of Figure 4B. It accounts for all observed conditions, and one can judge the importance of each detail. However, this function is complex, it needs a great deal of sample data, and it may offer illusory accuracy. See equation 6. In this equation, Z denotes a vector of features: which satisfy and which do not, e.g., vinyl siding, wood deck, etc. The term p_{Zi} denotes the joint probability that a house within 100 metres of the fire perimeter has feature set Z and will ignite. The term $p_{Z\cdot}$ denotes the probability that a house has feature set Z. The ratio $p_{ZI}/p_{Z\cdot}$ denotes the ignition probability given the feature set Z and presence within 100 metres of the fire perimeter. Term $p_{\cdot I}$ denotes the marginal ignition probability, i.e., for a house within 100 metres of the fire perimeter, knowing nothing about its conditions Z. Term v_Z denotes the expected value of repair cost as a fraction of replacement cost (new) for a house with feature set Z that experiences an ignition; R_i is the odds ratio for feature i (Table 5), and N_Z is the number of features in Z. Equation 6 assumes features are independent and do not interact; that is, the presence of one feature provides no information about another, and the odds ratio given the value of feature A (e.g., the kind of siding) is independent of feature B (e.g., eaves are enclosed). If N_Z is large, has many possible combinations, and has a significant chance of each possible value – as is probably the case here – then $p_{Z\cdot}$ will be small and $(p_{Z\cdot} + p_{\cdot I}) \approx p_{\cdot I}$ in equation 6b. The equation 6d will approach the simpler equation 6e. For simplicity, one can take v_Z as $v_{nc} = 0.94$ if the house does not meet the Guide's recommendations, and as $v_c = 0.74$ if the house does meet the recommendations.

$$y(x) = \frac{p_{ZI}}{p_{Z\cdot}} \cdot v_Z \cdot x \qquad (6a)$$

$$p_{Zi} = \frac{1 + (p_{Z\cdot}) + p_{\cdot I})\ )\ (R-1) - S}{2(R-1)} \qquad (6b)$$

$$R = \Pi_{i=1}^{n_Z} R_i \qquad (6c)$$

$$S = \sqrt{(1 + (p_{Z\cdot} + p_{\cdot I})\,(R-1))^2 + 4R(1-R)\,p_{Z\cdot} \cdot p_{\cdot I})} \qquad (6d)$$

$$S \approx 1 + p_{\cdot I}\,(R-1) \qquad (6e)$$

3. Like option 2 but considers only one or two features that have the largest or the smallest odds ratios from Figure 4B. This option is a compromise. It looks like equation 6 but reduces or avoids the concern that features might interact; however, it loses resolution on the importance of lesser features.

The project team has weighed the advantages and disadvantages of the three options and has selected option 2, subject to a sanity test using option 1.

Table 5. Odds ratios implied by CAL FIRE's observations from the 2018 Camp Fire

i	Feature	Condition	Compliant	R_i
0	Elevated deck or porch	Composite	FALSE	0.5
		Masonry or concrete	TRUE	0.3
		None	TRUE	0.5
		Wood	FALSE	2.5
1	Deck or porch on grade	Composite	FALSE	0.3
		Masonry or concrete	TRUE	0.3
		None	TRUE	2.0
		Wood	FALSE	2.7
2	DSpace	Compliant	TRUE	0.2
		Non-compliant	FALSE	5.0
3	Eaves	Enclosed	TRUE	0.8
		None	TRUE	2.0
		Unenclosed	FALSE	1.0
4	Exterior cladding	Combustible	FALSE	1.5
		Ignition-resistant	TRUE	0.6
5	Fence	Combustible	FALSE	1.8
		None	TRUE	0.7
		Non-combustible	TRUE	1.1
6	Patio/carport cover	Combustible	FALSE	1.5
		None	TRUE	0.7
		Non-combustible	TRUE	1.1
7	Roof	Asphalt	TRUE	0.9
		Concrete	TRUE	1.2
		Metal	TRUE	1.2
		Tile	TRUE	0.4
		Wood	FALSE	6.0
8	Vent screen	Mesh ≤ 4 mm	TRUE	0.7
		Mesh > 4 mm	FALSE	1.2
		No vents	TRUE	1.1
		No screen	FALSE	1.5
9	Windows	Multi-pane	TRUE	0.4
		Single pane	FALSE	3.0

3.7.4 Deaths, Non-Fatal Injuries, and Post-Traumatic Stress Disorder

Ahrens and Evarts' (2020) fatality rate agrees with the lower bound of the fatality rate suggested by von Kaenel (2020) and by PG&E wrongful death claims (Prime Clerk 2020). Injury rates suggested by Ahrens and Evarts (2020) also appear conservatively low compared to PG&E personal injury claims, which number 100 times the wrongful death claims (Prime Clerk 2020), as opposed to three times. The number of deaths and non-fatal injuries per occupant are therefore taken as

$$y_i(x) = p_I c_i x \tag{7}$$

where

x = fire occurrence: $x = 1$ if the house is within 100 m of a fire boundary, $x = 0$ otherwise

i = injury severity: 1 = instance of PTSD, 2 = non-fatal injury, 3 = death

$yi(x)$ = injuries of severity *i* as a function of fire occurrence *x* as a fraction of house occupants

p_I = ignition probability given that the house is within 100 m of a fire boundary

c_i = coefficient for non-fatal trauma injuries and deaths. These are taken from Ahrens and Evarts (2020), as supported by von Kaenel (2020) and Prime Clerk (2020). For instances of PTSD, the coefficient is taken as equal to the number of non-fatal injuries, as was done in Multi-Hazard Mitigation Council (2019, p. 303), which drew on Sutley et al. (2017a, b). See Table 6.

Table 6. Rates and acceptable costs to avoid deaths, non-fatal injuries, and post-traumatic stress disorder

i	Injury	c_i	v_i, acceptable cost to avoid
1	Post-traumatic stress disorder	0.0333	$150,000
2	Non-fatal trauma injury	0.0333	$6,100,000
3	Fatal injury	0.0090	$15,700,000

The analysis does not account for time of day. People are mostly in their homes at night, and many are out of the home during work and school hours. But values of c_i are already averaged over times of day. They are taken from annual totals and are not conditioned on time of day, which raises the question of whether reducing the number of houses that burn down will reduce the number of deaths in proportion.

Recall that, where the *Chico Enterprise-Record* (2018) could geolocate fatalities in the Camp Fire, 32 of 53 victims (60%) died inside a residence, 11 outside a residence (21%), eight in vehicles (15%), one under a vehicle (2%), and one at a Sacramento hospital (2%). Also recall that many of the dead in Paradise, California, were found inside their homes or trying to evacuate. It seems reasonable to conclude that, regardless of whether fire professionals encourage people to evacuate, an estimated 60% to 80% of fatalities can be avoided if victims' homes do not ignite. Protecting homes saves lives by preventing deaths that will otherwise occur in or near them.

The available data seem insufficient to make strong statements about whether the remaining 30% of deaths can be avoided by better evacuation messaging and community resources. However, without deeper research and under the assumption that better evacuation messaging and community resources should have some benefit, it seems reasonable to attribute avoided deaths and injuries in that way.

3.7.5 Additional Living Expenses and Indirect Business Interruption

As was done in Multi-Hazard Mitigation Council (2019), additional living expenses are taken as costing 10% of the building replacement cost (new) if the building ignites. Indirect business interruption is taken as 47% of additional living expenses.

3.7.6 Lower Insurance Premiums

Insurance premiums can be considered to have two parts: pure premium (the expected value of losses per year), and overhead and profit, which in the United States is about 42% of pure premium. To avoid double counting, insurance savings are calculated here based solely on reduced overhead and profit costs, that is, 0.42 times the reduction in property loss and additional living expenses. This benefit assumes that regulatory pressures and other business considerations cause premiums to adjust to reflect the new risk with the same 42% overhead and profit factor.

3.7.7 Job Impacts

Fires can cause job losses when workers are displaced so far from their community that they cannot practically commute to jobs that need their physical presence and when workplaces burn down. Fires also create short-term jobs in the construction sector as destroyed buildings are rebuilt, as the Bureau of Labor Statistics (2020) reports after the 2017 Tubbs and 2018 Camp Fires, but cause no apparent change in long-term employment. The project team infers that job losses are too small or too dependent on location to estimate. However, as noted earlier, every additional $1 million spent per year on residential construction adds about four full-time equivalent jobs.

3.7.8 Environmental Impacts

As discussed in Chapter 2, the literature on how to monetize pollution from houses burned in WUI fires is limited. The most mature mechanism seems to be the cost method. The Environmental Defense Fund (EDF 2020) reports that the 2013 US Government Interagency Working Group prices carbon at over $62 per ton. An EDF survey places the true social cost of carbon at $175 per ton of CO_2. Burning an average house to the ground releases about 9 tons of CO_2, suggesting an order-of-magnitude environmental cost of $600 to $1,600 for a destroyed house. In the present analysis, we use the lower, more conservative figure. The figure ignores the various plastics in the average burned house, so the $600 figure is conservative, if anything.

3.8 Benefits by house

Benefits are calculated for new houses and for fully retrofitted existing houses for each hazard level and each of the following benefit categories related to household losses (Chapters 2 and 3):

1. Property repair cost: building, contents, and appurtenant structures such as garages
2. Additional living expenses
3. Deaths, both in terms of number of people and in terms of their monetized equivalent using prevailing acceptable costs to avoid a statistical death
4. Non-fatal injuries, both as number of people and monetized similar to deaths
5. Instances of PTSD, both as number of cases and monetized similar to deaths
6. Maintenance costs, e.g., painting associated with fibre cement cladding
7. Lower insurance premiums (the proportion associated with administration and profit, as opposed to claims payments)

Of these categories, the methods presented earlier in this chapter account for all items except for 3 (direct business interruption insofar as people use their homes as workplaces) and 6 (pets and livestock). The authors are aware of adequate data on which to base a model of the loss of pets and livestock. As for home businesses, the authors judge that most work that can be carried out in a home can be transferred to temporary accommodations.

3.9 Benefits at community and national levels

Community-level benefits (reflected in Chapters 4 and 5) include the following:

1. Indirect and induced business interruption through (a) transfers from home businesses to other economic sectors and (b) personal income injected into the economy
2. Emergency response costs
3. Tax revenues
4. Environmental impacts, monetized to the extent practical
5. Long-term job creation (associated with initial domestic construction materials and labour for new houses and retrofitting)

Benefits can be calculated at two aggregate levels: (1) the typical community described in task 2d, and (2) the national level. Community benefit depends on community size, population growth, hazard level, and the rate at which new houses are added and existing houses are removed from the inventory. Let

u_0 = number of housing units at time 0

a = rate at which new housing units are added; ratio of new housing units in a year to the number of existing housing units at the beginning of the year

d = rate at which existing housing units are removed from service; ratio of the number of houses demolished in a year to the number of existing housing units at the beginning of the year

r = population growth rate; ratio of population added in a year to the population at the beginning of the year. If household size remains constant, $r = a - d$.

t = time allowed to retrofit or demolish all existing housing units to satisfy the National WUI Guide

n_n = number of housing units added by time t

n_d = number of housing units demolished by time t

n_r = number of housing units retrofitted by time t

b_n = long-term average benefit per new housing unit

b_r = long-term average benefit per retrofitted housing unit

b_d = present value of losses avoided by demolishing an existing housing unit

B_c = long-term average community benefit of all changes resulting from new construction, retrofitting existing houses, and demolishing old ones

B_n = long-term average national benefit

Then at the end of time t,

$$n_n = u_0 (1 + a)^t \tag{8}$$

$$n_d = u_0 (1 + d)^t \tag{9}$$

$$n_r = u_0 - n_d \tag{10}$$

$$B_c = n_n \cdot b_n + n_r \cdot b_r + n_d \cdot b_d \tag{11}$$

One can estimate benefit at the national level by evaluating equations 8–11 once each for low, moderate, and high hazard levels. That is, let u_{0h} denote the number of housing units at time 0 in hazard level h (i.e., h can take on any of low, moderate, or high values), let b_{nh}, b_{rh}, and b_{dh} denote the per-house benefits at hazard level h, and B_{ch} denotes the aggregate national benefit for houses in hazard level h. Then,

$$B_n = \Sigma_h B_{ch} \tag{12}$$

Benefits at the national level can be compared to prior work to check consistency, e.g., versus Multi-Hazard Mitigation Council (2019) and Porter and Scawthorn (2020).

3.10 Cultural and historical benefits

One can estimate the monetary value of a building's cultural or historical benefits using hedonic pricing. Equation 3 applies, with V set to the present value of future revenues from people paying to view an historical building, to see the artifacts it contains, or to participate in cultural activities inside.

3.11 Other benefit categories

The focus of task 2 is on houses, as opposed to workplaces, historical or cultural institutions, and critical facilities such as fire stations and hospitals. The National WUI Guide can be applied to non-residential infrastructure and can produce additional benefits. The project team acknowledges them and describes them qualitatively, but does not quantify them. These benefits include:

1. Reduced direct business interruption at non-residential workplaces
2. Reduced indirect business interruption at non-residential workplaces
3. Reduced loss of service to the community

3.12 Validation

Foregoing sections offer literature on the costs to satisfy the National WUI Guide. Benefits are harder to check. Validating benefit estimates would require:

1. A quantitative assessment of the benefits, drawing from recorded incidents of WUI fires in Canada and around the world
2. Justification that the benefit is realistic based on forensic studies and other evidence from WUI fires in Canada and around the world

We found insufficient empirical data from past fires to validate benefit estimates, aside from using CAL FIRE's DSpace and DINS data to establish the model parameters. ICLR recently produced a method to conduct WUI case study research that could greatly inform such an effort in the future (Westhaver and Taylor 2020).

3.13 Benefit-cost ratios

The project team presents benefit-cost ratios for:

- New buildings that fully comply with the National WUI Guide's recommendations, and retrofits that partially meet recommendations by archetype house and intensity level
- Typical community from task 2d
- National level

The fraction of the benefits derived from each benefit category can be taken from task 4b(ii).

3.14 Climate change

One can account for climate change by assuming that burn probability increases linearly with fire frequency. Using Wotton et al. (2010), one can fit a curve to the overall nationwide increase in fire frequency of the form

$$f_1(t) = a \cdot (t - 2000)^b \qquad (13)$$

Taking t as the year, one can fit the following values to Wotton et al.'s (2010) projections:

$a = 0.562$

$b = 0.2436$

The annual benefit increases with t in proportion to $f_1(t)$. The present value of future benefits decreases with t:

$$f_2(t) = c_1 \cdot exp\ (-r\ (t - 2020)) + c_2 \qquad (14)$$

where c_1 denotes the monetary fraction of annualized benefits and c_2 the non-monetary fraction ($c_2 = 1 - c_1$). The function $f_2(t)$ acts like a weighting factor for each year. The overall effect on benefit, and therefore on benefit-cost ratio, can be calculated as a factor f_3:

$$f_3 = \frac{\sum_{t=2021}^{t=2095} f_1(t) \cdot f_2(t)}{\sum_{t=2021}^{t=2095} f_2(t)} \qquad (15)$$

Losses scale linearly with burn rate. If we take wildfire increase as a proxy for burn rate (ignoring fire size), the benefit, and therefore the benefit-cost ratio, increase by a factor f_3 relative to stationary 2010 climate.

3.15 Demand surge

As previously noted, research to date suggests that demand surge tends to reach an upper limit around 20%, although at least one exception has been observed. Demand surge could play a significant role in long-term average losses and, therefore, in benefits and the benefit-cost ratio. Demand surge produces an increase in future losses, thereby increasing benefits and the benefit-cost ratio. To ignore demand surge entirely would tend to underestimate benefit, but to assume the upper bound of 20% seems unconservative. Without deeper study, the best choice seems to be simply to take the middle ground and add 10% (based on the authors' judgment) to WUI fire losses to reflect demand surge.

Conceivably, mandatory implementation of the National WUI Guide could increase long-term, widespread demand for non-combustible cladding. The increase would be neither temporary in response to a catastrophe, nor local. Any such effect would be outside the scope of demand surge but could cause a general demand-driven cost increase. However, as currently conceived, the National WUI Guide remains voluntary, reducing the potential for demand-driven increase in the cost of non-combustible cladding. In any case, lacking better information about the potential cost increase, an economic analysis seems beyond the scope of the present project.

4. Results

4.1 Archetypes

4.1.1 Sample Communities

Figure 13 shows nine communities for sampling houses: three samples each in high (red pins), moderate (yellow), and low (green) historical wildfire hazard areas. Circles show locations of 102 sample houses in or near sample communities. Table 7 lists sample communities that are selected to span Canadian municipalities in population, longitude, and latitude. The table shows an estimate of the fraction of each community in the wildland-urban interface, i.e., less than 500 metres from the wildland, based on a visual inspection of the satellite imagery. The figure is only intended as an order-of-magnitude estimate. Quebec and Indigenous neighbourhoods are not included in the sample communities because the data source for buildings, Zillow.com, has no coverage in these areas. See Section 4.1.7 for a discussion of houses in Quebec and Appendix B for a deeper discussion of Indigenous housing.

Figure 13. Communities for selecting sample houses. Colours indicate historical wildfire hazard: red for high, yellow for moderate, and green for low.

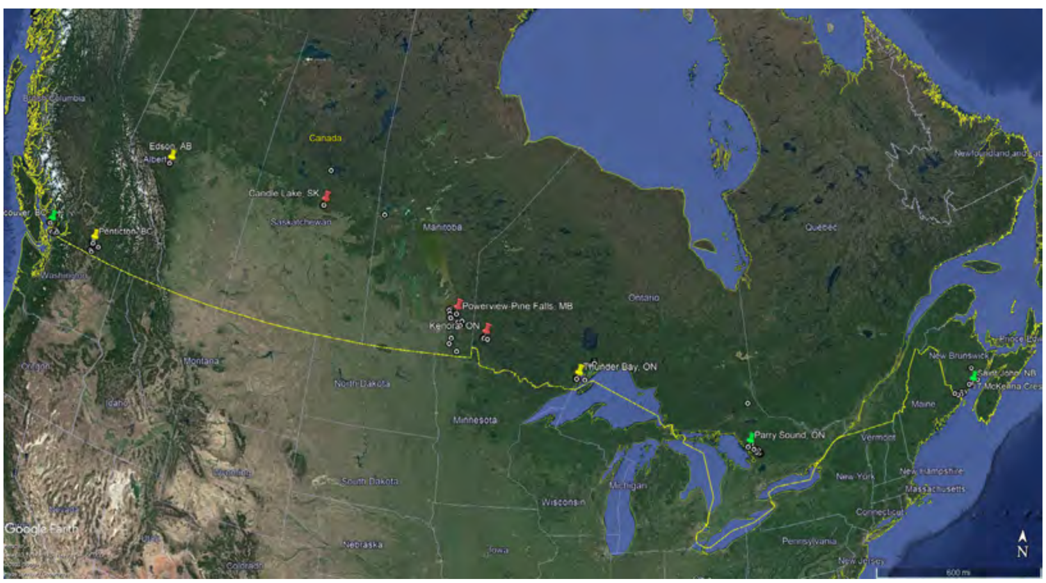


Table 7. Communities for sampling houses

Hazard	Community	Population	% of households in WUI
High	Kenora, ON	15,096 (2016)	50%
	Candle Lake, SK	DNK	100%
	Powerview-Pine Falls, MB	1,314 (2011)	100%
Moderate	Thunder Bay, ON	107,909 (2016)	25%
	Penticton, BC	33,761 (2016)	25%
	Edson, AB	8,414 (2016)	75%
Low	Vancouver, BC	631,486 (2016)	1%
	Parry Sound, ON	6,408 (2016)	100%
	Saint John, NB	67,575 (2016)	50%

We refer herein to small, medium, and large communities. The project team uses Statistics Canada's definitions of small, medium, and large population centres, taking the archetype as approximately the geometric mean of the extremes of each definition: 5,000 for a small population centre (with about 2,000 housing units), 50,000 for a medium population centre (about 20,000 housing units), and 500,000 for a large population centre (about 200,000 housing units).

4.1.2 Sample House Data

Table 8 shows median characteristics of the sample houses by historical wildfire hazard. In this table and others in this section, the column labelled "all" represents the total in all three hazard levels, and medians in the "all" column present the median among the superset of all three hazard levels. Table 9 shows the distribution of the number of storeys, Table 10 shows the distribution of roofing material, Table 11 shows the distribution of wall cladding material, and Table 12 shows the distribution of foundation and deck enclosures.

The project team considered whether the archetype existing house for the three hazard levels should be represented with one, two, or three archetype existing houses. Medians are similar for some attributes and different for others. The year built, roof material, cladding, and glazing area as a fraction of exterior cladding are similar across hazard levels. Storey count and square footage for high- and moderate-hazard houses are similar, while houses in the low-hazard sample are larger, generally because the sample houses in Vancouver, BC, are large. Vancouver represents the most populous community of low-hazard Canadian homes. (Toronto and Montreal are in the nil to very low hazard level.)

It does not seem reasonable simply to ignore Vancouver or to represent its larger houses (2 storeys, 2,500 square foot median living area) with the significantly smaller median house (1 storey, 1,500 square feet). Therefore, the project team uses two archetype existing houses: one for moderate-to-high hazard, one for low hazard.

Median attributes for the two sets of existing houses (moderate-to-high hazard, low hazard) are shown in Table 13. These attributes can be used to select existing houses to use as archetypes for low, moderate, and high hazard levels. The table shows the ID numbers of the sample houses that most closely resemble the median values in terms of square footage, number of storeys, roof material, and cladding. These houses are detailed in the next section.

