CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WF24014

International Journal of WILDLAND FIRE
International Association of Wildland Fire

Avoid getting burned: lessons from the McKinley wildfire in rural Alaska, USA

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Received: 24 January 2024
Accepted: 28 September 2024
Published: 25 October 2024

Cite this: Schmidt JI *et al.* (2024) Avoid getting burned: lessons from the McKinley wildfire in rural Alaska, USA. *International Journal of Wildland Fire* **33**, WF24014. doi:10.1071/WF24014

ABSTRACT

Background. Climate change and continued development in the wildland–urban interface (WUI) have increased risks to property and infrastructure from destructive wildfires. **Aims.** A better understanding of the factors associated with building survival will promote resilience of WUI communities. **Methods.** We studied factors associated with the likelihood that a building burned during the 2019 McKinley fire in the Alaska boreal forest, USA. We examined the potential influence of both ecological or socio-economic factors on building loss. **Key results.** The probability of a building burning was significantly associated ($P < 0.001$) with a building burning nearby (within 30 m). Having less flammable deciduous cover nearby (within 100 m) improved survival. Buildings with lower value on larger parcels were more likely to burn, as were buildings with larger perimeters. Other important factors associated with burning included the number of buildings both nearby (within 30 m) and within the property parcel boundary. **Conclusions.** Our results suggest that social and ecological factors contribute to building survival, indicating that a comprehensive social-ecological approach would provide the most effective support to WUI communities with wildfire risks. **Implications.** A comprehensive approach that integrates social, economic, and ecological factors is important in understanding building loss in WUI wildfires.

Keywords: Alaska, Arctic, decision making, mitigation, planning, risk, SES, socio-economic, wildland fire, WUI.

Introduction

Increased wildfire activity fuelled by climate change and human activities, including continued development into forested areas, is contributing to a growing number of severe and catastrophic wildfires in the wildland–urban interface (WUI) (Hammer *et al.* 2009; Moritz *et al.* 2012; Radeloff *et al.* 2018; Haynes *et al.* 2019). As the number of lives, homes, and property lost to wildfire has increased (Karter 2010*a*; Haynes *et al.* 2019; Badger 2021), many communities and governments are responding to the increased risk by urging the use of wildfire safety standards (US Government 2016), and promoting Firewise USA (NFPA 2018) or FireSmart in Canada (FireSmart 2018). Meanwhile, insurance companies have stopped offering new and cancelling existing policies (Adriano 2023; Blood 2023). The current state of affairs stresses the need to learn more about what homeowners and communities can do to reduce wildfire risk and prevent property destruction and loss of life.

Research on wildfires in smaller communities (<2500 residents) within the WUI is scarce (Bar Massada *et al.* 2009; Dye *et al.* 2021) despite these areas facing a higher incidence of fires (Karter 2010*b*). Existing studies often address larger communities (Gibbons *et al.* 2012; Syphard *et al.* 2012, 2013; Alexandre *et al.* 2016; Gibbons *et al.* 2018; Knapp *et al.* 2021). In contrast, our research focuses on a specific wildfire that destroyed 139 buildings in the relatively sparsely populated WUI between two communities with fewer than 2500 residents (US Census Bureau 2020). Previous research on smaller communities focused on modelling and simulations and did not explore spatial auto-correlation (Bar Massada *et al.* 2009; Dye *et al.* 2021). Strategies for mitigating wildfire risks in sparsely populated regions may differ due to limited suppression resources, lower incomes, and the challenge of engaging residents who may be wary of government involvement (Jacobs and Cramer 2020). Additionally, these areas may experience future development. Collaborating with homeowners, developers, and local governments to plan for wildfire-adapted communities is essential for mitigating risks to life and property (Moritz *et al.* 2014; Schoennagel *et al.* 2017). Producing actionable research findings can inform smart planning and reduce the negative consequences of wildfires on society (Syphard *et al.* 2013).