Table 8. Sample house median attributes

	Hazard			
	High	**Moderate**	**Low**	**All**
Count (sample size)	34	34	34	102
Storeys	1	1	2	1
Basement	FALSE	FALSE	FALSE	FALSE
Living area sq ft	1,323	1,245	2,466	1,547
Year built	1976	1961	1983	1974
Ext wall area sq ft	1,990	1,856	2,996	2,095
Roof material	Comp	Comp	Comp	Comp
Exterior cladding	Vinyl	Vinyl	Vinyl	Vinyl
Glazing area	20%	15%	20%	20%
Enclosed deck	FALSE	FALSE	FALSE	FALSE

Table 9. Sample house height distribution

	Hazard			
	High	**Moderate**	**Low**	**All**
Count	34	34	34	102
1 storey	62%	68%	32%	54%
1.5 storeys	9%	6%	6%	7%
2 storeys	29%	26%	56%	37%
3 storeys	0%	0%	6%	2%
Other	0%	0%	0%	0%

Table 10. Sample house roof distribution

	Hazard			
	High	**Moderate**	**Low**	**All**
Count	34	34	34	102
Composition	94%	79%	82%	85%
Metal	6%	21%	15%	14%
Wood	0%	0%	3%	1%
Other	0%	0%	0%	0%

Table 11. Sample house cladding distribution

	Hazard			
	High	**Moderate**	**Low**	**All**
Count	34	34	34	102
Vinyl	35%	47%	47%	43%
Wood	32%	21%	35%	29%
Log	6%	3%	6%	5%
Other combustible	0%	0%	0%	0%
Subtotal combustible	74%	71%	88%	77%
Stucco	15%	29%	6%	17%
Stone	6%	0%	3%	3%
Brick	0%	0%	3%	1%
Fibreglass	3%	0%	0%	1%
Cement board	3%	0%	0%	1%
Other non-combustible	0%	0%	0%	0%
Subtotal non-combustible	26%	29%	12%	23%

Table 12. Sample house deck enclosure

	Hazard			
	High	**Moderate**	**Low**	**All**
Count	34	34	34	102
TRUE	32%	47%	44%	41%
FALSE	68%	53%	56%	59%

Table 13. Median existing house attributes

	Hazard	
	Moderate-high	**Low**
Count	68	34
Storeys	1	2
Basement	FALSE	FALSE
Living area sq ft	1,261	2,466
Year built	1972	1983
Ext wall area sq ft	1,923	2,996
Roof material	Comp	Comp
Exterior cladding	Vinyl	Vinyl
Glazing area	15%	20%
Deck enclosure	FALSE	FALSE
Most similar sample ID	31	75

Table 14. Community utilities and transportation infrastructure

Attribute	Yes	No	Comment
Fraction of all homes in WUI	50%	50%	Like Kenora, ON, and Saint John, NB
Paved road	72%	28%	
Sufficient access routes	97%	3%	Each "no" required 500 ft more road
Above-ground electric	92%	8%	
Wood utility poles	100%	0%	Above-ground electric only
> 5 m clearance from wires to vegetation	17%	83%	Above-ground electric only
Fire hydrants	53%	47%	

4.1.3 Existing House Archetypes

The project team selects two real houses from the sample dataset that most closely resemble the attributes shown in Table 13. A 2018 house was selected (see Figure 15) to represent an existing house because its size and other attributes most closely match the median values from the sample.

Figure 14 shows the sample house most closely resembling the moderate-to-high hazard level column of Table 13 (ID 31 in database). This house is in The Pas, Manitoba, R0B 2J0, 53.8280N, -101.2426E. It is a one-storey house built in 1972 with 1,272 square feet of living space on the main floor, three bedrooms, 2.5 baths, finished basement, a 720-square foot double detached garage, approximately 2,030 square feet of roof area, 261 linear feet of perimeter, two exterior doors, one 9-foot garage door, and no deck.

Figure 14. (A) *Archetype existing house for moderate-to-high hazard level (ID 31), and* **(B)** *its double detached garage*

Figure 15 shows the sample house that most closely resembles the low exposure level column of Table 14 (ID 75 in database). The house is located at 9132 Gilmour Ter, Mission, BC, V4S 1H9, 49.1682N, -122.3938E. It was built in 2018. This three-bedroom, three-bath, 2,806-square foot rancher house has a loft, 12-foot ceilings, four exterior doors, triple attached garage, three 9-foot garage doors, approximately 5,900 square feet of roof area, 343 linear feet of perimeter, and no deck.

Figure 15. (A) *Archetype existing house for low hazard level (ID 75), and* **(B)** *its rear (east) elevation*

4.1.4 Newer House Data

The project team extracted a subset of newer houses, only those built in 2000 and later, from the full sample dataset. Table 15 presents median attributes for newer houses by hazard level. For consistency, the project team uses two archetype houses: one for moderate and high hazard, and one for low hazard. The two archetypes are similar in terms of roofing and cladding material (composition tile and vinyl siding) and differ in size: the low hazard archetype is taller, has greater square footage, and a larger fraction of its wall area is given to glazing. Note that both archetype houses are about 50% larger than their existing house counterparts and have 33% to 50% more glazing per square foot of exterior wall. The project team examined an even smaller subset of houses built in 2010 or later and found similar median characteristics, although the median low hazard house was even larger: 4,200 square feet rather than 3,600 square feet. As shown later in this analysis, the difference does not matter, so the post-2000 house set was retained.

Table 15. Median newer house attributes

	Hazard	
	Moderate-high	**Low**
Count	19	14
Storeys	1	2
Basement	FALSE	FALSE
Living area sq ft	1,724	3,674
Year built	2010	2018
Ext wall area sq ft	2,000	3,561
Roof material	Comp	Comp
Exterior cladding	Vinyl	Vinyl
Glazing area	20%	30%
Deck enclosure	TRUE	TRUE
Most similar sample ID	32	79

4.1.5 New House Archetypes

Figure 16 shows the existing house that stands in for the new house archetype in moderate-to-high hazard levels. This house was built in 2010. It has 1,724 square feet of living area, four bedrooms and three baths, four exterior doors, one 9-foot garage door, 1,580 square feet of roof area, 156 linear feet of perimeter, and an elevated wood deck of about 800 square feet.

Figure 17 shows the existing house that stands in for the new house archetype with low hazard. This house was built in 2010. It has 3,995 square feet of living area, four bedrooms and five baths, four exterior doors, one 16-foot garage door, a 135-square foot attached porch, a 300-square foot detached porch, 4,400 square feet of roof area, and 218 linear feet of perimeter.

Figure 16. Archetype moderate-to-high hazard new house (ID 32).

Figure 17. Archetype low-hazard new house (ID 79).

4.1.6 Summary of House Archetypes and Values Exposed to Loss

Table 16 summarizes attributes of the archetype houses: a pair for existing houses to be retrofitted and a pair to represent typical new houses. Addresses are omitted from the table to avoid worrying the owners. The replacement cost new (*V*) for the house is calculated using RSMeans (2019c). It excludes land value. The table shows content value estimated as 70% of the building replacement cost, according to a common homeowner insurance assumption. In 2016, the average Canadian household size was 2.4 people. For purposes of analyzing these four houses, household size is taken as the number of bedrooms minus one, which yields about the same average.

Table 16. Summary of archetype houses

Existing or new	**Existing**		**New**	
Hazard level	**Moderate-high**	**Low**	**Moderate-high**	**Low**
ID	31	75	32	79
Lat deg N	53.8280	49.1682	53.9381	49.0482
Long deg E	-101.2426	-122.3938	-107.1690	-122.8690
Bedrooms	3	3	4	4
Baths	2.5	3	3	5
Storeys	1	2	1.5	3
Basement	1	0	0	0
Living area sq ft	1,272	2,806	1,724	3,995
Roof area sq ft	2,030	5,900	1,580	4,400
Year built	1972	2018	2010	2010
Ext wall area sq ft	2,184	3,058	2,052	3,649
Roof material	Comp	Comp	Comp	Comp
Exterior cladding	Vinyl	Vinyl	Vinyl	Vinyl
Glazing area %	10%	20%	20%	20%
Glazing area sf	218	612	410	730
Has deck	FALSE	FALSE	TRUE–ELEVATED	TRUE–ON GRADE
Deck enclosure	NA	NA	FALSE	TRUE
Deck sf	0	0	800	435
Exterior doors	2	4	4	4
Garage door 9 ft	1	3	1	0
Garage door 16 ft	0	0	0	1
Perimeter lf	261	353	156	218
Encl eaves, soffits	FALSE	TRUE	TRUE	TRUE
House *V*, $	$486,000	$592,000	$451,000	$797,000
House *V*, $/sf	$380	$220	$260	$200
Content *V*, $	$341,000	$415,000	$316,000	$544,000
Occupants	2	2	3	3

4.1.7 Houses in Quebec

Although Zillow has no Quebec coverage, one can view a few house attributes from Google Earth Street View. The project team performed a small random sample of about 20 houses in Quebec and found them to be generally taller. Two storeys were more common than one, which makes the roof area smaller compared to the floor area. Quebec houses appear neither substantially larger nor smaller in living area than others examined here. They typically have a composition tile roof, as with the sample of houses from Zillow, although metal roofs appear to be more common than in the Zillow sample. There were a few stone masonry houses and several houses partly clad with brick veneer, but vinyl was the most common cladding. Basements appear to be more common than in the Zillow sample, which would tend to increase benefits and, therefore, benefit-cost ratios. Glazing area appears to be like the Zillow sample. Most of the Quebec houses have vegetation within a few feet of the house. Several have unenclosed wood-framed decks or porches, which would tend to increase benefit-cost ratios. Roof eaves commonly appear to be enclosed, which reduces costs and usually increases benefit-cost ratios. In summary, construction practices appear generally like the sample examined here.

4.2 Homeowner costs

4.2.1 Basic Recommendations for the House

Consider first the recommendations for the house itself, assuming the property follows recommendations only for SIZ 1A – the 1.5 metres closest to the house. For low exposure level, the National WUI Guide Table 7 recommends the house (zone 1A) to be of construction class CC1. For moderate and high exposure levels, the house should satisfy recommendations for construction CC1(FR), meaning having a fire-resistance rating of not less than 45 minutes based on fire exposure, in accordance with Clause 3.3.2(7)(b).

4.2.2 Recommendations for Exterior Walls

CC1 exterior wall cladding are recommended to be of non-combustible material. NFPA 130 and NFPA 101 define non-combustible materials; recommendations for exterior cladding for homes generally includes brick, stone, faux stone, stucco, and fibre cement. Not all CC1 non-combustible cladding automatically provide the one-hour fire-resistive rating for CC1(FR)(1) or the 45-minute fire-resistive rating for CC1(FR)(2), which in any case require the rating on the exterior side of the wall. A half-inch layer of type-X fire-rated gypsum wallboard beneath exterior cladding can provide a 45-minute rating; a ⅝-inch layer can provide a one-hour rating. Depending on the construction and thickness, a brick wall can achieve a one-hour to four-hour fire-resistance rating. A one-inch layer of stucco generally achieves a one-hour fire rating from the outside. A variety of faux stone veneer products generally meet Class A fire-resistive provisions from the outside. In addition to using non-combustible material, the exterior cladding must satisfy a few detailing recommendations (Section 3.3.2, sentences 3–5) that ensure complete cover and seals with gaps no larger than 3 mm wide.

CC2 exterior wall cladding must be ignition-resistant. This means, approximately, that it can be of any material with a flame-spread rating of 25 or less under CAN/ULC-S102. An equivalent set of acceptance criteria under ASTM E2768 also applies. It is common, but not universal, for vinyl siding to satisfy this provision. Table 17 lists five leading manufacturers and two arbitrarily selected vinyl siding products from each manufacturer. Eight of the ten products satisfy the provision, and two do not. CC3 exterior walls may be limited ignition-resistant, which eliminates the restriction on fire spread rating for vinyl siding and allows for wood cladding and log wall construction.

Table 17. Vinyl cladding fire spread ratings for some leading manufacturers and common products

Manufacturer	Product	Flame spread rating	Reference
CertainTeed	CedarBoards Insulated Siding	≤ 25	CertainTeed (2021a, p. 2)
CertainTeed	MainStreet	≤ 25	CertainTeed (2021b, p. 2)
Crane	CraneBoard Exterior Portfolio	≤ 25	Arcat (2016, p. 3)
	Elm Grove	≤ 25	Royal Building Products (2021, p. 2)
Alside	Charter Oak	≤ 20	Alside Inc. (ND, p. 2)
	Ascend	≤ 25	Alside, Inc. (2020, p. 4)
Variform	Nottingham	20	Variform, Inc. (2011, p. 5)
	Timber Oak Ascent	20	Variform, Inc. (2011, p. 2)
Royal	Haven® Insulated Siding	40	National Research Council of Canada (2017, p. 4)
	Select	85	National Research Council of Canada (2018, p. 6)

Cost for new construction with fibre cement rather than vinyl: The cost issue for the sample buildings is essentially to replace vinyl cladding with stucco, the most common of the non-combustible cladding materials in either the full existing building database or the post-2000 subset. Alternatively, the material most closely resembling vinyl siding is fibre cement board. A quick survey of vinyl siding retail costs at a big-box construction supply store (Home Depot) in Thunder Bay, Ontario, shows that vinyl siding products can cost $1.50 to $2.50 per square foot material cost, depending on the product line. HardiePlank cement board currently costs approximately $1.90 per square foot material cost at Home Depot. RSMeans (2019d) suggests a material cost of $1.40 per square foot for fibre cement siding – essentially the same as the Thunder Bay Home Depot retail cost after multiplying by the 1.11 location factor and bracketed by the material cost of vinyl siding, which suggests that RSMeans (2019d) is dependable, at least on material cost.

RSMeans (2019d, p. 135) estimates that installing 4-foot x 8-foot fibre cement board cladding on a new house costs between $3.10 per square foot (pre-tinted) and $5.20 per square foot (painted), with an average of $4.15 per square foot, including the first coat of paint or pre-tint. The same source suggests $6.30 per square foot for fibre cement board with lap siding, including paint.

The project team takes the average of these two, \$5.30 per square foot of exterior wall, excluding contractor overhead and profit. Fibre cement board is reputed to be durable, with a life comparable to that of the house (Sunshine Contracting 2019). Fibre cement board must be repainted every 10 to 15 years, at a cost of about \$0.82 per square foot for two coats (RSMeans 2019d, p. 236). Thus, the present value of repainting cost can be estimated as in equation 16.

$$PV = \Sigma_{i=1}^{n} \frac{c}{(1+r)^{i \cdot t}} \qquad (16)$$

PV is the present value of cost for future work, which in this case is square foot cost for future repainting. *C* is the cost for the work at time $i \times t$, *i* is an index to the times in the future when one must do the work (here, repaint), *r* is the discount rate, *t* is the number of years between the times when one must do the work, and *n* is the number of times one must do the work before the house reaches the end of its life. Thus, repainting for a new house ultimately adds a present value cost of \$0.82 x ($1/1.03^{12.5} + 1/1.03^{25} + 1/1.03^{37.5} + 1/1.03^{50} + 1/1.03^{62.5}$) = \$1.55. Between the initial cost and the repainting, the present value cost of fibre cement cladding on a new house is approximately \$5.30 + \$1.55 = \$6.85 per square foot.

For comparison with RSMeans' estimate of initial cost for fibre cement, Hanscombe Ltd. and ICLR (2019) suggest a unit cost between \$6.58 and \$9.47 per square foot for new construction, which would be consistent with RSMeans (2019d) if the spreadsheet includes contractor overhead and profit; RSMeans (2019d) does not and is consistent with the lifecycle cost including painting, estimated above.

RSMeans (2019d) estimates the total cost to install vinyl cladding on new construction ranges between \$4.40 (non-insulated) to \$7.70 (insulated) per square foot installed, approximately \$6.05 on average. Assuming a 30-year life for vinyl siding and 3% real cost of borrowing, the initial and future cost of vinyl at 0, 30, and 60 years has a present value of \$6.05 × ($1 + 1/1.03^{30} + 1/1.03^{60}$) = \$9.57 per square foot. Thus, the *initial* cost of fibre cement cladding on a new building is less than vinyl by \$5.30 - \$6.05 = (\$0.75) per square foot. And the lifecycle cost of fibre cement cladding on a new building, with future repainting, is less than vinyl by a present value of \$6.85 – \$9.57 = (\$2.72) per square foot.

To satisfy recommendations for CC1(FR) with one-hour rating on an exterior wall clad with fibre cement board requires a layer of ⅝-inch fire-rated gypsum board on the exterior side of the exterior wall. It adds about \$1.12 per square foot for the exterior layer (RSMeans 2019d, p. 179). To satisfy recommendations for the 45-minute fire-resistive rating on an exterior wall clad with fibre cement board to meet CC1(FR) involves adding a half-inch layer of fire-rated gypsum board on the exterior side of the exterior wall. The gypsum wallboard adds about \$0.75 per square foot of exterior wall (RSMeans 2019d, p. 179). Thus, the lifecycle cost of new, one-hour rated fibre cement cladding on a new building, with future repainting, is less than vinyl by a present value of \$6.85 + \$1.12 – \$9.57 = (\$1.60) per square foot. For a 45-minute rating, the difference is \$6.85 + \$0.75 – \$9.57 = (\$2.00), after rounding.

Cost to retrofit with fibre cement: For retrofit to satisfy recommendations for CC1, the project team assumes the average existing house is halfway through a useful life of 75 years, say 37.5 years old. If retrofitted immediately, the vinyl cladding (presumably replaced at age 30, about 7.5 years ago) must be demolished and replaced with fibre cement board. RSMeans (2019d) estimates that retrofitting a house with fibre cement board costs $5.60 (4-foot x 8-foot panels) to $6.75 (lap siding) per square foot of exterior wall, including demolition, installation, and paint; approximately $6.20 per square foot on average. The fibre cement board must be repainted every 12.5 years until the house is nearing the end of its useful life, that is, in 12.5 and 25 years, when the house is 50 and 62.5 years old, respectively. The present value of repainting twice adds $0.82 x ($1/1.03^{12.5}$ + $1/1.03^{25}$) = $0.95 per square foot of exterior wall. The total present value of lifecycle cost to demolish and replace vinyl cladding with fibre cement is, thus, $6.20 initially plus $0.95 in future repainting, for a total cost of $7.15 per square foot of exterior wall. The owner avoids replacing the vinyl when the house turns 60 years old, in 22.5 years. By equation 16, the present value of the cost to do so would have been $6.05/$1.03^{22.5}$ = $3.10 per square foot.

Thus, the lifecycle cost of fibre cement cladding, including future repainting, is more than vinyl by a present value of $7.15 (fibre cement) – $3.10 (vinyl) = $4.05 per square foot.

To satisfy recommendations for CC1(FR) with one-hour rating adds $1.12 per square foot. The lifecycle cost of one-hour fire-rated fibre cement cladding, including future repainting, is thus $4.05 per square foot for the fibre cement cladding plus $1.12 per square foot for the one-hour rated type-X gypsum wallboard, or $5.17 per square foot. To satisfy recommendations for CC1(FR) with a 45-minute rating adds $0.75 per square foot rather than $1.12 per square foot. Its cost is thus $4.80 per square foot.

Delayed retrofit with fibre cement: One could delay retrofit to satisfy recommendations for CC1. The average existing house in the sample of 102 houses examined here was built around 1975 and is now about 45 years old. Suppose the retrofit of existing houses were delayed 10 to 15 years, around the next time the vinyl cladding needs to be replaced. The initial cost to demolish and replace the existing vinyl cladding with fibre cement board is $6.20 per square foot, approximately equal to the cost of replacing the vinyl cladding with more vinyl ($6.05 per square foot). The house will be approaching the end of its 75-year life and may or may not need repainting; the project team neglects this possibility. Thus, the marginal cost for the cladding to satisfy recommendations for CC1 is essentially zero. Satisfying recommendations for a one-hour rating CC1(FR) is about $1.12 per square foot, or $0.75 for a 45-minute rating.

Cost implication for new construction with stucco with wire mesh rather than vinyl: RSMeans (2019d, p. 128) estimates $7.50 per square foot, including the first coat of paint. Subsequent coats every 10 to 15 years through year 62.5 add a total present value of $1.55 per square foot, for a total present value cost of $9.05 per square foot. Hanscombe Ltd. and ICLR (2019) estimate $10.25 to $14.76 per square foot for new construction with stucco cladding. Stucco achieves CC1(FR) with a one-hour rating. The net savings versus vinyl is $9.05 – $9.57 = ($0.52).

Cost to retrofit with stucco: According to RSMeans (2019d, p. 128), to retrofit an existing wood-frame building with three-coat stucco and wire mesh and paint costs $8.20, plus $0.95 per square foot for repainting at years 50 and 62.5 for a total cost of $9.15 per square foot for retrofit. Again, stucco achieves CC1(FR) with one-hour rating. The net cost versus vinyl is $9.15 – $3.10 = $6.05.

4.2.3 Recommendations for Roofing Materials, Eaves, Gutters, Downspouts, Openings, and Vents

All houses in the WUI must have Class A roof coverings, non-combustible valley and hip flashing, drip edges, roof penetrations, seals at penetrations and attachments, gutters, and downspouts. All houses must have enclosed eaves, soffits, and roof projections. Vent openings must be covered with non-combustible, fine mesh (no more than 3 mm apertures).

For all houses except those of construction class CC3, eaves, soffits, and roof projections must be built of non-combustible materials.

Cost for new construction or retrofit: The typical house in the database has composition tile roof, and metal gutters and downspouts. Hanscombe Ltd. and ICLR (2019) estimate that to enclose eaves, soffits, and roof projections adds about $5.00 per square foot to new construction. They estimate trivial added costs for wire mesh over vent coverings. RSMeans (2019d, p. 69) suggests that to retrofit an existing house with enclosed soffits costs about $8.30 to $11.60 per linear foot, or about $10.00 on average.

4.2.4 Door Recommendations

The National WUI Guide calls for exterior doors in CC1(FR) and CC1 to be non-combustible and have 20-minute ratings per CAN/ULC-S104 (Standards Council of Canada 2015). For comparison, the California Building Code (California Building Standards Commission 2019, Sec 708A.3) also requires a 20-minute fire rating *or* any of several options, including merely that the exterior surface or cladding be of non-combustible or ignition-resistant material, or that it be constructed of solid core wood with several detailed requirements. NFPA 1144 (National Fire Protection Association 2018, Sec 5.7.3) offers similar options: solid-core wood, non-combustible material, or a 20-minute rating. Doors on CC2 and CC3 need not be non-combustible and have no minimum fire rating.

Cost for new construction: Home Depot and Lowes both offer a variety of attractive 20-minute fire-rated pre-hung residential 36-inch by 80-inch steel entry doors for about $320 each. Manufacturers of 20-minute pre-hung steel doors include ReliaBilt, Masonite, Jeld-Wen, ThermaTru, and Steves & Sons.

RSMeans (2019a, p. 187) suggests that using metal rather than wood for a 9-foot garage door reduces the cost by about $165. For a 16-foot door, the cost is about the same. Hanscombe Ltd. and ICLR (2019) do not suggest prices for new garage doors.

Cost to retrofit: The retrofit cost for exterior entry doors on existing houses is the same as the renovation cost to demolish and install a residential pre-hung exterior entry door with lights, of medium quality ("better quality" under the terminology of RSMeans 2019d), 36 inches by 80 inches: about $605.00 per door according to RSMeans (2019d).

The retrofit cost to demolish and replace a 9-foot garage door is approximately $1,200 for a one-piece metal door or $1,600 for sectional door, according to RSMeans (2019d, p. 102). For a 16-foot door, the corresponding costs are approximately $1,500 or $1,800, respectively (RSMeans 2019d).

4.2.5 Window Recommendations

The National WUI Guide (Sec 3.3.9) calls for exterior glazing on CC1(FR) and CC1 to comply with SFM Standard 12-7A-2. Glazing on doors should have outer panes of tempered or heat-strengthened glass. Window glazing is not required to have tempered or heat-strengthened glass. So, for new construction, any marginal cost is the added material cost for tempered glass on doors: approximately $6.20 per square foot (Dillmeier Glass Company 2020) versus about $3.75 per square foot for conventional or standard glass (Lowes catalogue 2020). Thus, door glazing adds about $2.50 per square foot, which for the lites (the windows inset in the door) in a typical door appears to be negligible.

4.2.6 Recommendations for Decks, Balconies, and Other Building Attachments

Decks, balconies, and other building attachments for CC1(FR) and CC1 should be constructed of non-combustible material or conform to ASTM E 2726 and ASTM E 2632 requirements for resistance to burning brands and under-deck heating. The National WUI Guide Section 3.3.10 does not appear to call for decks to be enclosed. Fences within 10 metres of the house should be constructed of non-combustible material.

CC2 decks, balconies, porches, and other similar building extensions can be constructed of non-combustible or combustible materials, but should be enclosed without openings greater than 3 mm.

Cost for new construction: Many of the decks and balconies in the existing and post-2000 database appear to be wood. Many are not enclosed, but again enclosure does not appear to be recommended. Thus, the cost implication appears to be in substituting non-combustible material. Wood and wood-plastic composite deck boards and polymer deck tiles appear to dominate the Canadian market, judging by products shown on Home Depot's Canadian website. Aluminum decking would satisfy the recommendation but would look and feel very different from the wood and composite decks common today, and it does not seem like a simple substitute. However, according to Quarles (2009),

> There are several decking products that now meet the performance standards established by the [California Building Code], such as TimberTech XLM (timbertech.com), a solid PVC product with a Class A flame-spread rating, and Trex Accents Fire Defense (trex.com), a wood-polyethylene composite with a Class B flame-spread rating. Also approved for use is nominal 2-by solid-wood decking in several species, including redwood and some types of cedar.

TimberTech (2020) reports that the "TimberTech Azek Vintage Collection meets the requirement for Class A flame spread." TimberTech Azek decking is made of PVC but has a wood appearance and would seem to qualify as a reasonable substitute for the wood and composite common in the present market. Its material cost is $27 per square foot, versus $7 to $17 per square foot material cost for composite decking, a difference of about $15 per square foot. Hanscombe Ltd. and ICLR (2019) also suggest installed square foot costs for fibre cement at $30.20 versus wood deck at $15.61 per square foot, a difference of about $15 per square foot, plus about $0.35 for non-combustible ground cover under the deck. RSMeans (2019a–d) have no entry for decking made of fibre cement.

To retrofit, RSMeans (2019d) suggests demolition of an existing wood deck costs about $1.25 per square foot. Adding the foregoing new cost, including non-combustible ground cover, suggests retrofit costs of about $32.00 per square foot.

4.2.7 Structure Ignition Zones

Hanscombe Ltd. and ICLR (2019) suggest that removing combustible material and replacing it with rock, gravel, or pavers costs between $0.50 and $3.00 per square foot. These costs seem to only apply to retrofit. For new construction, presumably the cost to construct a non-combustible apron around the perimeter is the same as the cost for combustible landscaping.

To retrofit zone 1A with a non-combustible apron would, therefore, cost about $2.50 to $15.00 per linear foot of house perimeter. The project team uses an approximate average of these two values: $8.00 per linear foot.

To retrofit zones 1A and 1 to satisfy Section 3.4.1.2 can demand removing excess vegetation and ongoing vegetation control. Vaske et al. (2016) estimate the cost to remove excess vegetation in Colorado to be approximately $1,000 per acre, with a minimum cost of $1,000 for smaller properties. Maintaining priority zone 1 advises that "ground litter and downed trees should be removed at a frequency not less than annually," referred to here as vegetation control. Spring or fall yard cleanup generally costs approximately $200 to remove old and dying branches and cut back shrubs (HomeAdvisor 2021, Canada YardPro 2021, Halifax Landscaping Pros 2020). Many homeowners clearly do yard cleanup anyway, regardless of whether their home is in the WUI. However, to be conservative and to include some cost for the activities recommended by the National WUI Guide, it seems reasonable to add some cost, for example $100 for a typical house per year, equivalent to a present value of $3,000 for a 75-year life and 3% real discount rate. That $100 annual figure is slightly lower than the $125 assumed in Multi-Hazard Mitigation Council (2019), but is in the same ballpark.

The project team assumes this ongoing vegetation control cost applies up to an area of one acre, then scales linearly with acreage. The cost contributors to recommendations for zones 2 and 3 appear to resemble zone 1. Table 18 summarizes the initial clearing and maintenance costs for zones 1, 2, and 3. In the table, *R* refers to the approximate radius from the centre of the house, *A* is the total area of the priority zones, "clear" is the initial cost to clear the priority zones, "maintain" refers to maintenance costs, and "PV" to the present value using a 3% real discount rate and 75-year life. Figures are rounded to reduce the appearance of excess accuracy.

Table 18. Initial clearing and maintenance costs for priority zones

	R **(m)**	***A*** **(acre)**	**Clear**	**Maintain/year**	**PV maintain**	**PV clear + maintain**
House	7.0					
Zone 1A	8.5	0.06				
Zone 1	17	0.2	$1,000	$100	$3,000	$4,000
Zones 1–2	37	1.0	$1,000	$100	$3,000	$4,000
Zones 1–3	107	9.0	$9,000	$900	$26,000	$35,000

FireSmart Canada (2020) describes Indigenous approaches to vegetation management, though not in monetary terms. It may be that the vegetation control costs estimated here could be reduced using these techniques. In any case, vegetation management, whether by methods described here or those described in FireSmart Canada (2020), can be described as using "naturally occurring resources or engineered use of natural resources, to provide adaptation or mitigation services to the gradual and/or sudden impacts of climate change or natural hazards," the definition of natural infrastructure in Infrastructure Canada (ND, p. 18).

4.2.8 Energy Considerations

Vinyl siding and fibre board exterior cladding have similar insulation properties, with R values around 0.5 (Alaska Housing Finance Corp. 2020). For windows, where double-pane glazing is used to replace single-pane, the homeowner will enjoy energy savings of up to 40% (Natural Resources Canada 2020). The average Canadian household uses about 11,000 kWh of energy per year (Energy Rates Canada 2020), at a cost of about $0.174/kWh (Energy Hub 2020), suggesting an annual energy savings of about $770 per year. Over a 40-year life (Canadian Choice Windows and Doors 2020) at a 3% real discount rate, the energy savings amount to about $21,000. However, single-pane glazing has not been used in new Canadian construction since the middle of the 20th century, so it seems that retrofit to satisfy recommendations of the National WUI Guide will rarely substantially improve the energy efficiency of a house.

4.2.9 Cost Implications for Houses

The project team selects from the foregoing either what appears to be the most plausible candidate costs (if there is any strong reason to believe one option over another) or an average (where two or more costs seem equally plausible). Table 19 provides unit costs for new construction and retrofit. Costs are likely to change over time and perhaps between locations in Canada because of market volatility and local labour prices and availability. These costs may need to be revisited after about five years to ensure that benefit-cost ratios still seem accurate.

Table 19. Unit costs to satisfy recommendations of the National WUI Guide

Item	Unit	New	Retrofit	Delayed retrofit
Ext cladding fibre cement vs. vinyl CC1	sq ft ext wall	($2.72)	$4.05[a]	–
Add type-X GB for CC1(FR) 45-min rated	sq ft ext wall	$0.75	$0.75	$0.75
Add type-X GB CC1(FR) 1-hour rated	sq ft ext wall	$1.12	$1.12	$1.12
Non-combustible roofing	sq ft footprint	–	–	–
Enclose eaves and soffits	lf	$5.00	$10.00	$5.00
Non-combustible exterior entry door	ea	–	$605	–
Non-combustible garage door 9 ft	ea	($165)	$1,400	($165)
Non-combustible garage door 16 ft	ea	($165)	$1,650	($165)
Non-combustible deck and ground cover	sq ft	$15.00	$32.00	$15.00
Non-combustible apron in zone 1A	lf	–	$8.00	$8.00
Vegetation control zone 1 or zones 1–2	ea	$3,000	$4,000	$4,000
Vegetation control zones 1–3	ea	$35,000	$35,000	$35,000
Energy savings: single to multi-pane glass	Property	–	($21,000)	–
Contractor overhead and profit	Project cost	+20%	+20%	+20%

(a) Nil if cladding replacement can be delayed until the vinyl meets the end of its useful life.

Each archetype house can be configured seven different ways to satisfy recommendations in Table 7 of the National WUI Guide. Table 20 shows the combinations of construction class and priority zones, along with a label for the corresponding cost options calculated here. Note that one construction class can have multiple costs because it can appear with more than one set of priority zones. Cost options are unique. Even though "option 5" appears in more than one table cell, each instance has the same cost, as is shown in the following tables. The same is true for the baseline case and options 1, 4, and 6.

Table 20. Cost options to evaluate for each archetype

Exposure level	Priority zones that follow National WUI Guide Section 3.4				
	None	**1A**	**1A and 1**	**1A to 2**	**1A to 3**
Ember-only or low	CC1(FR)[1]: Baseline	CC1: Option 2	CC3: Option 5	CC3: Option 5	CC3: Option 6
Moderate	CC1(FR)[1]: Baseline	CC1(FR)[2]: Option 1	CC2: Option 4	CC3: Option 5	CC3: Option 6
High	CC1(FR)[1]: Baseline	CC1(FR)[2]: Option 1	CC1: Option 3	CC2: Option 4	CC3: Option 6

Table 21 provides estimated total costs to retrofit the moderate-to-high hazard archetype house: $7,000 to $45,000, depending on exposure level and choice to follow priority zone recommendations. Measures that rely on construction class CC1 or CC1(FR) (baseline and options 1, 2, and 3) cost $19,000 to $24,000. Vegetation control in a small-to-moderate yard (options 4 or 5) costs much less: $7,000 to $10,000. Option 6 is much more expensive at $45,000, if the homeowner bears the entire cost of vegetation maintenance over priority zones 1A to 3.

See Table 22 for retrofit costs for the low-hazard archetype house: $8,000 to $45,000. Measures that rely on construction class CC1 or CC1(FR) cost $26,000 to $31,000. As with the moderate-to-high hazard house, options 4 and 5 are much less expensive, about $8,000.

Table 21. Cost to retrofit moderate-to-high hazard house to satisfy the National WUI Guide

Item	Units	Unit cost	Qty	Total
Baseline: CC1(FR) 1-hour rating, where no priority zone recommendations are applied				
No change to roof material	sq ft	$0.00	2,030	$0
Replace exterior cladding (CC1)	sq ft	$4.05	2,184	$8,845
Add type-X GB 1-hour rated	sq ft	$1.12	2,184	$2,446
Replace deck with non-combustible	sq ft	$32.00	0	$0
Replace exterior entry doors	ea	$605	2	$1,210
Replace 9-ft garage door	ea	$1,400	1	$1,400
Enclose eaves and soffits	lf	$10.00	261	$2,610
Subtotal				$16,511
Overhead and profit		20%	$16,511	$3,302
Total[(a)]	sq ft	$15.58	1,272	$19,814
Option 1: CC1(FR) 45-minute rating where zone 1A recommendations are applied				
Baseline subtotal				$16,511
Remove type-X GB 1-hour rated[(b)]	sq ft	$1.12	-2,184	($2,446)
Add type-X GB 45-minute rated[(b)]	sq ft	$0.75	2,184	$1,638
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Subtotal				$17,791
Overhead and profit		20%	$17,791	$3,558
Total[(a)]	sq ft	$16.78	1,272	$21,349
Option 2: CC1 where zone 1A recommendations are followed				
Baseline subtotal				$16,511
Remove type-X GB 1-hour rated	sq ft	$1.12	-2,184	($2,446)
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Subtotal				$16,153
Overhead and profit		20%	$16,153	$3,231
Total[(a)]	sq ft	$15.24	1,272	$19,384
Option 3: CC1 where zone 1A and 1 recommendations are applied				
Baseline subtotal				$16,511
Remove type-X GB 1-hour rated	sq ft	$1.12	-2,184	($2,446)
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Vegetation control zone 1	ea	$4,000	1	$4,000
Subtotal				$20,153
Overhead and profit		20%	$20,153	$4,031
Total[(a)]	sq ft	$19.01	1,272	$24,184

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

(b) Here and elsewhere, we adjust the baseline or other cases by removing items that do not apply and adding new ones that do apply. For example, one-hour rated Type-X gypsum wallboard (generally 5/8-inch thick) costs $1.12 per square foot. We remove it from the baseline case because option 1 does not require one-hour rated gypsum wallboard. The 45-minute rated Type-X gypsum wallboard (generally half-inch thick) costs less, $0.75 per square foot, so we add the lower cost.

Table 21. *continued*

Item	Units	Unit cost	Qty	Total
Option 4: CC2 with zone 1A and 1 recommendations applied. Same as CC2 with zones 1A to 2 recommendations applied				
Enclose eaves and soffits	lf	$10.00	261	$2,610
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Vegetation control zone 1	ea	$4,000	1	$4,000
Subtotal				$8,698
Overhead and profit		20%	$8,698	$1,740
Total[a]	sq ft	$8.21	1,272	$10,438
Option 5: CC3 with zone 1A and 1 recommendations applied. Same as CC3 with zones 1A to 2 recommendations applied				
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Vegetation control zones 1–2	ea	$4,000	1	$4,000
Subtotal				$6,088
Overhead and profit		20%	$6,088	$1,218
Total[a]	sq ft	$5.74	1,272	$7,306
Option 6: CC3 with zone 1A to 3 recommendations applied				
Non-combustible apron zone 1A	lf	$8.00	261	$2,088
Vegetation control zones 1–3	ea	$35,000	1	$35,000
Subtotal				$37,088
Overhead and profit		20%	$37,088	$7,418
Total[a]	sq ft	$34.99	1,272	$44,506
Option 7: Like baseline, delayed retrofit				
Baseline subtotal				$16,511
Remove ext cladding cost	sq ft	$4.05	-2,184	($8,845)
Subtotal				$7,666
Overhead and profit		20%	$7,666	$1,533
Total[a]	sq ft	$7.23	1,272	$9,199
Option 8: Like option 1, delayed retrofit				
Option 1 subtotal				$17,791
Remove ext cladding cost	sq ft	$4.05	-2,184	($8,845)
Subtotal				$8,946
Overhead and profit		20%	$8,946	$1,789
Total[a]	sq ft	$8.44	1,272	$10,735
Option 9: Like option 2, delayed retrofit				
Option 2 subtotal				$16,153
Remove ext cladding cost	sq ft	$4.05	-2,184	($8,845)
Subtotal				$7,308
Overhead and profit		20%	$7,308	$1,462
Total[a]	sq ft	$6.89	1,272	$8,770

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

Table 22. Cost to retrofit a low-hazard house to satisfy the National WUI Guide

Item	Units	Unit cost	Qty	Total
Baseline: CC1(FR) 1-hour rating, where no priority zone recommendations are applied				
No change to roof material	sq ft	$0.00	5,900	$0
Replace exterior cladding (CC1)	sq ft	$4.05	3,058	$12,385
Add type-X GB 1-hour rated	sq ft	$1.12	3,058	$3,425
Replace deck with non-combustible	sq ft	$32.00	0	$0
Replace exterior entry doors	ea	$605	4	$2,420
Replace 9-ft garage door	ea	$1,400	3	$4,200
Enclose eaves and soffits	lf	$10.00	0	$0
Subtotal				$22,430
Overhead and profit		20%	$22,430	$4,486
Total(a)	sq ft	$9.59	2,806	$26,916
Option 1: CC1(FR) 45-minute rating with zone 1A recommendations applied				
Baseline subtotal				$22,430
Remove type-X GB 1-hour rated	sq ft	$1.12	-3,058	($3,425)
Add type-X GB 45-minute rated	sq ft	$0.75	3,058	$2,294
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Subtotal				$24,122
Overhead and profit		20%	$24,122	$4,824
Total(a)	sq ft	$10.32	2,806	$28,947
Option 2: CC1 with zone 1A recommendations applied				
Baseline subtotal				$22,430
Remove type-X GB 1-hour rated	sq ft	$1.12	-3,058	($3,425)
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Subtotal				$21,829
Overhead and profit		20%	$21,829	$4,366
Total(a)	sq ft	$9.34	2,806	$26,195
Option 3: CC1 with zone 1 and 1A recommendations applied				
Baseline subtotal				$22,430
Remove type-X GB 1-hour rated	sq ft	$1.12	-3,058	($3,425)
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Vegetation control zone 1	ea	$4,000	1	$4,000
Subtotal				$25,829
Overhead and profit		20%	$25,829	$5,166
Total(a)		$11.05	2,806	$30,995
Option 4: CC2 with zone 1A and 1 recommendations applied. Same as CC2 with zone 1A to 2 recommendations applied				
Enclose eaves and soffits	lf	$10.00	0	$0
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Vegetation control zone 1	ea	$4,000	1	$4,000
Subtotal				$6,824
Overhead and profit		20%	$6,824	$1,365
Total(a)	sq ft	$2.92	2,806	$8,189

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

Table 22. ***continued***

Item	Units	Unit cost	Qty	Total
Option 5: CC3 with zone 1A and 1 recommendations applied. Same as CC3 with zones 1A to 2 recommendations applied				
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Vegetation control zones 1–2	ea	$4,000	1	$4,000
Subtotal				$6,824
Overhead and profit		20%	$6,824	$1,365
Total[(a)]	sq ft	$2.92	2,806	$8,189
Option 6: CC3 with zones 1A to 3 recommendations applied				
Non-combustible apron zone 1A	lf	$8.00	353	$2,824
Vegetation control zones 1–3	ea	$35,000	1	$35,000
Subtotal				$37,824
Overhead and profit		20%	$37,824	$7,565
Total[(a)]	sq ft	$35.68	1,272	$45,389
Option 7: Like baseline, delayed retrofit				
Baseline subtotal				$22,430
Remove ext cladding cost	sq ft	$4.05	-3,058	($12,385)
Subtotal				$10,045
Overhead and profit		20%	$10,045	$2,009
Total[(a)]	sq ft	$4.30	2,806	$12,054
Option 8: Like option 1, delayed retrofit				
Option 1 subtotal				$24,122
Remove ext cladding cost	sq ft	$4.05	-3,058	($12,385)
Subtotal				$11,738
Overhead and profit		20%	$11,738	$2,348
Total[(a)]	sq ft	$5.02	2,806	$14,085
Option 9: Like option 2, delayed retrofit				
Option 2 subtotal				$21,829
Remove ext cladding cost	sq ft	$4.05	-3,058	($12,385)
Subtotal				$9,444
Overhead and profit		20%	$9,444	$1,889
Total[(a)]	sq ft	$4.04	2,806	$11,333

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

Table 23 presents the marginal cost to build a new house like the archetype in moderate-to-high hazard areas, about $8,000 to $12,000 for options that use construction class CC1 or CC1(FR). Options 4 and 5 are much less expensive, at about $4,000. Option 6 is much more expensive, about $42,000, but it assumes that the homeowner is entirely responsible for vegetation control over the adjacent nine acres.

Table 24 lists the marginal costs for low-hazard areas: from $0 ± $3,000 for options that involve construction class CC1 or CC1(FR). Options 4 and 5 cost about $4,000, while option 6 costs about $42,000, for the same reasons mentioned above.

The project team finds a significant added cost for a new house in moderate-to-high hazard levels to satisfy the National WUI Guide compared to Headwaters Economics (2018) because of two design differences. The house examined by Headwaters Economics (2018) had cedar plank siding, which raises the cost of the as-is house by $26,000, and had no added cost for multi-pane glass with tempered outer pane, which lowers the cost of the retrofit by $1,000 to $2,000.

Many new houses may have cedar plank siding, but few houses in the project team's sample appear to have wood siding. Finding industry studies of the market share for various types of siding is difficult, but several vendors assert that vinyl is the most common by far, followed by aluminum and fibre cement (e.g., TrustedPros 2020, D'Angelo & Sons 2018, Canadian Woodworking and Home Improvement 2017). Cedar seems to be a high-end choice for Canada (Greaves 2017). Correcting for these differences, the project team's findings are in line with the costs suggested by Headwaters Economics (2018).