Promoting resilience to wildfires involves understanding the WUI as a socio-ecological system (SES) where societal and ecological elements interact (Chapin *et al.* 2006; Moritz *et al.* 2014; Steelman 2016). Social attributes include building design, land use, risk perception, and suppression efforts, while ecological characteristics encompass the type of ecosystem, fire history, and weather. Activities like vegetation manipulation and fuel reduction have both social and ecological effects. Understanding WUI SESs can enhance safety and reduce property loss (Lampin-Maillet *et al.* 2010; Galiana-Martin *et al.* 2011). The best strategies are likely to include a combination of social and ecological actions (Moritz *et al.* 2022). Our unique study analyses social, economic, and ecological factors that predict which buildings burn and which survive during wildfires, emphasising the importance of combined socio-ecological actions for effective strategies.

Previous research on building survival in WUI fires typically focused on specific aspects of the SES, often combining ecological features with building spatial arrangement or land management. (Gibbons *et al.* 2012; Syphard *et al.* 2013; Alexandre *et al.* 2016; Syphard and Keeley 2019). However, no empirical studies have comprehensively examined a broad range of social-ecological parameters simultaneously, and few have explored the issue of spatial scale (Alexandre *et al.* 2016; Syphard and Keeley 2019). Context-specific and place-based approaches are crucial, given the diverse SES combinations in the WUI. Despite its extensive wildfire history and WUI development, no research has investigated building loss in Alaska's boreal forest. Our research addresses three critical gaps: (1) enhancing understanding of building loss in boreal forest ecosystems; (2) evaluating SES characteristics influencing building loss at multiple scales; and (3) discerning factors that may affect building loss differently in sparsely populated WUI areas. By exploring various socio-ecological factors, we aim to contribute insights for promoting wildfire-adapted communities in boreal forest regions.

Materials and methods

Study area

The McKinley wildfire started on 17 August 2019, during one of the hottest and driest summers on record in south-central Alaska (AICC 2019; Bhatt *et al.* 2021) and was believed to be caused by human activity. Driven by high winds, the fire moved rapidly, burning 1331 ha (3288 acres) over 3 days, destroying 52 residential buildings, 84 outbuildings, and three commercial buildings. In total, 1028 properties were affected, and approximately 350–400 people were evacuated (McDonald 2019; Zak 2019).

The McKinley wildfire swept from north to south along the George Parks Highway and the Alaska Railroad, shutting down the only direct surface transportation links between Alaska's two main urban centres, Anchorage and Fairbanks (Fig. 1, inset, lower right). Although the area receives heavy use from travellers and recreationists, it is sparsely populated. Based on building density, this area does not meet the housing density threshold of one house per 40 acres (16.2 ha) to classify it as a wildland–urban interface (WUI) (USDA and USDOI 2001). However, it is managed as WUI in Alaska and falls under the highest wildfire suppression category (AKDFFP 2023). The area affected by the fire contains no incorporated communities but lies within the Matanuska-Susitna Borough (MSB), a large (65,420 km^2) county-level government that provides limited public services financed through local property taxes. About 70% of the area within the fire perimeter was undeveloped in 2019, but the 118 parcels, averaging 3 ha (7.5 acres) per parcel, contained buildings. Developed parcels, including homes, recreational cabins, and a few commercial establishments serving travellers, were scattered in clusters near the highway.