Table 23. Marginal cost to build new moderate-to-high hazard house to satisfy the National WUI Guide

Item	Units	Unit cost	Qty	Total
Baseline: CC1(FR) 1-hour rating, no priority zone recommendations applied				
No change to roof material	sq ft	$0.00	1,580	$0
Fibre cement exterior cladding CC1	sq ft	($2.72)	2,052	($5,581)
Add type-X GB 1-hour rating	sq ft	$1.12	2,052	$2,298
Non-combustible deck	sq ft	$15.00	800	$12,000
Non-combustible exterior entry door	ea	$0.00	4	$0
Non-combustible 9-ft garage door	ea	($165)	1	($165)
Enclose eaves and soffits	lf	$5.00	156	$780
Subtotal				$9,332
Overhead and profit		20%	$9,332	$1,866
Total[(a)]	sq ft	$6.50	1,724	$11,198
Option 1: CC1(FR) 45-minute rating with zone 1A recommendations applied				
Baseline subtotal				$9,332
Remove type-X GB 1-hour rating	sq ft	$1.12	-2,052	($2,298)
Add type-X GB 45-minute rating	sq ft	$0.75	2,052	$1,539
Non-combustible apron zone 1A	lf	$0.00	156	$0
Subtotal				$8,573
Overhead and profit		20%	$8,573	$1,715
Total[(a)]	sq ft	$5.97	1,724	$10,287
Option 2: CC1 with zone 1A recommendations applied				
Baseline subtotal				$9,332
Remove type-X GB 1-hour rating	sq ft	$1.12	-2,052	($2,298)
Non-combustible apron zone 1A	lf	$0.00	156	$0
Subtotal				$7,034
Overhead and profit		20%	$7,034	$1,407
Total[(a)]	sq ft	$4.90	1,724	$8,440

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

Table 23. *continued*

Item	Units	Unit cost	Qty	Total
Option 3: CC1 with zones 1 and 1A recommendations applied				
Baseline subtotal				$9,332
Remove type-X GB 1-hour rated	sq ft	$1.12	-2,052	($2,298)
Non-combustible apron zone 1A	lf	$0.00	156	$0
Vegetation control zone 1	ea	$3,000	1	$3,000
Subtotal				$10,034
Overhead and profit		20%	$10,034	$2,007
Total[(a)]	sq ft	$6.98	1,724	$12,040
Options 4 and 5: CC2 or CC3 with zones 1A and 1 or zones 1A to 2 recommendations applied				
Enclose eaves and soffits	lf	$5.00	0	$0
Non-combustible apron zone 1A	lf	$0.00	156	$0
Vegetation control zone 1 or 1–2	ea	$3,000	1	$3,000
Subtotal				$3,000
Overhead and profit		20%	$3,000	$600
Total	sq ft	$2.09	1,724	$3,600
Option 6: CC3 with zones 1A to 3 recommendations applied				
Non-combustible apron zone 1A	lf	$0.00	156	$0
Vegetation control zones 1–3	ea	$35,000	1	$35,000
Subtotal				$35,000
Overhead and profit		20%	$35,000	$7,000
Total[(a)]	sq ft	$24.36	1,724	$42,000

Table 24. Marginal cost to build new low-hazard house to satisfy the National WUI Guide

Item	Units	Unit cost	Qty	Total
Baseline: CC1(FR) 1-hour rating, no priority zone recommendations applied				
No change to roof material	sq ft	$0.00	4,400	$0
Fibre cement exterior cladding CC1	sq ft	($2.72)	3,649	($9,925)
Add type-X GB 1-hour rating	sq ft	$1.12	3,649	$4,087
Non-combustible deck	sq ft	$15.00	435	$6,525
Non-combustible exterior entry door	ea	$0.00	4	$0
Non-combustible 16-ft garage door	ea	($165)	1	($165)
Enclose eaves and soffits	lf	$5.00	218	$1,090
Subtotal				$1,612
Overhead and profit		20%	$1,612	$322
Total[(a)]	sq ft	$0.48	3,995	$1,934
Option 1: CC1(FR) 45-minute rating with zone 1A recommendations applied				
Baseline subtotal				$1,612
Remove type-X GB 1-hour rating	sq ft	$1.12	-3,649	($4,087)
Add type-X GB 45-minute rating	sq ft	$0.75	3,649	$2,737
Non-combustible apron zone 1A	lf	$0.00	218	$0
Subtotal				$261
Overhead and profit		20%	$261	$52
Total[(a)]	sq ft	$0.08	3,995	$314

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

Table 24. *continued*

Item	Units	Unit cost	Qty	Total
Option 2: CC1 with zone 1A recommendations applied				
Baseline subtotal				$1,612
Remove type-X GB 1-hour rating	sq ft	$1.12	-3,649	($4,087)
Non-combustible apron zone 1A	lf	$0.00	218	$0
Subtotal				($2,475)
Overhead and profit		20%	($2,475)	($495)
Total[(a)]	sq ft	($0.74)	3,995	($2,970)
Option 3: CC1 with zones 1 and 1A recommendations applied				
Baseline subtotal				$1,612
Remove type-X GB 1-hour rated	sq ft	$1.12	-3,649	($4,087)
Non-combustible apron zone 1A	lf	$0.00	-218	$0
Vegetation control zone 1	ea	$3,000	1	$3,000
Subtotal				$525
Overhead and profit		20%	$525	$105
Total[(a)]	sq ft	$0.16	3,995	$630
Options 4 and 5: CC2 or CC3 with zones 1A and 1 or zones 1A to 2 recommendations applied				
Enclose eaves and soffits	lf	$5.00	0	$0
Non-combustible apron zone 1A	lf	$0.00	218	$0
Vegetation control zone 1 or 1–2	ea	$3,000	1	$3,000
Subtotal				$3,000
Overhead and profit		20%	$3,000	$600
Total	sq ft	$0.90	3,995	$3,600
Option 6: CC3 with zones 1A to 3 recommendations applied				
Non-combustible apron zone 1A	lf	$0.00	218	$0
Vegetation control zones 1–3	ea	$35,000	1	$35,000
Subtotal				$35,000
Overhead and profit		20%	$35,000	$7,000
Total[(a)]	sq ft	$10.51	3,995	$42,000

(a) Total square foot costs are calculated by dividing the total estimated cost by the living area.

4.2.10 Summary of Square Foot Costs for Archetype Houses

One can summarize square foot costs for every cost option. Table 25 presents the marginal square foot costs to retrofit the existing moderate-to-high hazard archetype house to satisfy the National WUI Guide. It is laid out just like the National WUI Guide's Table 7, which shows acceptable combinations of exposure level and priority zones. For example, if vegetation within 100 metres of the house means it has a high exposure level (bottom row) and yard vegetation touches the exterior wall (with no management of priority zones as recommended in the Guide, left column), then the house must be retrofitted to satisfy recommendations for construction class CC1(FR) with one-hour fire-rated exterior walls, at a cost of $16 per square foot of living space, the baseline case detailed earlier in Table 21.

Table 26 does the same for retrofitting the existing low-hazard archetype house. See Table 27 for the new moderate-to-high hazard archetype house and Table 28 for the new low-hazard archetype. The tables round square foot costs to the nearest dollar to reduce the appearance of excessive accuracy. They categorize costs in three broad cost groups:

CG1 Cost group 1, shown with light-shaded cells, corresponds to construction classes CC1 and CC1(FR) with their recommendations for non-combustible cladding, non-combustible decks, etc. The recommendations have stronger influence on retrofit costs than on new construction.

CG2 Cost group 2 is shown with unshaded cells. These cells represent cases where WUI fire risk is controlled largely by vegetation control in priority zones 1 and 2 and without construction class CC1. Cost group 2 tends to have lower costs than either of the other cost groups. The contrast with CG1 is less pronounced or non-existent for the new house archetypes.

CG3 Cost group 3 is shown with dark-shaded cells. These correspond to the buildings that must control vegetation in priority zone 3. They are all of construction class CC3. The cost of vegetation control over a large area drives the high square foot price (which here is calculated as if borne by a single owner). Lower square foot costs for low-hazard new construction is merely an artifact of the archetype house's larger living area in the denominator of the calculation of cost per square foot.

Table 25. Retrofit costs for moderate-to-high hazard archetype house (dollars per square foot)

Exposure level	Priority zones that follow National WUI Guide Section 3.4				
	None	**1A**	**1A and 1**	**1A to 2**	**1A to 3**
Ember-only or low	$16	$15	$6	$6	$35
Moderate	$16	$17	$8	$6	$35
High	$16	$17	$19	$8	$35

Table 26. Retrofit costs for low-hazard archetype house (dollars per square foot)

Exposure level	Priority zones that follow National WUI Guide Section 3.4				
	None	**1A**	**1A and 1**	**1A to 2**	**1A to 3**
Ember-only or low	$10	$9	$3	$3	$36
Moderate	$10	$10	$3	$3	$36
High	$10	$10	$11	$3	$36

Table 27. New construction cost for moderate-to-high hazard archetype house (dollars per square foot over current cost)

Exposure level	Priority zones that follow National WUI Guide Section 3.4				
	None	1A	1A and 1	1A to 2	1A to 3
Ember-only or low	$6	$5	$2	$2	$24
Moderate	$6	$6	$2	$2	$24
High	$6	$6	$7	$2	$24

Table 28. New construction cost for low-hazard archetype house (dollars per square foot over current cost)

Exposure level	Priority zones that follow National WUI Guide Section 3.4				
	None	1A	1A and 1	1A to 2	1A to 3
Ember-only or low	$0	($1)	$1	$1	$11
Moderate	$0	$0	$1	$1	$11
High	$0	$0	$0	$1	$11

Some patterns emerge from these tables. First, retrofit is always costlier than satisfying the National WUI Guide for a new house, so Tables 25 and 26 have higher square foot costs than Tables 27 and 28. Retrofit costs single-digit dollars to tens of dollars per square foot. Costs for new construction ranges from near zero to single-digit dollars per square foot, unless one must control vegetation in a very large yard for many decades, which can cost tens of dollars per square foot of living space.

Second, costs slightly increase from the top to the bottom rows of the tables. Recommendations increase with higher exposure levels, resulting in increasing construction costs. There are exceptions: non-combustible cladding is less expensive than vinyl in the long run because vinyl must be replaced every 20 to 40 years and non-combustible cladding generally lasts the life of the building. Consequently, construction class CC1 (with non-combustible cladding) can be slightly less expensive than CC2 or CC3, which tend to have vinyl cladding.

Third, the costs from the left to the right side of the tables have a bathtub shape: higher on the left, lower in the middle, then higher on the right. Structure recommendations (on the left) are generally more costly than yard maintenance (satisfying priority zones 1A to 2, in the middle). But for very large properties, where up to nine acres of vegetation must be maintained annually (zone 3), the present value of all that maintenance can be very large. In some cases, yard maintenance is more costly than the marginal cost for fire-resistive exterior walls, tempered glass windows, etc.

The cost framework breaks down in WUI neighbourhoods with houses that are close together. In a neighbourhood with houses spaced only a few metres apart, priority zone 3, with a 100 metre radius, can overlap many other properties, as illustrated in Figure 18. The figure shows the approximate boundaries of priority zones 2 (gold) and 3 (yellow) around the house labeled 071, a newer house in a low hazard North Vancouver WUI neighbourhood. If all the neighbours maintain their yards, house 071 could have construction class CC3, but the owner would not have to bear the $11 per square foot cost implied in Table 28. This also means that if neighbours' yards are not maintained, then house 071 might have to be retrofitted from CC3 to CC2, CC1, or even CC1(FR)-45-minute, but that is an implementation issue outside the scope of the present benefit-cost analysis.

Figure 18. A house in the WUI can benefit from shared yard maintenance costs. It can also fail to satisfy the National WUI Guide if owners of any of 10 or more nearby houses fail to maintain their yards.

4.3 Archetype house hazard, vulnerability, and exposure level

4.3.1 Archetype House Hazard

Table 29 provides burn rate *G* for each of the sample communities. The table lists hazard level as defined in the National WUI Guide Section 2.6.2, the name of each of the nine sample communities, the fire regime type at that community according to the maps presented in Erni et al. (2020, Figure 4), and the burn rate in percent per year for that fire regime type according to Erni et al. (2020, Table A2). The table shows weighted average burn rates for the three hazard levels, weighted by the 2016 population of the three sample communities in each category.

The weighted average burn rates shown in Table 29 agree with Taylor's written communication of October 7, 2020, which equates high hazard with a rate greater than 0.217% per year, moderate with 0.013% to 0.217% per year, and low with less than 0.013% per year. Taylor's median rates (written commun., February 12, 2021) are 0.61% per year for high hazard, 0.086% for moderate, and 0.0068% for low. These median values are about 0.82 to 0.92 times the weighted average values shown below. One would expect medians to be lower than expected values for burn rates that are geographically distributed by a power law (at least for a subset of power law distributions with a well-defined mean). For purposes of a benefit-cost analysis, the use of these values seems more appropriate than to use the medians.

Table 29. Fire hazards in sample communities

Hazard	Community	Fire regime type	Burn rate, %/year^{-1}
High	Candle Lake, SK	6	0.7327
	Powerview-Pine Falls, MB	6	0.7327
	Kenora, ON	6	0.7327
	Weighted average		0.7327
Moderate	Penticton, BC	14	0.1654
	Edson, AB	7	0.0872
	Thunder Bay, ON	7	0.0872
	Weighted average		0.1048
Low	Vancouver, BC	15	0.0048
	Parry Sound, ON	1	0.0295
	Saint John, NB	1	0.0295
	Weighted average		0.0074

4.3.2 Archetype House Vulnerability

Table 30 presents the vulnerability functions for the four archetype houses under as-is conditions and conditions that follow National WUI Guide recommendations using equation 5. As noted in Section 3.7.3, equation 5 distinguishes no features besides construction that follows or does not follow recommendations in the National WUI Guide. The expected value of repair cost as a fraction of replacement cost new (called the mean damage factor) is either 50.8% (in the case of construction that does not follow the Guide) or 28.1% (construction that follows the Guide), given that the house is within 100 metres of the fire perimeter. It may seem questionable that the losses are not closer to 100% of value. However, only 54% or 38% of houses within the perimeters of the seven California wildfires of 2017–2018 ignited, according to CAL FIRE.

Table 31 presents the vulnerability functions for the same houses using equations 6a–d and the odds ratios for all the observable features. These vulnerability functions are more extreme: as-is houses have mean damage factors of 70% to 85%, while houses that follow recommendations of the Guide have mean damage factors of 0.2% to 2%. Table 32 presents the vulnerability functions for the same houses using equations 9a–d and the odds ratios for only two features with the most extreme odds ratios – the highest and lowest. These vulnerability functions are more extreme than those calculated using equation 5 and less extreme than those that use all the features: as-is houses have mean damage factors between 64% and 79%, while houses that follow recommendations of the Guide have mean damage factors between 18% and 38%.

It is possible that the vulnerability functions in Table 32 are more accurate than the set in Table 30 (which ignore any detailed features) and those in Table 31 (which may exaggerate the effects of following the Guide by ignoring correlation). On the other hand, they may underestimate the benefit of following the Guide. The low-exposure retrofitted house has a higher vulnerability than the moderate-to-high exposure house. Similarly, the low-exposure as-is new house has a higher vulnerability than the moderate-to-high exposure as-is new house. These are artifacts of limitations in the CAL FIRE data for pZ^*, especially that the CAL FIRE odds ratio figure (Figure 4B) reflects defensible space (structure ignition zone under the National WUI Guide), but the database does not. For these reasons, the project team uses the vulnerability functions in Table 31.

Table 30. Vulnerability (i.e., the response function) by equation 5

	Existing				New			
	Mod-high hazard		Low hazard		Mod-high hazard		Low hazard	
	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide
v_Z	0.94	0.74	0.94	0.74	0.94	0.74	0.94	0.74
p_I	0.54	0.38	0.54	0.38	0.54	0.38	0.54	0.38
$y(x=1)$	0.508	0.281	0.508	0.281	0.508	0.281	0.508	0.281

Table 31. Vulnerability (i.e., the response function) by equation 6 using all relevant features

	Existing				New			
	Mod-high hazard		Low hazard		Mod-high hazard		Low hazard	
	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide
p_{*I}	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
p_{Z*}	0.0051	0.0038	0.0013	0.0077	0.0026	0.0077	0.0064	0.0089
R	5.10	0.02	0.74	0.01	7.94	0.01	2.57	0.00
S	3.20	0.47	0.86	0.46	4.73	0.46	1.84	0.45
p_{ZI}	0.004	0.00008	0.00059	0.00011	0.00231	0.00010	0.00479	0.00003
$y(x=1)$	0.805	0.016	0.437	0.010	0.849	0.010	0.705	0.002

Table 32. Vulnerability by equation 6 with two most important features (largest and smallest *R*)

	Existing				New			
	Mod-high hazard		Low hazard		Mod-high hazard		Low hazard	
	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide	As-is	Follows Guide
p_{Z*}	0.58	0.19	0.58	0.89	0.38	0.13	0.14	0.15
R	4.00	0.40	4.00	0.40	5.00	0.40	5.40	0.22
S	1.994	0.644	1.994	0.695	2.338	0.651	2.957	0.517
p_{ZI}	0.394	0.068	0.394	0.462	0.294	0.046	0.118	0.038
$y(x=1)$	0.640	0.265	0.640	0.383	0.722	0.256	0.789	0.180

4.3.3 Comparison of Vulnerability with Canadian Wildfire Experience

Westhaver (2017) provides FireSmart data regarding 49 houses affected by the 2016 Fort McMurray wildfire. Let us compare that study's data with Table 31, considering low and extreme FireSmart hazard levels, as well as two aggregates (a combination of low and moderate, and a combination of high and extreme). Table 33 shows the probabilities of destruction conditioned on these FireSmart hazard levels. Buildings with low FireSmart hazard ratings experienced an average of 27% loss. Buildings with low or moderate FireSmart ratings experienced an average 34% loss. Houses with high or extreme FireSmart ratings experienced 71% loss. Those with extreme FireSmart ratings experienced an average of 90% loss. Comparing with Table 31, the last two columns bracket as-is mean damage factors. The first two columns are higher than the estimated vulnerability for houses that satisfy the National WUI Guide. One should not read too much into the comparison: Westhaver (2017) made a purposive sample rather than gathering a random sample or offering population statistics.

Table 33. Vulnerability implied by Westhaver's (2017) sample of 49 Fort McMurray buildings

Outcome	Low	Low or moderate	High or extreme	Extreme
Survived	73%	66%	29%	10%
Destroyed	27%	34%	71%	90%
Total	100%	100%	100%	100%

4.3.4 Sample House Exposure Data

Sample houses are selected at random within each sample community. The project team estimates fuel types at 0 to 100 metres and 100 to 500 metres from the house using Google Earth Street View. The project team then determines the exposure level for each house based on the simplified method of the National WUI Guide (see Table 3 in the National WUI Guide). The simplified method seems justified here for at least two reasons. First, the project team lacks mapping data on fuel densities (an element of the detailed method). Second, the National WUI Guide recommends the detailed method when "a high level of accuracy" is needed; it does not seem to be necessary for a statistical study like this where errors will tend to cancel each other.

The fraction of sample houses in each hazard level that have a given exposure level represents an estimate that a house in the general population with that same hazard level would have that same exposure level.

Table 34 shows the estimated probability that a house with a given hazard level (row) has a given exposure level (column), based on the number of observations of exposure level for the 102 houses in the sample. The table combines ember-only and low exposure levels because houses in these two exposure levels have the same construction class according to the National WUI Guide Table 7.
Table 35 shows the same probabilities for the subset of houses that post-date 2000. Newer houses in the moderate hazard communities are more likely to have moderate rather than ember-only or low exposure level, but that could just be because of smaller sample size. Roughly, there is about a 25% chance of low exposure level, 50% chance of moderate exposure, and 25% chance of high exposure.

Table 34. Chance of an existing house having a given exposure level, knowing the hazard level

Hazard level	Exposure level using the simplified method			Sum
	Ember-only or low	Moderate	High	
Low	18%	76%	6%	100%
Moderate	35%	35%	29%	100%
High	26%	59%	15%	100%

Table 35. Chance of a new house (built post-2000) having a given exposure level, knowing the hazard level

Hazard level	Exposure level using the simplified method			Sum
	Ember-only or low	Moderate	High	
Low	7%	93%	0%	100%
Moderate	13%	63%	25%	100%
High	18%	64%	18%	100%

4.4 Per-house benefits and benefit-cost ratios

Table 36 shows retrofit costs and benefits. Costs are shown for each cost group: cost group 1 corresponds to buildings with construction class CC1; cost group 3 corresponds to buildings that have treated priority zone 3, under the assumption that the owner pays for vegetation control over the entire priority zone; and cost group 2 represents the remaining cases of construction classes 2 and 3 with recommended treatment applied to priority zones 1A and either or both 1 and 2. Retrofit appears to be cost-effective for the archetype house in high- and moderate-hazard communities, but not for low hazard. Total costs, benefits, and benefit-cost ratios are rounded to reduce the appearance of excessive accuracy.

Limited burn probability data prevent the calculation of vulnerability and benefit for each allowable combination of exposure level and priority zone. All options that follow Guide recommendations are assumed to produce the same burn probabilities. It may be that both p and v of equation 5 vary enough between priority zone management options that they ought to be estimated separately. More detailed data are needed to do so.

Table 37 presents benefits and costs to build new houses like the archetypes to satisfy the National WUI Guide. The National WUI Guide appears to be cost-effective at all hazard levels. In a place with low hazard, it makes sense to build a new house with construction class CC1 or CC1(FR) because the cost to do so is less than the long-term cost to control vegetation. Applying the National WUI Guide recommendations appears to be cost-effective, both for retrofitting existing buildings and for new buildings in high and moderate exposure levels. Retrofit does not appear to be cost-effective in low-hazard regions, but can be highly cost-effective for new construction. New design tends to be about two to three times as cost-effective as retrofit for high and moderate hazard conditions.

Cost group 2 (vegetation control in priority zones 1A and either or both priority zones 1 or 2) tends to be the lowest-cost option and, thus, the option with the highest benefit-cost ratio. It appears to be two to three times as cost-effective – having two to three times the benefit-cost ratio – compared to the options that involve no priority zone management or management of just zone 1A. Of course, priority zone management needs long-term maintenance (or enforcement on the part of the local jurisdiction). If priority zones 1 or 2 extend onto a neighbour's property or public property, their participation in managing the SIZs will be necessary to meet Guide recommendations. The option for priority zone management from zones 1A to 3 has a low benefit-cost ratio because of the cost to control vegetation all the way to zone 3, with its area being approximately nine acres. If many neighbours and the local jurisdiction share the cost of vegetation control in priority zone 3, and priority zone management can be assured through the life of the houses, then the per-house cost of cost group 3 is about the same as that of cost group 2, and the benefit-cost ratio remains high.

This analysis operates at the level of entire houses. Appendix C includes a brief discussion of the relative benefits of individual fire-resistive features.

Figure 19A illustrates retrofit benefits by category. The figure reflects retrofitting the moderate- and high-hazard archetype house, but the results for retrofitting the low-hazard archetype house are similar. Protecting the building and contents represents half the benefit. Savings on the overhead and profit part of the insurance policy represent another quarter of the benefit (if insurance premiums adjust to the lower risk and that overhead and profit adjust with the pure premium). Deaths and non-fatal injuries represent about one-fifth of the total benefit. The remaining 5% or so of benefits reflect additional living expenses, indirect business interruption (the cost to the broader economy), and environmental impacts (at least that portion that can be monetized). See Figure 19B for the relative benefits of new construction by benefit category. The figure resembles the contributions for retrofit.

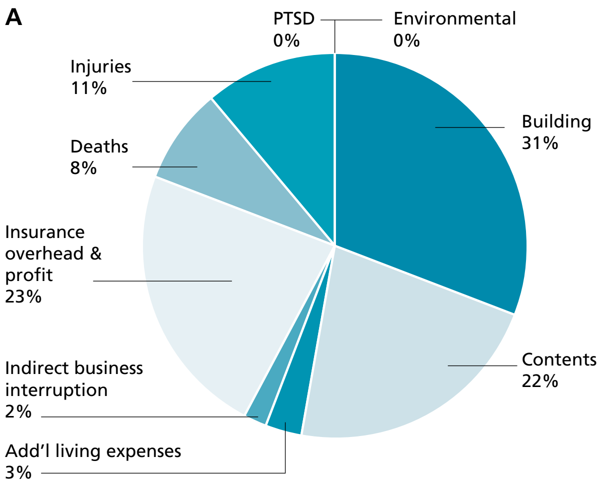
Table 36. Retrofit benefits, costs, and benefit-cost ratios for satisfying National WUI Guide

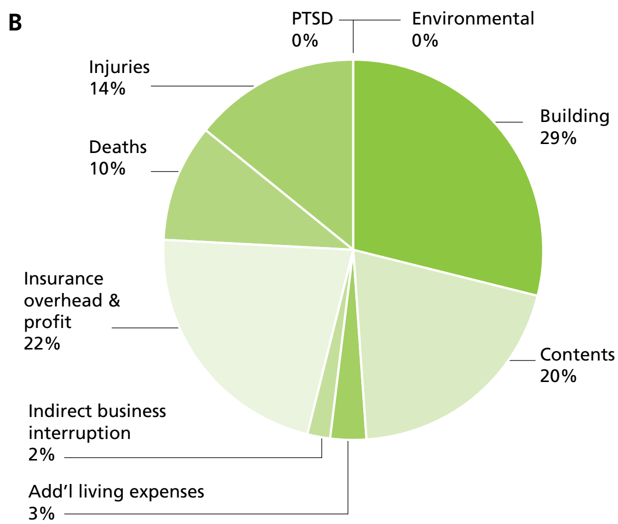
	High hazard level		Moderate hazard level		Low hazard level	
	As-is	**Follows Guide**	**As-is**	**Follows Guide**	**As-is**	**Follows Guide**
Annual monetary loss						
Building	$2,392	$49	$342	$7	$16	$0
Contents	$1,675	$34	$240	$5	$11	$0
Additional living expenses	$254	$7	$36	$1	$2	$0
Indirect business interruption	$120	$3	$17	$0	$1	$0
Insurance overhead and profit	$1,815	$38	$260	$5	$12	$0
Monetary subtotal	$6,256	$131	$895	$19	$42	$1
Annual non-monetary losses (acceptable cost to avoid casualties and pollution)						
Deaths	$302	$8	$43	$1	$2	$0
Injuries	$441	$11	$63	$2	$2	$0
PTSD	$11	$0	$2	$0	$0	$0
Environmental	$4	$0	$1	$0	$0	$0
Non-monetary subtotal	$758	$19	$108	$3	$4	$0
Present value of losses (3% discount rate for monetary losses, 50-year remaining life, with climate change and demand surge)						
Building	$91,355	$1,876	$13,067	$268	$610	$15
Contents	$63,948	$1,313	$9,147	$188	$427	$11
Additional living expenses	$9,719	$253	$1,390	$36	$65	$2
Indirect business interruption	$4,568	$119	$653	$17	$31	$1
Insurance overhead and profit	$69,309	$1,446	$9,913	$207	$463	$12
Deaths	$21,273	$536	$3,043	$77	$117	$4
Injuries	$31,127	$784	$4,452	$112	$171	$5
PTSD	$763	$19	$109	$3	$4	$0
Environmental	$249	$5	$36	$1	$1	$0
Benefit (as-is minus Guide implementation)						
Building	$89,479	31%	$12,798	31%	$595	32%
Contents	$62,635	22%	$8,959	22%	$417	23%
Additional living expenses	$9,465	3%	$1,354	3%	$63	3%
Indirect business interruption	$4,449	2%	$636	2%	$30	2%
Insurance overhead and profit	$67,863	24%	$9,707	24%	$451	25%
Deaths	$20,737	7%	$2,966	7%	$113	6%
Injuries	$30,343	11%	$4,340	11%	$166	9%
PTSD	$744	0%	$106	0%	$4	0%
Environmental	$244	0%	$35	0%	$1	0%
Benefit (nearest $1,000)	$286,000		$41,000		$2,000	
Cost (nearest $1,000)						
Cost group 1 (CC1)	$21,000		$21,000		$28,000	
Cost group 2 (veg control)	$9,000		$9,000		$8,000	
Cost group 3 (management of zone 3)	$45,000		$45,000		$45,000	
Benefit-cost ratio (rounded)						
Cost group 1 (CC1)	14		2		0.1	
Cost group 2 (veg control)	32		5		0.2	
Cost group 3 (management of zone 3)	6		1		<0.1	

Table 37. New design benefits, costs, and benefit-cost ratios for satisfying the National WUI Guide

	High hazard level		Moderate hazard level		Low hazard level	
	As-is	**Follows Guide**	**As-is**	**Follows Guide**	**As-is**	**Follows Guide**
Annual monetary loss						
Building	$2,341	$27	$335	$4	$34	$0
Contents	$1,639	$19	$234	$3	$24	$0
Additional living expenses	$249	$4	$36	$1	$4	$0
Indirect business interruption	$117	$2	$17	$0	$2	$0
Insurance overhead and profit	$1,776	$21	$254	$3	$26	$0
Monetary subtotal	$6,122	$73	$876	$10	$88	$0
Annual non-monetary loss						
Deaths	$318	$5	$46	$1	$3	$0
Injuries	$466	$7	$67	$1	$4	$0
PTSD	$11	$0	$2	$0	$0	$0
Environmental	$4	$0	$1	$0	$0	$0
Non-monetary subtotal	$799	$12	$114	$2	$7	$0
Present value of losses (3% discount rate for monetary losses, 75-year remaining life, with climate change and demand surge)						
Building	$108,730	$1,277	$15,552	$183	$1,569	$6
Contents	$76,111	$894	$10,886	$128	$1,098	$4
Additional living expenses	$11,567	$173	$1,654	$25	$167	$1
Indirect business interruption	$5,436	$81	$778	$12	$78	$0
Insurance overhead and profit	$82,491	$984	$11,799	$141	$1,190	$4
Deaths	$35,909	$524	$5,136	$75	$301	$1
Injuries	$52,543	$766	$7,515	$110	$441	$2
PTSD	$1,288	$19	$184	$3	$11	$0
Environmental	$421	$5	$60	$1	$4	$0
Benefit						
Building	$107,453	29%	$15,369	29%	$1,563	32%
Contents	$75,217	20%	$10,759	20%	$1,094	23%
Additional living expenses	$11,394	3%	$1,630	3%	$166	3%
Indirect business interruption	$5,355	1%	$766	1%	$78	2%
Insurance overhead and profit	$81,507	22%	$11,658	22%	$1,186	24%
Deaths	$35,386	10%	$5,061	10%	$300	6%
Injuries	$51,776	14%	$7,406	14%	$439	9%
PTSD	$1,269	0%	$182	0%	$11	0%
Environmental	$416	0%	$60	0%	$4	0%
Benefit (nearest $1,000)	$370,000		$53,000		$5,000	
Cost (nearest $1,000)						
Cost group 1 (CC1)	$11,000		$11,000		$1,000	
Cost group 2 (veg control)	$4,000		$4,000		$4,000	
Cost group 3 (management of zone 3)	$42,000		$42,000		$42,000	
Benefit-cost ratio (rounded)						
Cost group 1 (CC1)	34		5		5	
Cost group 2 (veg control)	93		13		1	
Cost group 3 (management of zone 3)	9		1		0.1	

Figure 19. Relative contribution by benefit category for (A) retrofit and (B) new design.





4.5 Municipal and utility costs

4.5.1 Policy Analysis and Development Plans

The National WUI Guide Section 4.2.1 discusses policy analysis and development plans. It advises that "the legal framework and norms that guide land use planning differ by community." At a local level, "municipalities develop and implement … detailed tools for land use planning, including community plans, zoning bylaws, subdivision plans or land severances, site plan approvals, and building permits."

The National WUI Guide lists demographic characteristics that could impact planning. For example, the National WUI Guide recommends that communities account for total population count, aging, ownership status, age of housing stock, language, community coordination, income, and disability. But the National WUI Guide offers no guidance on desirable content, level of effort, or expertise to create or modify any planning documents or processes. The project team suspects that many, perhaps most, communities may have difficulties substantially satisfying Section 4.2.1 until its recommendations are specified in more detail, either within the document or in related commentary.

For the same reason, the project team finds estimating costs on an item-by-item basis to be impractical. The project team suggests one possible approach to develop robust, actionable recommendations as follows. The National Research Council could convene working groups of representatives from provincial, territorial, Indigenous, and municipal governments to draft more concrete language for Section 4.2.1. The groups' goal would be to write between one and five pages of text to include in this section that outline how WUI planning should be developed and implemented into laws, bylaws, and ordinances.

Whatever recommendations are ultimately added to the National WUI Guide regarding policy analysis and development plans, they will almost certainly be constrained by what municipalities, provinces, territories, and tribes can afford to do. The added recommendations will remain in some sense proportional to all the other considerations of land-use planning, zoning, and so on, that have nothing to do with WUI. The project team suspects that communities will accept planning recommendations that increase their planning effort by no more than 1%, and perhaps less. For present purposes, the project team assumes 0.5%, or about 1 day per year.

The project team estimates 0.034% of the population is employed as urban planners. It also assumes an average household size of 2.5 people, an annual salary of $86,000 per year, a labour multiplier of 2.0, and a 1% increase in effort. Using these figures implies the National WUI Guide would add 0.00034 (planner per resident) x 2.5 (residents per household) x $86,000 (planner salary per year) x 2 (municipal cost per planner salary cost) x 0.005 (added planner hours per hour of planner labour), or about $0.75 per household per year.

4.5.2 Tax Consequences

The National WUI Guide Section 4.2.2 discusses tax consequences, which presumably, could come from land-use constraints and changes in development. The project team suspects that the National WUI Guide will not impact community growth in terms of the size and speed, or which communities grow. That suspicion is supported by a past CEO of the International Association of Building Officials Inc. (Tim Ryan, verbal commun., January 12, 2021).

Marginal construction costs for new construction of $12,000 could significantly impact affordability. The National Association of Home Builders (Zhao 2020) estimates that "a $1,000 [USD, or CAD$1,250] increase in the median new home price ($344,652) would price 158,857 US households out of the market. In other words, 158,857 households would qualify for the new home mortgage before the change, but not afterwards." For scale, a $1,000 USD increase amounts to 0.3% of $344,562, and 158,857 households represents 0.1% of all US households. It seems likely, however, that much or all the incremental cost would be mitigated or even hidden from buyers by at least four factors:

1. ***Not all households are shopping for homes***. Zhao (2020) writes of how many fewer households in the United States would be unable to afford a new house. But not all 128 million US households are buying houses in any given year under normal conditions. In 2020, the US market for first-time home buyers was about 2.5 million, or 2% of all households (Liu 2020). So the number of households in the market for first-time home buying in any given year who might be at the affordability margin is more like 2% of 0.1% of households, or 1 in 50,000. Second- and third-time home buyers would likely have greater equity than the 10% Zhao assumes, which means that in a community of 125,000 people, one household might be priced out of the market for first-time home purchase in any given year, and fewer second- and third-time buyers. And that number neglects other mitigating factors that follow.
2. ***Trade-offs between fire resistance and features***. One could buy a smaller house or a house with fewer high-end features in exchange for greater fire resistance, which means that a $1,000 increase in the construction cost of a house holding all features constant, does not mean that the house must increase in price by $1,000. New home buyers could buy less house without being priced out of the market.
3. ***Developers would absorb part of the marginal cost***. Developers must compete with the market for existing houses, and so would face market pressure and lower profitability. That is a non-trivial issue, since Canadian developers are, after all, Canadians and would suffer financially from these market pressures.
4. ***Lower mortgage rates reduce monthly cost of ownership***. Monthly costs are what really matter to the home buyer, as opposed to total purchase price. Zhao (2020) assumes a 10% down payment and a 30-year fixed rate mortgage at an interest rate of 3.75% with zero points. As of this writing, 15-year interest rates are under 2%, and a three-year mortgage rate is about 3%. The difference between 3% at 30 years versus 3.75% at 30 years is $1,572 in savings *per year*. This means ordinary fluctuations of interest rates swamp the effect of a $1,500 change in purchase price and might even swamp the changes considered here.

For all these reasons, the project team suspects that implementing the National WUI Guide would neither significantly raise the price of new houses nor significantly reduce the market for development. Household housing budgets would remain constant, new houses in the WUI would become more fire-resistant and either smaller or otherwise less luxurious, the value of new houses would remain constant, and tax revenues would not change, at least not because of land-use constraints or changes to new buildings. This reasoning is supported by the evidence offered by Simmons and Kovacs (2017) summarized in Chapter 2.

However, lower risk from wildfire increases economic stability and, therefore, increases the stability of revenues from income tax and goods and services tax (GST). These accrue approximately in proportion to the reduction in indirect business interruption losses. For GST, the project team estimates 5% of indirect business interruption benefits accrue to the federal government. Provinces enjoy a varying fraction of harmonized sales tax (HST), generally 10% of indirect business interruption benefits.

4.5.3 Access and Egress Routes and Areas of Refuge

As discussed in Chapters 2 and 3, the most expensive, common cost items for access and egress routes and areas of refuge appear to be paving, access routes, and possibly bridges, although other items such as signage and grading changes may also apply. The presumed leading cost items are as follows:

1. ***Paving***. Roads should be built of a hard, all-weather surface. The project team found several neighbourhoods in several of the sample communities with unpaved roads. Overall, 28% of households in the sample lived on unpaved roads. As suggested in Chapter 2, adding a hard, all-weather surface to otherwise unpaved roads in these neighbourhoods would cost approximately $250,000 per mile of undivided two-lane rural road. At 50 households per mile, that equates with about $5,000 per household.

2. ***Access routes***. NFPA 1141 requires one access route for developments with 100 or fewer households, two for developments with 101 to 600 households, and three for more. There are probably neighbourhoods that do not meet this provision. For example, the Candle Lake, Saskatchewan, neighbourhood appears to have only one access route. Another neighbourhood of about 120 homes west of Penticton, BC, also appears to lack sufficient access routes but could be supplied with one by adding 500 feet of road. Using the costs cited in Chapter 2, adding another 500 feet of road to connect the Candle Lake or Penticton developments to a nearby highway would cost $450,000, or about $4,000 per household. Among the sample of 102 households, 3% lacked sufficient access, and in each case, the addition of about 500 feet of road would address the deficiency.

3. ***Bridges***. Some developments may only have access over bridges that cannot support firefighting apparatus, which can weigh 50,000 pounds when fully loaded with water. The project team could find no examples of bridges posted with their live-load capacity near any of the study communities. Presumably, some exist with live-load capacities less than 50,000 pounds. Based on British Columbia costs, replacing a 40-foot, two-lane, single-span bridge can cost $200,000. The project team lacks the data necessary to estimate the quantity of deficient bridges that would need to be replaced.

4.5.4 Enhanced Water Supply for Firefighting

Communities that rely on wells for drinking water could have insufficient flow for firefighting purposes. The project team found a few neighbourhoods in or near some of the sample communities without fire hydrants, suggesting (though not proving) reliance on well water. As discussed in Chapter 2, the cost to provide a municipal water supply system with buried 6-inch mains of ductile iron pipe and hydrants is approximately $1.5 million per mile, which for rural house spacing (200-foot wide lots) amounts to $30,000 per household.

4.5.5 Underground Power, Non-Combustible Poles, and Vegetation Management

The project team was able to find wooden poles in all the sample communities, as well as power lines with vegetation less than 5 metres away. Some neighbourhoods lack any utility poles other than metal streetlights, strongly suggesting underground power lines. As discussed in Chapter 2, replacing wooden power poles with non-combustible poles costs approximately $4,000 per household. Placing the power lines underground would increase that cost to $30,000 per household. Vegetation management costs about $60 per household per year.

4.5.6 Planning for Buses, Watercraft, and Emergency Communication

It is unclear exactly what would be involved in planning for buses, watercraft, and emergency communication. The project team imagines that this would involve approximately 20 to 40 labour hours per year for a medium-sized municipality to draft plans, perform table-top exercises, and arrange agreements with radio, television, telephone, and wireless service providers and with private providers of buses and watercraft. The labour would thus cost a medium-size municipality approximately $1,000 to $2,000 per year. The project team cannot estimate the cost for contingent contracts with providers of buses and watercraft and can only guess that they would be on the same order as the labour costs.

4.5.7 Firefighting Response Planning, Evacuation Planning, and Resources

It is unclear exactly what would be involved in firefighting response planning and evacuation planning, but the project team imagines that this would involve approximately 40 to 80 labour hours per year for fire department leadership in a medium-sized municipality to draft plans, perform table-top exercises, and occasionally exercise WUI fire response activities. If the cost to a community to employ a firefighter is about double the salaries paid, then the added response planning might cost approximately $5,000 to $10,000 per year. Enhanced exercises by fire departments would presumably take the place of other kinds of exercises and not add to the cost of firefighter response planning.

4.5.8 Emergency Communication Equipment, Planning, and Training

Costs for equipment to communicate with the public have already been covered by the National Public Alerting System and Wireless Public Alerting System. Planning effort and labour costs are included through firefighting response planning.

4.5.9 Public Education Development and Implementation

Public education literature already exists, as discussed in Chapter 2. Emergency managers, especially fire departments, can package and distribute this literature to homeowners and homeowner associations. The effort to do so might amount to 8 to 16 labour hours per year for fire department leadership of a medium-sized community, costing perhaps $1,000 to $2,000 per year.

4.5.10 Total Municipal and Utility Costs

For the purpose of estimating municipal and utility costs to implement the National WUI Guide, let us consider a medium-sized community with 20,000 housing units and a population of 50,000 and apply the overall average statistics of road paving, access routes, water supply, etc. As discussed earlier, it is assumed that half the houses (10,000) are in the WUI, less than 500 metres from the wildland. The community has 28% of its WUI housing on unpaved roads. Of households in the WUI, 92% are served by above-ground electric distribution on wooden poles, 83% of which lack 5 metres of clearance between wires and vegetation. About half of the houses in the WUI have fire hydrants.

Table 38 presents an order-of-magnitude estimate of the total municipal and utility costs to implement the National WUI Guide. Most of the total capital cost ($140 million of $170 million) is to construct a piped water distribution system with hydrants within the WUI.

Most of the operation and maintenance cost ($460,000 out of $480,000 per year) is to maintain at least 5 metres of clearance between vegetation and power lines. Costs for a larger or smaller community could vary significantly from these figures and would depend heavily on whether the community already had a piped water distribution system with fire hydrants. Some communities could avoid the large capital cost of a piped water distribution system by acquiring firefighting equipment that could draft and pump from nearby water bodies.

Table 38. Municipal and utility costs for a sample community

Item	Units	Comment
Policy analysis and development plans	$15,000/year	$0.75/household/year x 20,000 households
GST consequences	(5%) of business interruption	GST revenues increase by 5% of business interruption saving (long-term average)
HST consequences	Varies; (10%) of business interruption	HST revenues increase by ~10% of business interruption savings (varies by province)
Paving	$14,000,000	28% x $5,000/WUI household x 10,000 WUI households
Access and egress routes and areas of refuge	–	2 of 9 communities need one additional $450,000 road
Enhanced water supply for firefighting	$140,000,000	47% x $30,000/WUI household x 10,000 WUI households
Power	$460,000/year	92% above-ground electric x 83% without adequate clearance x $60/WUI household/year x 10,000 WUI households
Planning for buses, watercraft, and emergency communication	$3,000/year	
Firefighting response planning, evacuation planning, and resources	$7,500/year	
Emergency communication equipment, planning, and communication	–	
Public education development and implementation	$1,500/year	
Total	$155,000,000 + $480,000/year	Present value for 75 years at 3% = $170 million

4.6 Community-level costs and benefits

4.6.1 Transforming a Sample Community

The cost and benefit to a community from implementing the National WUI Guide both depend on community size, growth, and hazard level. They will change over time as existing houses are either retrofitted or demolished and as new houses are added.