Although much of the boreal forest where the McKinley widlfire burned remains in the surrounding unoccupied parcels, there are occupied portions where buildings are closely spaced (<30 m), and the forest has been thinned and cleared. Pre-fire aerial imagery shows that many landowners retained deciduous trees while clearing evergreens. Boreal forests are a fire-driven ecosystem with highly flammable black and white spruce (*Picea*), and their natural fire return intervals range from 75 to >100 years (Hoecker *et al.* 2020). However, this interval has been shortening (Flannigan *et al.* 2009; Kasischke *et al.* 2010). Lightning-ignited fires typically begin in mid-June and are suppressed naturally by rains in August (Bieniek *et al.* 2012). Even though lightning-caused wildfires burn the most area, most ignitions in Alaska, especially in the WUI, are caused by humans (DeWilde and Chapin 2006; Calef *et al.* 2017). Human-caused fires are more likely to occur outside of a typical wildfire season than lightning-caused ones (Calef *et al.* 2017), though the wildfire season has been expanding due to climate change (Grabinski and McFarland 2020).

Data sources

Building burn status

The MSB created a damage assessment database from reports by property owners after the wildfire that

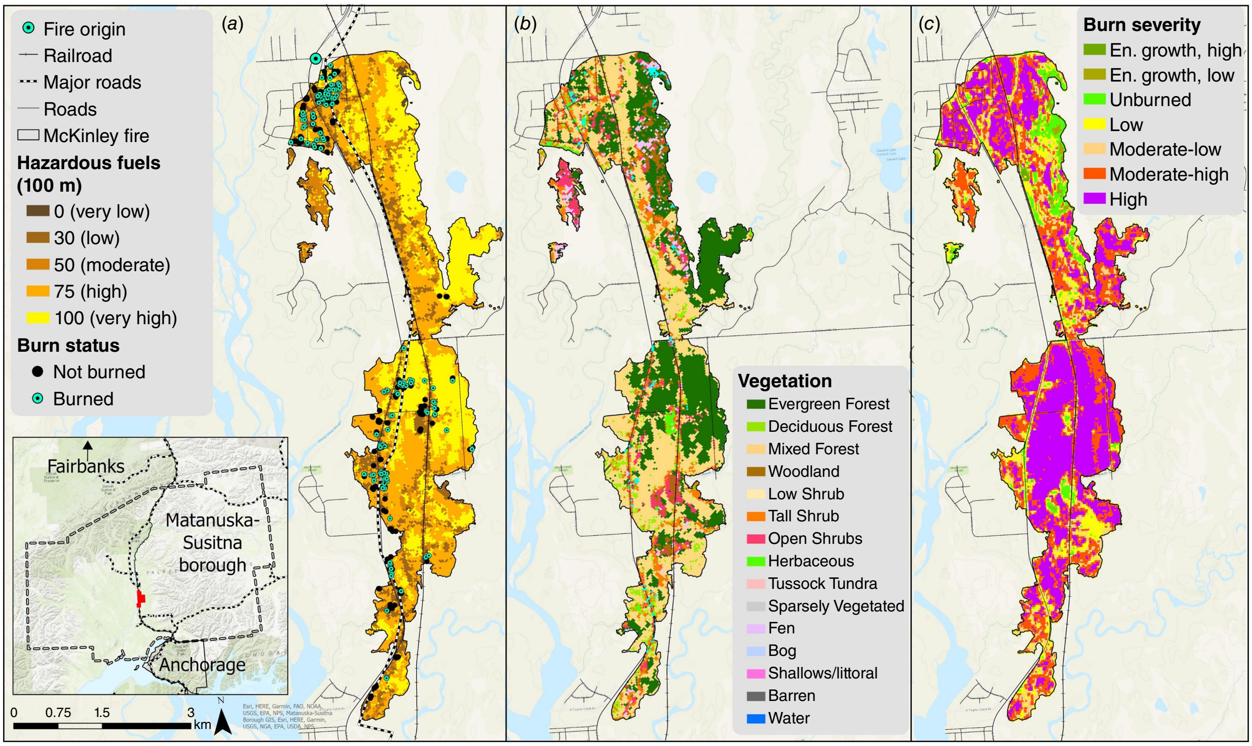

Fig. 1. Location of burned and unburned buildings along with (*a*) 100-m hazardous fuels, (*b*) vegetation used to create hazardous fuels, and (*c*) burn severity within the 2019 McKinley wildfire perimeter. En. growth means enhanced growth after fire with low to moderate burn severity.