For the purposes of illustration, let us estimate long-term average community benefits at a point 10 years after implementing the National WUI Guide. The reason to choose some specific number of years is as follows: both total costs and benefits change over time as new, fire-resistant buildings are introduced into the building stock, as existing houses are either retrofitted or removed from the building stock, and as the total inventory gradually shifts toward following recommendations in the National WUI Guide. Total dollar costs and benefits grow with that shift, that is, with time. So one must pick a point in time at which to measure those dollar costs and benefits. The project team chose 10 years because that seems to be around the earliest time one might see a significant change in the building stock. A more distant time horizon seems harder for the public to visualize and easier to dismiss as irrelevant.

Imagine that at the end of 10 years, every existing house in the WUI meets Guide recommendations. That could happen through some combination of vegetation management, replacing aging vinyl siding, and people's enthusiasm to cost-effectively reduce their risk. Also imagine that all new houses built in the WUI starting today are built to satisfy the National WUI Guide. The premise might be optimistic. But what would be the consequence for a single community that for some combination of reasons manages to achieve this goal?

For illustration purposes, let us select a single medium-sized sample community with a realistic proportion of its buildings inside the WUI. As discussed in Section 2, Statistics Canada (2012) considers a medium-sized community to have a population of 30,000 to 99,999. Referring to Table 7, Kenora, Ontario, Penticton, BC, and Saint John, New Brunswick qualify as medium-sized. Recall from Table 14 that two of three medium-sized sample communities had about half their housing in the WUI.

Consider a medium-sized population centre with 20,000 housing units, of which half (10,000) are in the WUI at the start of the 10-year period. Let us assume the community grows at about the same rate as Canada's population as a whole, about 1.1% per year (Statistics Canada 2020a). We assume that the new population in the WUI is housed in new homes that follow Guide recommendations, and that for every three new homes, one old home is demolished, as is the case in the United States (Porter and Yuan 2020). Let us assume that new houses are not more likely to be placed in the WUI, or at least that community growth causes the WUI to retreat so that about half of new houses are placed in the WUI.

For the purposes of equations 8–11, b_n, b_r, and b_d are taken from Table 35 and Table 36, and

u_0	=	10,000	initial number of houses in the WUI
r	=	0.011 year^{-1}	population growth rate,
n	=	0.0165 year^{-1}	new houses added per year as fraction of existing
d	=	0.0055 year^{-1}	houses demolished per year as a fraction of existing
t	=	10 years	time at which costs and benefits are calculated

At the end of 10 years, the community that began with 10,000 housing units in the WUI adds approximately 1,700 new units that meet Guide recommendations (an increase of 17%), removes approximately 600 (about 6% of the original stock), and retrofits the remaining 9,400 existing housing units.

Let us now check whether such a transformation is realistic. Certainly, the construction of 1,700 new houses and demolition of 600 old ones comports with population growth. The retrofit of 9,400 existing houses would involve about 940 retrofits a year, versus the construction of approximately 170 a year and demolition of about 60 per year. Transforming four times as many buildings as were built and demolished would seem impractical if the transformation were accomplished structurally, by converting CC2 or CC3 buildings into CC1. The construction industry would have to suddenly double, triple, or quadruple in size. But if the existing houses were retrofitted by a combination of vegetation control and the modest structural recommendations of CC2, the transformation would seem to be more practical, at least as it relates to the existing construction and landscaping industries.

4.6.2 Distribution of Measures among Residences

To estimate community-level costs, one must make some assumptions about how many people choose to satisfy the National WUI Guide using the different available options. Let us assume that most (90%) new houses that follow National WUI Guide recommendations fall into cost group 1 and are built with construction class CC1 or CC1(FR). That might happen so that they can satisfy the National WUI Guide regardless of how well neighbours maintain their yards or how close they are to the WUI. Insurers might encourage that kind of construction using insurance incentives for cost group 1 because satisfying the National WUI Guide via cost group 1 bakes in risk reduction; cost group 2 needs maintenance, and would need the insurer to check that maintenance to ensure the Guide has been followed. Municipalities might also encourage WUI-fire safe construction via cost group 1 to avoid the costs of monitoring vegetation control. The remaining 10% of new houses are brought into concurrence with the Guide via cost group 2, that is, they are built to construction class CC2 or CC3 with vegetation control.

To estimate the community-level costs to retrofit existing houses, the project team makes some additional assumptions regarding how 940 houses a year are brought into concurrence with the Guide. As just noted, without an impractical growth in the construction industry, it seems realistic that only a modest fraction of retrofitted homes – for example, 10% or about 94 per year – could or would be retrofitted along the lines of cost group 1. That is, about 94 existing houses are structurally retrofitted to satisfy recommendations for CC1 or CC1(FR), perhaps those that are normally having their vinyl cladding replaced. In a community with 20,000 housing units, most of which have vinyl siding, about 3% of them (or 600) would have their vinyl cladding replaced in any given year. Half of these (300) would be in the WUI. It seems plausible that one in three homeowners would opt to replace vinyl with non-combustible cladding, especially under the encouragement of the municipality, insurers, and possibly even the real estate industry.

Most of the remaining 90% of retrofitted homes would be brought into concurrence with the Guide largely by vegetation management and fall into cost group 2. A small number are brought into concurrence via vegetation control out to priority zone 3, but let us assume that either the number is very small or the costs are shared among many neighbours, so the high cost of cost group 3 can be ignored. It seems plausible that insurers and municipalities would promote more retrofit through cost group 2 than they do for new construction. Cost group 1 is more expensive and places greater demands on a local construction industry with finite capacity. These estimates suggest total community-level costs to bring homes into concurrence with the Guide of approximately $100 million, as defined in Table 39.

Table 39. Total household costs for community-level implementation

	High hazard	Moderate hazard	Low hazard
Per-household costs, retrofit (Table 36)			
Cost group 1	$21,000	$21,000	$28,000
Cost group 2	$9,000	$9,000	$8,000
Per-household costs, new houses (Table 37)			
Cost group 1	$11,000	$11,000	$1,000
Cost group 2	$4,000	$4,000	$4,000
Number of retrofitted houses			
Cost group 1	940	940	940
Cost group 2	8,460	8,460	8,460
Number of new houses			
Cost group 1	1,560	1,560	1,560
Cost group 2	170	170	170
Total household cost ($ million)			
Total	$110	$110	$100

4.6.3 Total Community-Level Costs and Benefits

Table 40 presents the estimated long-term average costs and benefits to households, the municipality, and the local utility in the sample medium-sized community 10 years after implementing the National WUI Guide. Recall from Figure 19 that 75% to 80% of the benefits are monetary, and the rest is associated with life safety.

The table counts the marginal benefit of having the 1,700 new houses and 9,400 existing houses satisfy the National WUI Guide, and the losses avoided by demolishing 600 existing homes as benefits. The dollar benefit figures already include the value of the avoided monetary and life-safety benefits, but knowing how many deaths, injuries, and instances of PTSD are involved may be valuable. Results are rounded to reduce the appearance of excessive accuracy. As discussed in the methodology section, about 70% of the avoided deaths can be attributed to more fire-resistive buildings, and the other 30% to evacuation communication and resources. The present methodology cannot make similar assertions about avoided non-fatal injuries.

A large population centre (with 100,000 housing units in the WUI) might experience costs and benefits 10 times the values shown in Table 40. A small population centre (starting with 2,000 housing units in the WUI) would experience costs and benefits one-tenth as great as those shown in the table. However, municipal costs would depend greatly on whether the community already had sufficient firefighting water supply, e.g., a piped water supply system with fire hydrants or with firefighting apparatus that could draft from nearby water bodies.

Table 40. Long-term benefit to a medium-size community with 10,000 WUI housing units from 10 years of implementing the National WUI Guide

	High hazard	Moderate hazard	Low hazard
Household cost ($ million)	$110	$110	$100
Municipal and utility cost ($ million)	$170	$170	$170
Benefit ($ million)	$4,000	$570	$30
Benefit-cost ratio	14	2	0.1
Avoided deaths	20	3	0
Avoided injuries	75	10	0
Avoided PTSD cases	75	10	0
Construction and landscape jobs	50	50	40
GST savings ($ million)	$3	$0.4	$0.0
HST savings ($ million)	$6	$0.9	$0.0

The foregoing estimates of community-level costs and benefits account for the sample distribution of houses by exposure level and some realistic assumptions about (1) the fraction of houses in a community that are in the WUI, (2) the different approaches used for new houses and existing houses to satisfy the National WUI Guide, and (3) using the archetype houses to stand in for all houses.

4.7 National benefits

When Johnston and Flannigan (2018) developed their map of the WUI in Canada, no national inventory of the quantity of buildings in the WUI could be determined because they lacked a detailed map of building footprints. Microsoft (2019) has since produced a map of 11.8 million building footprints in Canada. Assuming about 85% are dwellings with an average of three to four people per building (considering single-family and multi-family dwellings), those 11.8 million buildings would house at least 30 million Canadians, or perhaps nearly all 38 million. It may now be possible to estimate population within the WUI.

However, this project team has not performed those calculations and must use more approximate methods to scale up the community-level costs and benefits to the nation. The project team begins with Johnston's (2016) estimate that 60% of communities have some portion of their area in the WUI. Based on the (very approximate) estimates in Table 14, we can estimate that around half of housing in those communities is in the WUI. We assume that 60% of communities is 60% of the population. (Importantly, the population of the smallest 60% of communities accounts for a smaller fraction of the population, but Johnston makes no mention of community size.)

We further assume that low-, moderate-, and high-hazard areas of Figure 6A account for 40%, 40%, and 20% of Canada's WUI population (60% of the nation's population of 38 million people and 15 million households). Table 41 presents an estimate of total national costs and benefits, on a provisional order-of-magnitude basis. Figures are rounded to reduce the appearance of excessive accuracy. Tax savings are already included in the total monetary benefit and are not double counted but are shown separately as well. Again, Figure 19 shows that 75% to 80% of the benefits are monetary, and the rest is associated with life safety.

Table 41. Long-term national benefits and costs of the National WUI Guide

	High hazard	Moderate hazard	Low hazard	National [(a)]
Households in WUI (million)	0.9	1.8	1.8	4.5
Household cost ($ million)	$10,000	$20,000	$18,000	$48,000
Municipal and utility cost ($ million)	$15,000	$31,000	$31,000	$77,000
Benefit ($ million)	$360,000	$103,000	$5,000	$470,000
Benefit-cost ratio	14	2	0.1	4
Avoided deaths	1,800	500	20	2,300
Avoided injuries	6,600	1,900	80	8,600
Avoided PTSD cases	6,600	1,900	80	8,600
Construction jobs	4,100	8,300	6,900	19,000
GST savings ($ million)	$300	$80	$4	$380
HST savings ($ million)	$500	$150	$8	$660

(a) Totals are rounded to reduce appearance of excessive accuracy.

Importantly, benefits and, therefore, benefit-cost ratios vary in direct proportion to burn rates. It would be practical to calculate burn rates by community and thereby improve the estimates of national benefit.

4.8 Climate change and demand surge

The foregoing analyses all account for climate change using the procedures proposed in Section 3.14. The long-term increase in fire frequency suggests that climate change will produce a 42% increase in losses, and, therefore, in benefits and the benefit-cost ratio, relative to a stationary 2010 climate. As previously noted, the project team adds 10% to account for demand surge. Together, these two factors increase losses and, therefore, benefits and benefit-cost ratio by slightly more than 50%.

4.9 Allocation of costs and benefits by stakeholder group

Examining how costs and benefits accrue to different stakeholders in greater detail is worthwhile. Doing so will help proponents of the National WUI Guide understand the interests of decision-makers who follow or decline to follow the National WUI Guide. Table 42 lists stakeholder groups and quantifies how those costs and benefits are distributed. See Multi-Hazard Mitigation Council (2020) for background on this allocation and for ideas on how to align the interests of different stakeholder groups.

Table 42. Allocation of costs and benefits among stakeholder groups

Stakeholder	Costs	Benefits
Developer	CC1 and CC1(FR) costs. Not quantified here: cost to understand and adapt to National WUI Guide recommendations; possibly costs to educate suppliers and contractors.	Lower fire insurance overhead and profit costs during holding period, perhaps 2% of the total of these benefit categories.
First owner	Construction costs transferred from developer; vegetation maintenance costs.	Lower insurance overhead and profit cost. Assuming a 10-year ownership period, perhaps 15% of the total of these categories. Possibly higher resale value (not quantified here).
Later owners	Vegetation maintenance costs; possibly higher purchase price (not quantified here).	Like first owner.
First and later renters and owner-occupants		Lower risk of death, non-fatal injury, and PTSD. Lower content loss. Lower insurance overhead and profit costs for people with renter's insurance. Lower displacement costs, especially uninsured renters. Benefits in these categories in proportion to tenancy period as a fraction of the 75-year life of the property. Non-monetary losses not quantified here: mementos, peace of mind, and pets.
Insurer	Data collection, management, and actuarial analysis associated with policy underwriting that recognizes satisfying National WUI Guide (not quantified here).	Lower building and content claims, lower additional living expense claims, lower claims management costs. Benefits in these categories in proportion to policy life as a fraction of 75-year life of the property.
Lender	Data collection, management, and actuarial analysis associated with mortgage underwriting that recognizes satisfying National WUI Guide (not quantified here).	Lower mortgage default risk (not quantified here).
Municipality	Policy analysis and development plans; paving; added access routes; firefighting response planning, evacuation planning, and resources; planning for buses, watercraft, and emergency communication; public education development and implementation.	Reduced firefighting and other first responder monetary costs and health impacts; lower debris removal costs and environmental impacts; retention of community character; reduced risk of permanent relocation of residents.
Electric and water utilities	Construction of water distribution system; vegetation management around above-ground lines; undergrounding or pole replacement (if used).	Reduced property loss; lower debris removal costs and environmental impacts; greater stability of demand, service, and revenues; reduced risk of permanent relocation of employees.
Taxing authorities		Provinces enjoy a varying fraction of indirect business interruption benefits (generally 10%) through HST stability. Federal government enjoys 5% of indirect business interruption benefits through GST stability.

4.10 Non-residential buildings

This impact analysis focuses on residential construction, but the National WUI Guide considers all building types. Most buildings in the wildland-urban interface are residential, just as most buildings are residential regardless of proximity to the wildland-urban interface. Commercial districts of larger communities tend to be more removed from the wildland, but many are not. A larger fraction of non-residential buildings than residential buildings are built of non-combustible material such as unreinforced or reinforced masonry, but many are built of wood, including commercial buildings in the wildland-urban interface.

5. Conclusions

5.1 Summary of conclusions

5.1.1 Sampling Produced Realistic Archetype Houses

The project team examined 102 houses in nine communities nationwide, including three communities each in low-, moderate-, and high-hazard areas. Sample communities include small, medium, and large population centres spanning the country from British Columbia to New Brunswick.

Archetype existing houses were selected to approximate median characteristics of the sampled buildings in terms of square footage, storeys, cladding, and roofing. Archetype houses were selected to represent new construction from a subset of sampled houses built since 2000.

The archetypes are real houses drawn from Zillow.com. Selecting archetype houses in this way reduces the chance for the project team to skew results to accidentally favour either more or less costly mitigations to satisfy the National WUI Guide. The archetypes seem more plausible because they are real houses.

5.1.2 New Construction Costs $6.00 More Per Square Foot

It costs about $6.00 more per square foot, or about $12,000 total for a new 2,000-square foot house, for new construction to satisfy the National WUI Guide by structural means, i.e., using construction class CC1 or CC1(FR). The cost is about a third of that if one can control vegetation in the 10 to 30 metres nearest the house (priority zones 1 and 2). This finding contrasts with that of Headwaters Economics (2018), which estimates that it is less expensive to build a fire-resistant house than a typical one. However, Headwaters uses a typical house under as-is conditions with relatively expensive cedar plank siding. By contrast, most of the 102 houses sampled here appear to have vinyl siding. Our sample agrees with at least four Canadian vendors and trade magazines, who assert that vinyl is the most common siding for Canadian construction by far, and at least one asserted that wood siding is a rare, high-end choice. The difference accounts for $10.00 per square foot of construction cost. The difference highlights the importance of using a careful sample of real houses to characterize the attributes of the building stock. A made-up example cannot be used without running the risk of biasing the results.

5.1.3 Retrofit Costs $16.00 Per Square Foot

We found that it costs about $16.00 per square foot to retrofit an existing archetype house to satisfy the National WUI Guide by structural means, i.e., using construction class CC1 or CC1(FR). The cost comes mostly from replacing vinyl cladding with non-combustible cladding and replacing windows that have non-tempered outer panes with windows that have tempered outer panes. Thus, to retrofit a 2,000-square foot house immediately costs about $32,000. Retrofit cost is much lower, about $7.00 per square foot of living space, if one can control vegetation within 10 to 30 metres of the house instead of structurally retrofitting the cladding and glazing.

5.1.4 National WUI Guide Saves Up to $34 Per Added $1 of Cost

The benefit of satisfying the National WUI Guide is mostly driven by the frequency with which houses experience wildfires. In high-hazard areas, the benefit-cost ratios are estimated to be 34:1 for new construction and 14:1 for retrofit. Mitigation via vegetation management in priority zones 1 and 2 is even more cost-effective by a factor of two to three, although more problematic to ensure for the long term.

In regions of moderate hazard, we estimate the benefit-cost ratios to be up to 5:1 for new construction and about 2:1 for retrofit by purely structural mitigation. Benefit-cost ratios are three times higher if one can rely on vegetation management. In low-hazard locations, retrofit is not cost-effective, but new construction that satisfies the National WUI Guide through structural means also has a benefit-cost ratio of 5:1, thanks to lower costs and a longer remaining useful life.

These benefit-cost ratios account for climate change, which tends to increase future losses and, therefore, increases benefits and benefit-cost ratios. The climate projections considered here suggest that climate change will increase average fire losses and, therefore, benefit-cost ratio by about 40% relative to a stationary 2010 climate. Demand surge (the temporary local increase in construction costs associated with higher labour costs) further increases benefits by about 10%.

5.1.5 Community Costs Vary by Need

Table 43 recaps the community costs estimated here. Some apply on a household basis, some by neighbourhood, and some by municipality. Some are capital costs, while others apply annually, as noted in the table. Some are highly approximate and may only be accurate on an order-of-magnitude basis.

Table 43. Community costs to satisfy recommendations of the National WUI Guide

Item	Cost	Comment
Policy analysis, develop plans	$1.50 per household per year	
Tax consequences	None foreseen	Long-term increase and stability in provincial and national tax revenues per Table 41.
Paving roads in unpaved neighbourhoods	$5,000 per household	Only count households in unpaved neighbourhoods.
Add access routes in neighbourhoods	$500,000 per access route	One for neighbourhoods of 101 to 600 households with only one access route, one for neighbourhoods of 601 or more households, and two for neighbourhoods of 601 or more households and one access route.
Add bridge on access route	$200,000 per bridge	Two-lane stream crossing on a neighbourhood access route.
Water supply	$30,000 per household	Only for neighbourhoods without sufficient piped water and fire hydrants.
Underground electricity	$30,000 per household	Optional; least likely electricity options to be used.
Non-combustible utility poles	$4,000 per household	Appears to be optional.
Vegetation management near power lines	$6 per household per year	
Bus, watercraft, and emergency communication plans	$1,500 per municipality per year	
Firefighting response planning, evacuation planning, and resources	$7,500 per municipality per year	
Emergency communication equipment, planning, and training	None foreseen	
Public education development and implementation	$1,500 per municipality per year	

5.1.6 Community Benefit-Cost Ratio of 14:1

After 10 years of new construction that satisfies the National WUI Guide and retrofit of existing houses, a community of 50,000 people with about 20,000 housing units, including 10,000 in the WUI, will add about 1,700 new houses in the WUI. Fully following the National WUI Guide would mean retrofitting about 9,400 existing houses and removing about 600 older homes from the building stock in the WUI.

In a community in a high-hazard location, the benefits that result from those changes will produce a long-run average benefit of $4 billion in avoided future losses to the building stock, save 20 lives, and avoid 150 injuries and instances of PTSD. The construction, retrofit, and maintenance work would add about 50 long-term jobs.

The aggregate benefit-cost ratio to a community in a high-hazard region is about 14:1, counting benefits and costs to homeowners, tenants, the broader economy, the municipality, and utilities. The benefit-cost ratio that remains inside the property lines (that is, costs and benefits to owners and tenants) is about 35:1. These are long-run averages, accounting for probabilities of ignition and damage.

It is useful to understand exactly how or where the 20 lives are saved, and whether people survive because their house or emergency responders protect them or because they evacuate more safely. The model developed here is simple, perhaps overly so. The estimate of 20 lives saved assumes that people die in approximate proportion to the number of houses that burn down, and that US fatality rates per destroyed house apply to Canada. The life-safety benefits do not imply that it is safe to stay and defend the home; evacuation when instructed still makes sense. The National WUI Guide does not recommend residents stay and defend their homes in place. But, in fact, many people fail to evacuate for a variety of reasons. So for reasons discussed earlier, it seems reasonable to attribute about 70% of avoided deaths to fire resistance of homes and 30% to communication and other community resources.

In a moderate-hazard, medium-sized community, the benefits still outweigh the costs: $570 million saved at a cost of $280 million (total societal cost, of which about $110 million is paid by homeowners). Following the National WUI Guide saves three lives and avoids about 10 injuries and 10 instances of PTSD.

5.1.7 National Benefit-Cost Ratio of 4:1

If the National WUI Guide were followed nationwide, after 10 years it could embed about $470 billion in long-term fire savings in new and retrofitted existing housing stock, at a long-term cost of about $48 billion to owners and $77 billion to municipalities and utilities. Thus, we estimate an overall benefit-cost ratio of approximately $4 saved per $1 spent.

Adopting the Guide would save over 2,000 lives and avoid 9,000 injuries and 9,000 instances of PTSD after 10 years. It would generate about 19,000 long-term jobs, and HST and GST revenues would experience greater stability and higher long-term average values. Savings baked into 10 years of nationwide use are estimated to exceed $1 billion.

Most of the municipal cost would take the form of providing adequate firefighting water supply with fire hydrants. Most of the utility cost would take the form of maintaining 5 metres of clearance between electric distribution lines and nearby vegetation.

The foregoing totals reflect the savings embedded in the housing stock after 10 years. Costs would be realized in those 10 years, while benefits would be realized over the subsequent life of the mitigated property. Both costs and benefits are depicted in present-value dollars, discounting monetary benefits at 3% per year over a 75-year useful life of the property. Benefits would continue to accrue as new housing is built to satisfy the National WUI Guide.

The same general principles apply to non-residential building stock. However, the non-residential building stock amounts to perhaps 15% of the residential stock. It tends to be in city centres farther from the WUI, and non-residential buildings in the WUI might amount to only 5% to 10% of residential WUI buildings. Thus, if we were to account for non-residential buildings, the total costs and benefits might rise by perhaps 5% to 10%.

The 4:1 benefit-cost ratio estimated here falls somewhat lower than the 6:1 estimate in our prior study (Porter and Scawthorn 2020), but still generally agrees. The discrepancy is reasonable given that the prior study excluded municipal and utility costs, especially paving, firefighting water supply, and vegetation control near electric distribution system lines. Adding these costs reduces the benefit-cost ratio. The prior study also differed in some details, especially in that it did not consider using construction classes CC2 and CC3 in combination with vegetation control in priority zones 2 and 3.

5.2 Innovations and new insight produced here

5.2.1 New Method to Estimate Fire Vulnerability

The project team drew on observations of 1,065 California structures that experienced the 2018 Camp Fire, whose fire-resistive attributes CAL FIRE examined in detail in the year prior to the fire. CAL FIRE was able to use those data to develop odds ratios for a structure experiencing ignition when exposed to the fire. The project team used these odds ratios and the underlying observational data to estimate the ignition probability for each of the archetype houses, both before and after retrofit or design to satisfy recommendations of the National WUI Guide. Some underlying ignition probability and damage data drew on CAL FIRE data from fires between 2014 and 2019. The resulting vulnerability methodology reduces our reliance on expert judgment, which had been required for the *Natural Hazard Mitigation Saves* study (Multi-Hazard Mitigation Council 2019).

Westhaver, working with the ICLR, has produced similarly useful data from the Fort McMurray wildfire. Future data collection like that of Westhaver and CAL FIRE could further improve the response functions, especially by considering application of priority zone recommendations and correlation among fire-resistive features.

5.2.2 New Benefit-Cost Analysis for WUI Fire Mitigation

The Multi-Hazard Mitigation Council (2019) appears to represent the first large-scale benefit-cost analysis of WUI fire mitigation. The present analysis expands on the prior study in several ways. First, it reflects the recommendations of Canada's National WUI Guide, which differ from those of the United States. Second, because it draws on new empirical vulnerability information derived from recent CAL FIRE data, it has a stronger empirical basis. Third, it reflects Canada's WUI fire hazard from Erni et al. (2020). Fourth, it employs four detailed, realistic archetype houses whose attributes reflect median values from a representative sample of 102 Canadian houses. Because of that, it was practical to estimate detailed costs and long-term average benefits for new and retrofitted houses. Fifth, it provides new details of benefits in terms of avoided losses in nine categories:

1. Building repair cost
2. Content loss
3. Additional living expenses
4. Indirect business interruption
5. Insurance overhead and profit
6. Deaths
7. Non-fatal injuries
8. Instances of PTSD
9. Pollution

5.2.3 New Insight into Where the National WUI Guide Is and Is Not Cost-Effective

The study demonstrates, at least on a preliminary basis, that the National WUI Guide makes long-term economic sense (at least in terms of benefit-cost ratio) in Canada's moderate- and high-hazard areas, and not (apparently) for retrofit in low-hazard areas. However, new construction in low-hazard areas that satisfies the National WUI Guide can be cost-effective, especially if implemented structurally by improving cladding, glazing, and fire-resistive features of the building.

5.2.4 Disagreement About Cost

Like *Natural Hazard Mitigation Saves* (Multi-Hazard Mitigation Council 2019), this study suggests that satisfying the National WUI Guide may not be cost-free for the typical house, although the cost estimated here is somewhat lower than the cost in that work. The agreement does not result from the fact that the same project team performed both cost estimations. The cost estimates were performed on different archetype houses and by different analysts. (In the former case, Scawthorn examined one house; in the present case, Porter examined four houses.)

The agreement between *Natural Hazard Mitigation Saves* and the present study, and their disagreement with Headwaters Economics (2018), does not mean that the present study is right and Headwaters Economics is wrong. Rather, it suggests that satisfying the National WUI Guide sometimes has a positive initial cost (as with the archetype houses examined here and in Natural Hazard Mitigation Saves) and sometimes produces initial savings (as found by Headwaters Economics).

5.3 Limitations and future work

All studies are limited. Table 44 lists 12 opportunities to build on the present study with details following. The topics are grouped in three broader categories: the science of climate change, engineering details to develop the National WUI Guide into a standard, and social issues about Indigenous and northern communities.

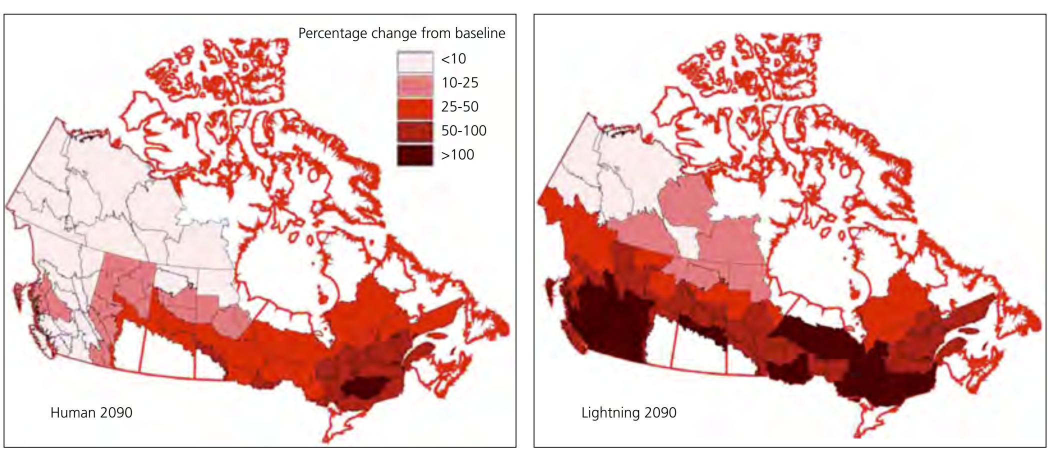
Table 44. Summary of limitations and opportunities for future work

A. Climate change
1. Refine wildfire frequency, severity, and firefighting considerations
B. From guide to standard
2. Develop user tool to estimate user-specific impacts
3. Produce incentives to align stakeholder interests
4. Develop a guide to nature-based fire management
5. Examine health effects of volatile organic compounds
6. Estimate impacts on renters and economically disadvantaged people
7. Better understand Canadian fire vulnerability
8. Reconcile recommendations with NBC and other codes
9. Understand public service, emergency response, historical and cultural impacts
10. Examine commercial and other non-residential buildings
C. Indigenous people and northern communities
11. Detail Indigenous nature-based solutions
12. Estimate impacts on Indigenous people and northern communities

5.3.1 Climate Change Issues

1. ***Refine wildfire frequency, severity, and firefighting considerations***. The present analysis accounts for climate change solely through changes in nationwide ignition frequency (Figure 20). NRC could undertake a deeper analysis accounting for spatially and temporally varying burn rate, fire severity, and firefighting capability. It could assign hazard level by future burn rate, rather than based on past hazard. Doing so would make hazard levels more consistent with the goals of the National WUI Guide and demonstrate its relevance to communities that do not yet recognize how it matters to them.

Figure 20. Projected increase in fire occurrence rate relative to the period 1980–2005 (Wotton et al. 2010).



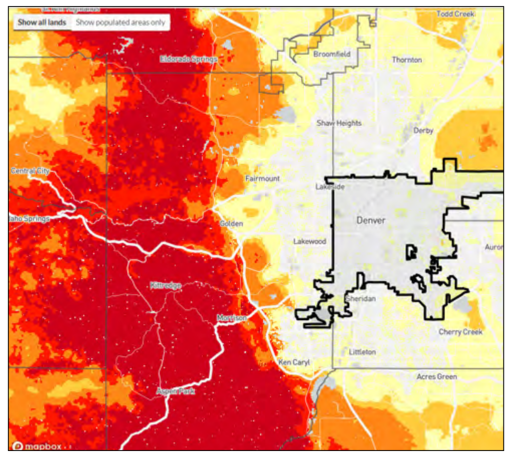
5.3.2 From Guide to Standard

2. ***Develop user tool to estimate user-specific impacts***. The present study presents impacts on archetypes houses, communities, and the nation, but does not speak to homeowners and other stakeholders about their specific properties. NRC could develop a web-based user tool that communicates risk, costs, benefits, and stakeholder shares, with elements like those shown in Figure 21. Doing so would help homeowners to better understand the value of the National WUI Guide and facilitate voluntary uptake.

Figure 21. Possible elements of a web-based user tool: mitigation options, costs, benefits, and risk map. (Map image: public domain)

Exposure level	Priority zones compliant with National WUI Guide Section 3.4				
	None	1A	1A and 1	1A to 2	1A to 3
Ember-only or low	$6	$5	$2	$2	$24
Moderate	$6	$6	$2	$2	$24
High	$6	$6	$7	$2	$24

Benefit (nearest $1,000)	$444,000	100%	$63,00
	Cost (nearest $1,000)		
Cost group 1 (CC1)	$10,000		$10,
Cost group 2 (veg control)	$4,000		$4,
Cost group 3 (compl Zone 3)	$42,000		$42,
	Benefit-cost ratio (rounded)		
Cost group 1 (CC1)	44		
Cost group 2 (veg control)	111		1
Cost group 3 (compl Zone 3)	11		



3. ***Produce incentives to align stakeholder interests***. This study discusses how misaligned interests among stakeholders could inhibit uptake of the National WUI Guide. NRC could collaborate with the National Institute of Building Sciences' incentivization project (Multi-Hazard Mitigation Council 2020) to produce incentives suggested in Figure 22 to align the interests of various stakeholders and promote use of the National WUI Guide.

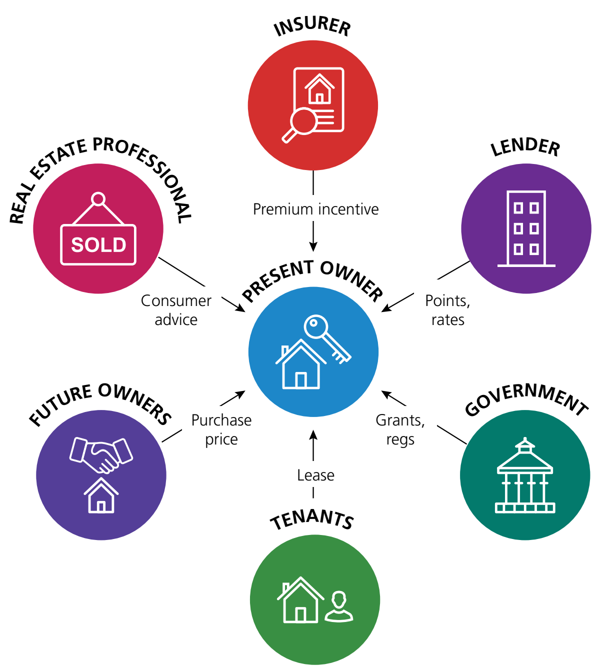
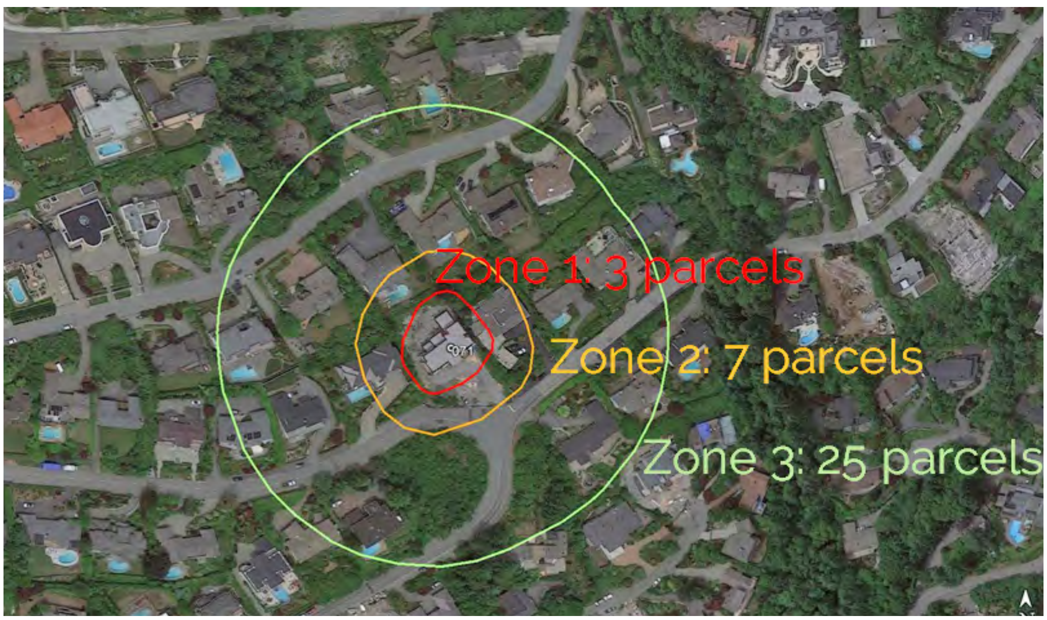


Figure 22. Incentives from co-beneficiaries to the present owner can help offset the cost of mitigation. (Image: Porter 2020, with permission)

4. ***Develop guide to nature-based fire management***. The study found that vegetation management according to the National WUI Guide is highly cost-effective, but priority zones 1, 2, and 3 may touch multiple parcels. Vegetation management can require long-term cooperation among multiple property owners and potentially the municipality or other public landowner. Figure 23 illustrates the problem for one of the sample properties examined here, in which priority zones 1, 2, and 3 touch 3, 7, and 25 parcels, respectively. NRC could develop a guide for how to coordinate vegetation control, with detailed options for different ways to do so.

Figure 23. Vegetation management in priority zones 1, 2, and 3 can require cooperation between many property owners.



5. ***Examine health effects of volatile organic compounds***. The present analysis treats environmental impacts solely in terms of tons of CO_2 produced when houses burn down and the monetary cost of carbon credits. But what are the health impacts of burning the volatile organic compounds the average house contains, for example textiles (an average 121 m^2 house contains 720 kg), polyvinyl chloride (240 kg), polyurethane (240 kg), and polyethene (100 kg)? Are they released into the air (Figure 24), soil, or water? Examining this topic will serve public health, improve the benefit-cost ratio, and engage the public health community in advocating for the National WUI Guide.

Figure 24. What are the health impacts of burning 1,300 kg of volatile organic compounds? (Image: Harvest, CC BY-SA 4.0)

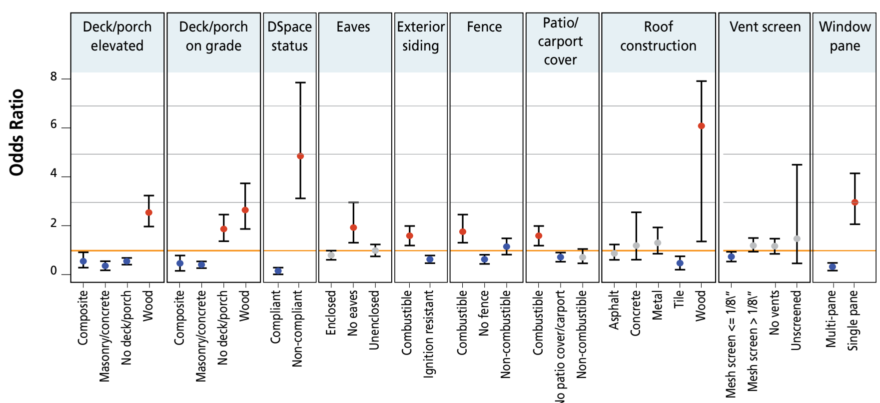
Figure 25. A townhouse for rent in Penticton, BC

6. ***Estimate impacts on renters and economically disadvantaged people***. The present analysis presents benefits at the societal level and does not distinguish between owner-occupied homes and rental units. Rentals currently represent 32% of Canadian homes. Would rental units (e.g., Figure 25) be impacted differently because of their physical characteristics, location, or other attributes? Would owners be less likely to satisfy recommendations of the National WUI Guide because they enjoy a smaller fraction of the benefits? NRC could examine the impacts of the National WUI Guide on rental units. Doing so will better serve the needs of over 30% of Canadians and shed light on a potential barrier to uptake.

7. ***Better understand Canadian wildfire vulnerability***. The present analysis relies on detailed data from houses in California. The National WUI Guide overlaps heavily but not completely with the California Building Code, for example differing in measures for priority zones. The present study shows general agreement between California and Westhaver's (2017) analysis (Section 4.3.3), but NRC could update the response functions developed here by closer synthesis with Westhaver (2017, Figure 26) and possibly others. Doing so will advance basic knowledge of fire risk, improve the impact analysis, and boost its credibility.

Figure 26. Reconciling or merging California (left) and Canadian (right) data could improve NRC's understanding of fire response functions for Canadian buildings. (Top image: CAL FIRE 2020; bottom image: Westhaver 2017)

Camp Fire Odds Ratio (OR) for each construction feature by sub-material and DSpace status for structures with a corresponding DSpace and DINS point.



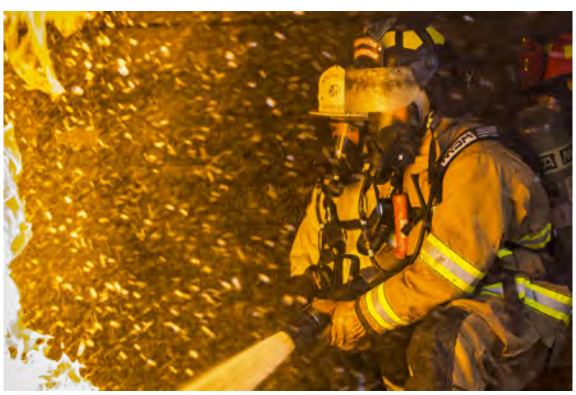
Red points were variables with an OR and 95% CI greater than one, grey point CI fell within one, and blue point OR and 95% CI fell below one.

FireSmart Hazard Level for All Homes Assessed in All Situations								
	Low (0-42 points)		Moderate (43-58 points)		High (59-70 points)		Extreme (71+ points)	
	'FireSmart' rated				Not 'FireSmart' rated			
	#	%	#	%	#	%	#	%
Paired Urban Homes – Survived	10	77	2	15	1	8	0	0
Paired Urban Homes – Destroyed	4	31	4	31	1	7	4	31
High Heat Exposure – Survived	3	100	0	0	1	0	1	0
Isolated Urban Ignitions – Destroyed	2	40	1	20	0	0	2	40
Isolated Urban Survivors	2	40	0	0	1	40	0	20
Paired C. R.* Homes– Survived	1	20	3	60	1	20	0	0
Paired C. R.13 Homes – Destroyed	0	0	0	0	2	40	3	60
Surviving Homes by Haz. Level (N = 26)	16	62%	5	19%	4	15%	1	4%
Homes Destroyed by Haz Level (N = 23)	6	26%	5	22%	3	13%	9	39%

8. ***Reconcile recommendations with NBC and other codes***. The present analysis does not attempt to reconcile the National WUI Guide with the National Building Code or with other building codes. Cross-committee coordination will address possible conflicts over capillary breaks (Figure 27), ventilation, energy, and possibly other recommendations. Doing so will address justifiable concerns of builders, make it easier for homeowners to satisfy recommendations of the National WUI Guide, and facilitate enforcement by building officials.

9. ***Understand public service, emergency response, and historical and cultural impacts***. We have not estimated the effect of the National WUI Guide on public services, emergency response costs (e.g., Figure 28), and historical or cultural impacts. NRC could undertake this, with input from firefighting professionals and historical and cultural experts. Better understanding of these issues may improve buy-in from emergency response agencies, as well as historical and cultural communities.

Figure 28. Would more fire-resistant houses reduce firefighting costs? (Image: public domain)



10. ***Examine commercial and other non-residential buildings***. Many combustible non-residential buildings stand in the wildland-urban interface (Figure 29). Commercial and industrial buildings that satisfy the National WUI Guide might yield much greater reduction in business interruption and job losses, as well as increased sales tax revenues, making an even stronger business case. Schools, emergency service buildings, and other communal buildings might yield much greater benefits in public services, life safety, and cultural and historical values. Topic 9 discussed the need for methods to set a monetary value on public service and historical and cultural resources, which would help inform this topic.