documented physical addresses receiving building damage due to the McKinley wildfire. However, not all residents participated in this process, so we also used aerial imagery before (2017, 0.3 m) and after (2020, 0.3 m) the wildfire to determine which buildings were lost during the wildfire (MSB 2023). We linked areal building images to the spatial buildings outline database obtained from MSB (MSB 2021). Buildings present in the pre-fire aerial imagery but absent in post-fire imagery were digitised and classified as burned. Building outlines were also removed if they were not visible at either time point. Buildings appearing only in the post-fire imagery were excluded from the analysis.

Explanatory variables

We used a variety of social and ecological variables to determine why some buildings burned and others survived (Table 1). The goal was to include variables capturing SES aspects based on available data. For detailed information about the variables, see Supplementary Appendices S1 and S2.

Social variables

Building and property characteristics can be important for understanding loss due to wildfire (Syphard and Keeley 2019; Knapp *et al.* 2021; Pierce *et al.* 2022). We consider characteristics of the built environment social variables, as they reflect people's income, personal preferences, and land use rules. Information on the characteristics of the parcels and buildings came primarily from the property appraisal records maintained by the MSB to assess properties for tax purposes. Alaska requires local governments to appraise property at full market value (AS 29.45.110). However, taxable assessed values may be less than appraised if properties qualify for one or more exemptions under state and local statutes (AS 29.45.010). Information available in the appraisal records is limited, as building permits are not required outside incorporated cities in the MSB. Data included parcel size, number and type of buildings, floor area of the main building, appraised value of land, and total building value on the property. The building wall surface length was calculated by taking the square root of the building size (ft^2).

The spatial arrangement of buildings was explored by calculating the distance to the nearest building and the presence or absence of a building within 30 and 100 m (Alexandre *et al.* 2016; Knapp *et al.* 2021). Development density was assessed by summing the number of buildings and parcels within 10, 30, and 100 m buffers. Discussions with firefighters revealed that unkempt properties (i.e. junkyards) could hinder suppression efforts. Therefore, pre-fire aerial imagery was used to identify which buildings

Table 1. List of the variables used for the analysis and the theme they represent.

Explanatory variable	Theme	Type	Data source
Parcel lot size	Social	Building	MSB[A]
Mobile home on the property	Social	Building	MSB[A]
Building size	Social	Building	MSB[A]
Building wall surface area length	Social	Building	MSB[A]
Land value	Social	Value	MSB[A]
Building value	Social	Value	MSB[A]
Number of residential units	Social	Land use	MSB[A]
Commercial building	Social	Land use	MSB[A]
Total buildings on parcel	Social	Land use	MSB
Junkyard on the property, adjacent to property (yes/no)	Social	Land use	Aerial photography
Distance to nearest building (m)	Social	Land use	Aerial photography
Building within 10, 30, 100 m buffer around the building (yes/no)	Social	Land use	Aerial photography
Number of buildings within 30 m buffer around the building	Social	Land use	Aerial photography
Number of neighbouring parcels within 10, 30, 100 m buffer around the building	Social	Land use	MSB[A]
Distance to nearest burnt building (m)	Social/Ecological	Land use/Fire	Aerial photography
Burned building within 30 m	Social/Ecological	Land use/Fire	Aerial photography
Distance to fire starting point (m)	Ecological	Fire	Georeferenced photo
Within fire perimeter on day 1 (yes/no)	Ecological	Fire	VIIRS[B]
Average burn severity for the parcel (dNBR)	Ecological	Fire	Sentinel-2[C]
Average burn severity within a 30 m buffer	Ecological	Fire	Sentinel-2[C]
Average burn severity in 10, 30, and 500 m buffer, excluding building footprint (dNBR)	Ecological	Fire	Sentinel-2[C]
Percent of tree cover within 100 m (%)	Ecological	Vegetation	Aerial photography/GIS
Undetectable vegetation within 10 m building (yes/no)	Ecological	Vegetation	Aerial photography/GIS
Average or maximum 100 m or 500 m hazardous vegetation value within 30, 100, and 500 m buffer	Ecological	Hazard	ABoVE[D]
Average merged wildfire exposure value for the parcel	Ecological	Exposure	ABoVE[D]
Average or maximum 100, 500 m, or merged wildfire exposure value within 30, 100, 500 m buffer	Ecological	Exposure	ABoVE[D]
Average merged wildfire exposure within the four cardinal quadrants of 100 m buffer around the building	Ecological	Exposure	ABoVE (30 m)