Figure 27. The National WUI Guide will need cross-committee coordination to address possible conflicts over capillary breaks, ventilation, energy, and possibly other recommendations. (Image: public domain)

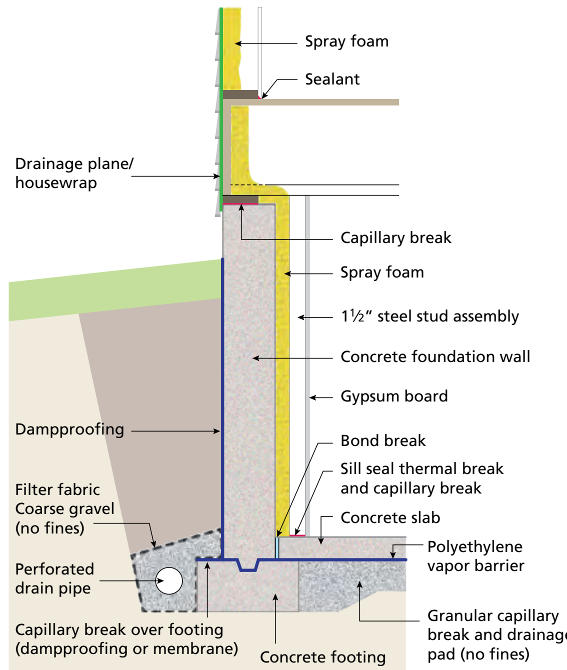


Figure 29. Businesses in Candle Lake, SK, face the same fire hazard as houses, with a much greater potential for business interruption losses, job losses, and tax revenue impacts. (Image: Google Earth)

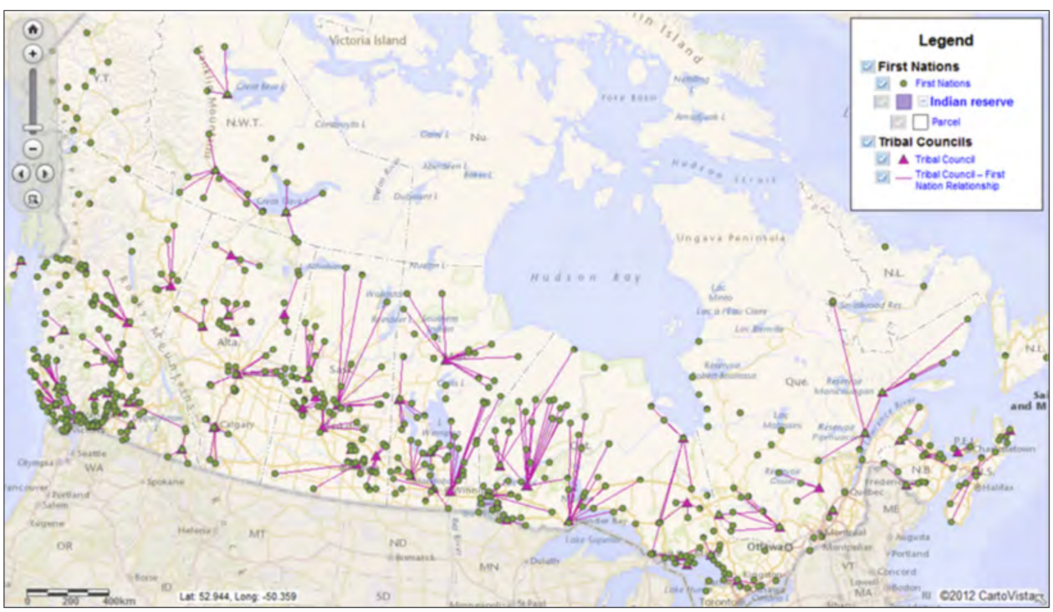
5.3.3 Indigenous People and Northern Communities

11. ***Detail Indigenous, nature-based solutions***. The study found that vegetation management to satisfy recommendations of the National WUI Guide is highly cost-effective and that Indigenous communities have achieved lower exposure levels using natural infrastructure (e.g., Figure 30). NRC could collaborate with Indigenous experts to develop detailed implementation guidance, which could help to spread mature, practical guidance from Indigenous communities and facilitate collaboration between Indigenous and non-Indigenous communities.

12. ***Estimate impacts on Indigenous and northern communities***. The present analysis examines a stratified sample that spans communities by hazard level, community size, and longitude. It also examines the impact of the National WUI Guide on Indigenous communities that are adjacent to other sample communities, but where it does so, it lacks important house-specific details that require real estate data. It does not address northern communities that can be geographically isolated with less access to mutual aid from nearby communities. An analysis of following the National WUI Guide in Indigenous and northern communities might reveal different impacts (Figure 31), which is important to better engage them and serve their needs.

Figure 30. Indigenous nature-based solutions can represent a highly cost-effective implementation strategy for the National WUI Guide. (Image: FireSmart Canada 2020)

Figure 31. An analysis of isolated Indigenous and northern communities might reveal different impacts.



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Appendix A: Principles of archetype selection

A.1 Comparison with CHBA discussion document

The Canadian Home Builders' Association (2020) proposes "a set of guiding principles that can be used to create house archetypes and select statistical data for impact analysis of proposed provisions in codes, standards and guides." The procedure used to select archetypes in the present study seems to agree with all the discussion document's principles, at least to the extent that they apply to the National WUI Guide and with practical limits on the number of archetypes that can be examined in the present study. This appendix details how the present study accords with each principle.

A.2 Principle 1: Data source, scope, and scalability

1 a) Develop archetypes or their features, wherever possible, from publicly available data sources or re-use archetypes from previous evaluations of proposed measures.

Authors' response: In the present impact analysis, we rely solely on publicly available, free data from Zillow.com and Google Earth. We understand that NRC purchased data about approximately 1,000 buildings from CMD Group (M. Leslie Inc. 2015). It might be valuable to compare these data with the archetypes examined here. None of the buildings in the CMD Group dataset seem to be single-family dwellings (M. Leslie Inc. 2015, p. 6), but most Canadians live in single-family dwellings (Statistics Canada 2017b). The two datasets do not appear to be comparable, and neither seems to tell much about the other.

1 b) Select archetype geometry, features, and context so that any impact on a proposed measure can be multiplied using housing stock statistics to

i. obtain national overall impact,
ii. express a range of impacts, or
iii. assign appropriate proportional weight to each impact.

Authors' response: Archetypes are selected from a larger sample. We compiled statistics of:

- *Geometry: storeys, basements, bedrooms, square footage, perimeter, cladding surface area, glazing surface area, and roof area*
- *Features: roof material, cladding material, number of exit doors, and number and size of garage doors*

With these statistics, one can estimate the mean and distribution (range) of incremental costs from the sample, which facilitates extrapolation to the population.

1 c) State the source of the archetype specifications and identify any modifications or assumptions made in the impact analysis.

Authors' response: Sources and data collection methodology are explicitly documented to facilitate duplication and expansion.

A.3 Principle 2: House geometry and spaces

2 a) Use house geometry criteria, and space criteria where appropriate, to create

i. simple archetypes to evaluate a broad range of impacts,

ii. representative archetypes to evaluate specific features addressed by proposed measures, and

iii. comparable archetype options allowing the development of useful metrics such as "per envelope area" or "per floor area" impacts.

Authors' response: We weighed a choice between simple hypothetical archetypes and possibly more complex real ones. We chose real archetypes to reduce the potential for accidental biases. Scholars talk about the "spherical cow problem" (e.g., Wikipedia 2020), in which complex phenomena are oversimplified for analytical convenience. Complexities in real buildings often increase costs, so simplifications run the risk of underestimating costs. Following Einstein's 1933 paraphrased suggestion (e.g., Robinson 2018), we opted to make everything as simple as possible, but no simpler. Still, we have used our archetypes to develop useful impact metrics of cost per square foot.

2 b) Use house geometry criteria, and space criteria where appropriate, to align cost data generated from archetypes with statistics of benefit calculations.

Authors' response: We agree and have done so.

A.4 Principle 3: Construction types, features, and occupancy

3 a) Align the construction type, construction features, and occupancy type of archetypes with the scope and application of the proposed measures.

Authors' response: We agree and have done so. Archetypes are selected solely from the geographic locations and occupancy classes that dominate the likely impact of the proposed measures.

3 b) Use specific construction features to create meaningful and focused archetypes that evaluate key impacts of proposed measures.

Authors' response: We agree and have done so. The proposed measures affect roofs, wall cladding, windows, exterior doors, decks, balconies, and yard fuels. We describe archetypes at this level of detail and evaluate impacts on a component-by-component basis.

3 c) Select construction features representative of the vintage/age of housing stock with which the impact of proposed measure is compared.

Authors' response: We agree and have done so. Impacts on existing houses are estimated using archetypes selected from a sample of existing houses for sale selected without regard for age. Impacts on new construction are estimated using archetypes selected from newer construction, representative of post-2000 or post-2010 construction.

3 d) Select construction materials representative of their (non-)availability in regions.

Authors' response: We agree and have done so.

3 e) Include natural or landscaping features (e.g., vegetation, terrain, soil type) if they facilitate evaluating key impacts of proposed measures.

Authors' response: We agree and have done so, especially regarding a 5-foot non-combustible apron around the perimeter.

A.5 Principle 4: Location and regional practices

4 a) Integrate location-specific attributes into the archetypes to highlight the impact of the proposed measures in different regions and in rural and remote locations.

Authors' response: We agree and have done so to the extent practical. Archetype data collection spanned real houses from east to west, large and small communities and urban and remote locations. However, to limit the number of archetypes that must be analyzed, we limited the analysis to four actual houses. The same methodology could be applied to additional houses selected from the sample set to examine differences in practice.

4 b) Integrate regional construction practices into the archetypes to highlight the impact of the proposed measures in specific regions.

Author's response: Same response as above.

A.6 Principle 5: Local administrative differences

5 a) Apply different compliance or enforcement lenses to archetypes to explore the impact of the local administration of proposed measures.

Authors' response: We raised this question in our stakeholder review of archetypes. One stakeholder highlighted that in British Columbia, moisture protection contends with fire protection or adds detailing constraints; for example, one cannot simply swap out vinyl siding that has moisture-protection features for non-combustible siding that lacks these features, such as HardiePlank. The issue is worth examining in greater depth than this project might be able to afford.

Appendix B: Comparing Indigenous and non-Indigenous communities

B.1 Sample communities and sample houses

The Government of Canada (ND) provides a map of First Nations. The project team used the map to identify Indigenous communities near the other sample communities discussed in Section 4.1.1. Selecting nearby Indigenous communities makes comparisons easier, although it obscures impacts on Indigenous communities that are distant from non-Indigenous ones, which has implications discussed in Section B.6. Other more remote regions will not offer the same opportunities for comparison, though they could provide insight that the choices made here cannot.

In this analysis, the project team sampled four Indigenous communities near other communities: two in high hazard level and one each in medium and low (Figure 32). The project team also attempted to represent communities with a range of community sizes, but could not span the country geographically from east to west within the constraints of time and budget, and could not span the country from south to north at all.

Figure 32. Sample Indigenous communities

B.2 Vancouver Katzie community

The Katzie First Nation has a reserve, Barnston Island No. 3, near Vancouver's New Westminster District on the south shore of Barnston Island (Figure 33). This is a low-hazard region near a large community (> 100,000 population). The neighbourhood has fewer than 100 homes but no access routes, bridge to the island, or fire stations. It does have fire hydrants, so presumably, if needed, fire engines could be ferried across Parson's Channel from nearby Surrey Fire Service Hall 5. Vancouver also has two fireboats. It appears as if none of the community's houses is far from the island's shore, suggesting that fireboat monitors might satisfy demands for sufficient fire flow.

The community has paved roads like all the houses in the nearby Zillow listings. Electricity comes from above-ground power lines on wooden poles, like the Zillow sample. Power lines sometimes appear to lack 5 metres of clearance to vegetation, like the Zillow sample. In all respects except access, the community features of the neighbourhood (paving, electricity, and firefighting water flow) are like the nearby sample community.

Figure 33. Katzie at Barnston Island No. 3

None of the Katzie houses on Barnston Island No. 3 appears in Zillow, so some attributes cannot be estimated, such as number of bedrooms and bathrooms. However, the houses can be viewed from Google Earth Street View. They generally have vinyl cladding, composition roofs, and a single storey. Their proximity to Parson's Channel and their low elevation suggest they do not have basements. They average 1,520 square feet in living area, just under one-third the average area of the Zillow-listed sample houses in Vancouver.

Eight of ten sample houses (80%) have a low exposure level according to the simplified method; the other two (20%) have ember-only exposure. By contrast, Vancouver houses listed on Zillow all have moderate exposure levels. Therefore, benefit-cost ratios for the Katzie houses are probably like those in the nearby sample community.

B.3 Sagkeeng Anicinabe First Nation community

Sagkeeng Anicinabe First Nation has a reserve in Fort Alexander, Manitoba, just west of Powerview-Pine Falls, a small community (< 10,000 population) in a high-hazard region (Figure 34). The neighbourhood of the Sagkeeng community examined here has between 100 and 600 houses and two access routes, meaning sufficient access routes. It has paved roads, unlike most sample Zillow-listed houses in Powerview-Pine Falls.

Figure 34. Sagkeeng Anicinabe community near Powerview-Pine Falls, MB

The community has no fire hydrants. By contrast, 42% of Zillow-listed homes in nearby Powerview-Pine Falls have fire hydrants. However, most of the Fort Alexander houses are within a few hundred feet of Lake Winnipeg, close enough that light fire apparatus could draft from the lake if they have the right equipment.

Electricity comes from above-ground power lines on wooden poles. Power lines appear sometimes to lack 5 metres of clearance to vegetation. In these respects, the Indigenous community resembles nearby neighbourhoods in Powerview-Pine Falls.

The houses along the main route can be viewed from Google Earth Street View, but not close enough to be certain of cladding material. It seems likely that the houses do not have basements, considering how close they are to the lake. However, their first floors appear to be about 15 feet above the level of the lake, so it seems possible that some houses would have basements. Houses are all single storey with small footprints. A sample of 10 arbitrarily selected houses averaged about 925 square feet in plan area, about two-thirds the size of the 1,300 square foot average in nearby Powerview-Pine Falls.

Five of ten sample houses have low exposure level by the simplified method, four had ember-only exposure, and one had moderate exposure. By contrast, most of the sample houses in Powerview-Pine Falls have moderate exposure level by the simplified method.

B.4 Penticton Indian Band

Penticton Indian Band has a community immediately west of Penticton, BC, a medium-sized community (10,000 to 100,000 population) in the moderate hazard region (Figure 35). The community of 100–600 houses has two access routes, which is adequate. The community appears to have paved roads, like most of the houses in nearby Penticton listed on Zillow.

Figure 35. Penticton Indian Band community near Penticton, BC

Shadows of utility poles indicate above-ground electricity, like the sample houses in nearby Penticton. Foliage is sparse and set back far enough from roads to suggest that power lines generally have 5 metres of clearance to vegetation, unlike most of the sample houses in Penticton. Images are not clear enough to check the presence of fire hydrants. There are no obvious water bodies from which to draft.

Google Earth Street View does not reach the community, so the project team has no information about wall or roof cladding. Shadows suggest single-storey houses, but it is hard to tell. Assuming mostly single-storey homes, the average house is about 1,500 square feet, about two-thirds the average 2,200-square foot house in the sample of nearby Penticton houses listed on Zillow.

Six of the ten sample houses (60%) in the Penticton Indian Band neighbourhood have ember-only exposure; the rest (40%) are moderate hazard, using the simplified method. Exposure levels are higher in the nearby sample Penticton houses listed on Zillow: 31% high hazard, 38% moderate, 8% low, and 23% ember-only.

B.5 Conclusions on Indigenous versus non-Indigenous WUI fire risk

Exposure levels are generally lower in the Indigenous communities: low in Barnston Island No. 3 versus moderate in the non-Indigenous Vancouver neighbourhood; low to ember-only in Fort Alexander versus mostly moderate in nearby Powerview-Pine Falls; and low to ember-only in Penticton Indian Band versus high to moderate in Penticton non-Indigenous neighbourhoods. This observation tends to support FireSmart Canada's (2020, p. 4) assertion that "many Indigenous communities across Canada are already carrying out valuable work in the areas of … fire prevention and risk reduction."

In electricity, paving, access, and adequacy of firefighting water supply, Indigenous communities resemble their neighbours, with some advantages and some disadvantages (Table 45), and few obvious conclusions about house fire vulnerability present themselves. The homes of Indigenous people appear to be smaller on average than those of their neighbours. But where wall cladding and roof finishes can be estimated, they appear to be made of the same material.

These Indigenous communities seem to have reached long ago the same conclusion as derived here: that vegetation management is a low-cost, high-benefit approach to fire resilience.

These conclusions are based on a very small sample: only three Indigenous neighbourhoods and 30 houses. But they do tend to agree with prior work by FireSmart Canada (2020) that asserted that Indigenous communities manage vegetation near their homes well.

Table 45. Comparison of Indigenous and adjacent non-Indigenous communities

Parameter	Indigenous	Non-Indigenous
Vancouver Katzie First Nation Community near Vancouver, BC		
Square footage	1,520 sf	4,840 sf
Exposure level (ember-low/mod/high)	80%/20%/0%	0%/100%/0%
Paved	100%	100%
Hydrants	100%	82%
Sagkeeng Anicinabe First Nation near Powerview-Pine Falls, MB		
Square footage	925 sf	1,340 sf
Exposure level (ember-low/mod/high)	90%/10%/0%	32%/63%/5%
Paved	100%	42%
Hydrants	0%	42%
Penticton Indian Band near Penticton, BC		
Square footage	1,520 sf	2,190 sf
Exposure level (ember-low/mod/high)	60%/40%/0%	31%/38%/31%
Paved	100%	92%
Hydrants	0%	69%

B.6 Knowledge gaps and limitations of these conclusions

The foregoing conclusions in Chapter 5 are limited. They either entirely miss or only tangentially address important issues that matter to the impact of the National WUI Guide on Indigenous communities. For example, people who work in Indigenous communities often point to a lack of adequate servicing and public utilities. Indigenous communities across the country face ongoing boil-water advisories, some ongoing for several decades, an example of inadequate servicing.

Conditions like "if they have the right equipment" mentioned in Section B.3 are important. They matter to whether homes of Indigenous people burn down or not. They also hint at other limitations of the comparisons performed here. Studying adjacent communities helps to compare some features like house size, but it obscures the issue of what happens when resources cannot be shared. One Indigenous community might have access to the firefighting apparatus in the nearby non-Indigenous community, but a remote Indigenous community will not have the same opportunities. The present brief study did not compare Indigenous and non-Indigenous communities that were too far apart to share resources.

The present study also did not address issues of repeated and prolonged emergency evacuation of residents in Indigenous communities and the disproportionate representation of Indigenous people among the displaced. These are important topics with real costs that are not covered in the current BCA approach.

The present project is narrowly framed on a set of readily quantified expected present values of benefits and costs. But wildland-urban interface fires have much broader implications. They affect different populations differently. Some groups are more vulnerable to harm than others, some are more frequently affected, and some are differentially affected because they belong to a racial, ethnic, economic, or otherwise marginalized group. (For example, median income among Indigenous Canadians is about half that of the general population, so affordability may be a more serious constraint on uptake of the National WUI Guide for many more Indigenous people.) This study cannot sufficiently explore social and political issues that may affect uptake of the National WUI Guide or related measures in Indigenous communities.

A better understanding of the status of Indigenous communities and their costs and benefits of satisfying the National WUI Guide would be valuable. To do so, the National Research Council could supplement this study as follows:

1. Gather a larger statistical sample of houses within and outside Indigenous communities. It may be necessary to examine the homes of Indigenous people in person since few if any appear in Zillow.
2. Use a sample of houses that better span Indigenous communities from north to south and east to west, isolated and connected, and small to large.
3. Consider renter status and how that affects whether the National WUI Guide can be practically implemented, especially on a voluntary basis. Indigenous populations might have less control of their houses because they are more likely to be renters. Landlords may have less interest in the National WUI Guide because they enjoy fewer benefits. They will probably be less likely to follow it voluntarily and more likely to resist efforts to transfer its recommendations to the building code in the future.
4. Examine in greater detail constraints on the water, electric services, and paving available in Indigenous communities, comparing them with non-Indigenous communities.
5. Identify and describe other cultural and legal constraints or opportunities that differentially affect Indigenous communities' abilities to follow the National WUI Guide.

All these tasks might be supported by engineers and other technical experts but should be directed or at least informed by representatives from Indigenous communities and by sociologists, economists, and legal experts familiar with these and closely related issues.

Appendix C: Most cost-effective recommendations

It may be useful to know which low-cost recommendations of the National WUI Guide, taken separately, provide high benefit, even if they do not individually fully satisfy all recommendations of the National WUI Guide. Table 46 lists 10 fire-resistive features whose cost and effect on ignition probability have been estimated. For each feature, the table shows three numbers: (1) an ignition probability factor (the 2018 Camp Fire odds ratio from Figure 4B), (2) an estimate of the retrofit cost for the high-hazard archetype house, and (3) a relative benefit-cost ratio (BCR). The relative BCR is a new term introduced here defined as the inverse of the ignition probability factor divided by the retrofit cost in $10,000s. A lower ignition probability factor is better – it means less chance that the house will ignite in a WUI fire. Lower cost and higher relative BCR are also better.

The most cost-effective of the features are the ones with the highest relative BCR: no fence, no patio or carport roof, fine wire mesh over vents, and vegetation control within 10 metres of the house. Retrofit costs are taken mostly from the high-hazard existing archetype house, except where that archetype lacks the given feature, in which case we take the cost estimate from elsewhere. The retrofit cost for an asphalt shingle roof is taken as zero because almost all roofs are this type anyway.

The table does not account for the interaction between options. For example, vegetation control allows one to avoid the expense of structural recommendations such as non-combustible cladding, and so has a higher relative BCR than shown here.

Table 46. Relative cost-effectiveness of various recommendations for reducing fire risk

Feature	Ignition probability factor	Retrofit cost ($)	Relative BCR
Non-combustible elevated deck	30%	$14,000	2
Non-combustible deck on grade	30%	$14,000	2
Vegetation control within 10 m	20%	$6,000	8
Enclosed eaves	80%	$3,000	4
Non-combustible cladding	60%	$13,000	1
No fence	70%	$500	29
No patio or carport roof	70%	$500	29
Asphalt shingle roof	90%	$0	N/A
Fine mesh over vents	70%	$500	29
Multi-pane glazing	40%	$6,000	4

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