[A]MSB, Matanuska-Susitna Borough property appraisal database.
[B]Sentinel dataset, 10 m scale (ESA 2020).
[C]VIIRIS I-Band 375 m (NASA 2023).
[D]ABoVW, Arctic-Boreal Vulnerability Experiment landcover data was used for hazardous fuels and wildfire exposure (Wang *et al.* 2019).

occurred on parcels with junkyards and adjacent parcels with junkyards.

Fire characteristics

Previous research found that the distance and time from the start of a fire might influence building loss (Maranghides *et al.* 2013). The starting location of the McKinley wildfire was Mile 91 on the George Parks Highway. This location was digitised, and then the Euclidean distance from the fire start to each building was calculated. We used Visible Infrared Imaging Radiometer Suite remote sensed data (VIIRIS I-Band 375 m (NASA 2023)) to determine which buildings were reached by the fire on the first day. Burn severity can also be an important factor for explaining building loss; we used remote sensed Sentinel-2 (10 m, Copernicus S2 (ESA 2020)) to calculate the Normalised Burn

Ratio (NBR) before (July 2019) and after the wildfire (July 2020) and then calculated the differenced NBR (dNBR), which is the pre-fire NBR minus the post-fire NBR. To ensure that our remote sensed dNBR accurately captured burn severity, we also conducted 61 composite-based index (CBI) plots to assess burn severity on the ground (Appendix S3). Average burn severity was calculated for each parcel and assigned to the buildings on that parcel. Average burn severity was calculated within 10, 30, 100, and 500 m buffers of the building footprint, including and excluding the building footprint. This was done because research shows that buildings can be fuel (Knapp *et al.* 2021); thus, we wanted to explore whether the inclusion of the building affected measured burn severity.

Vegetation

Vegetation cover and type can influence the survival of buildings during a wildfire (Alexandre *et al.* 2016; Gibbons *et al.* 2018). In summer, deciduous trees tend to have higher moisture content in their leaves than spruce needles, and they may extinguish embers (Wilson and Ralph 1985) and influence the spread of fire (Rothermel 1972). The presence of green vegetation has been associated with building loss (Gibbons *et al.* 2018; Knapp *et al.* 2021). To capture the amount of green cover around buildings, we generated a grid of hexagons with 10 m buffer (2 m side length), 30 m (4 m side length), and 100 m (12.5 m side length). The hexagon was classified as green if the deciduous tree cover was observed. We then determined the total percent of green hexagons around each building at various scales. Given the promotion and success of Firewise principles (NFPA 2018), we classified buildings as being 'Firewise' if they had undetectable vegetation within 10 m or 30 m. Few buildings had no visible vegetation within 100 m.

Wildfire hazard and exposure

In Alaska, we used a new wildfire exposure approach (Schmidt *et al.* 2024) modified from previous research in the Canadian boreal forest (Beverly *et al.* 2010, 2021). Exposure reflects the potential that a wildfire will get close enough to impact a location. Areas with higher exposure will be more exposed to intense wildfire activity than areas with lower exposure. This approach used a land cover layer with 15 cover types (Wang *et al.* 2019), reclassified into a flammability hazard rating based on wildfire torching, spotting, and spread potential of each cover type. High hazard fuels include tall woody vegetation (>3 m) such as evergreen species while lower hazard fuels are water-soaked areas like bogs and littorals and sparsely vegetated areas. Moderate fuels are shrubs and grasses, which are typically green in summer. Focal statistics were used in ArcGIS Pro to calculate the average flammability hazard rating within a 100 and 500 m circle, which reflect short and long-distance ember dispersal, respectively. The products are two wildfire exposure layers (100 and 500 m). The merged wildfire exposure layer was created by taking the maximum from the 100 and 500 m within a 500-m buffer of buildings and outside the buffer using the 500 m. Average and maximum hazardous vegetation scores and wildfire exposure were also calculated at different scales within 30, 100, and 500 m buffers around buildings. The McKinley wildfire spread from north to south. Directionality of hazards can be important (Gibbons *et al.* 2012; Syphard *et al.* 2012), so we calculated the average exposure in four quadrants: (1) northern (315°–45°); (2) eastern (45°–135°); (3) southern (135°–225°); and (4) western (225°–315°).

A complete list of the variables used for this analysis and data sources is in Supplementary Appendix S1. Several parameters were derived from each data source, which are explained below. Some parameters were also calculated at various scales. We typically used scales of 10, 30, and 100 m to capture the distances used to explore human ignition zones around buildings and Firewise and FireSmart principles (Syphard *et al.* 2012, 2014; Alexandre *et al.* 2016; FireSmart 2018; NFPA 2018). Longer-distance ember dispersal and dynamics were explored at 500 m (Beverly *et al.* 2010; Alexandre *et al.* 2016; Gibbons *et al.* 2018). The scales have also been used in other research on the distance embers travel, allowing fire to move across the landscape (Bierwagen 2005; Cohen 2008; Beverly *et al.* 2010; Syphard *et al.* 2014; Alexandre *et al.* 2016).

Statistical methods

We modelled the probability that building i burned, b_i, generally as a function of ecological variables affecting wildfire risk, x_i, and social characteristics of property parcels and buildings, z_i:

$$b_i = f(x_i, z_i) + u_i \tag{1}$$

Since wildfire tends to spread spatially outward, the error term, u_i, may contain spatial auto-correlation. We considered both spatial errors, where the error term u_i includes a random error ε_i and a correlation parameter ρ times a weighted sum of nearby error terms, and spatial lags, where u_i contains ε_i plus a correlation parameter λ times a weighted sum of nearby burn probabilities, b_j: (Anselin 1988):

$$u_i = \varepsilon_i + \rho \Sigma_j d_{ij} \varepsilon; \ + \lambda \Sigma_j d_{ij} b_{j,} \tag{2}$$

where d_{ijj} represents the inverse distance between building i and building j. Observations represent binary outcomes, burned vs unburned buildings, rather than probabilities. Given the nature of the errors for the binary outcome, we started by specifying Eqn 1 as logistic regression:

$$\log(b_i/(1 - b_i)) = \alpha + \beta x_i, \quad + \gamma z_i + u_i, \tag{3}$$

with constant α, and parameter vectors β and γ estimated via maximum likelihood. Since the theory of spatial correlation is incompletely developed for logistic regression, we also estimated Eqn 1 using a linear probability model, testing residuals for spatial correlation using the standard Moran global I statistic (Moran 1950). If the Moran test indicated significant spatial correlation, we estimated spatially autocorrelated linear regression equations adjusting for spatial lag and spatial error in u_i (Drukker *et al.* 2013*b*):

$$b_i = \alpha + \beta x_i, \quad + \gamma z_i + u_i, \tag{4}$$

where u_i is given by Eqn 2 and $\varepsilon_i \sim (N(0, \sigma^2 I_n)$.

The inclusion of the dependent variable in the spatially correlated error term implies a potential for feedback from an individual building i's burn status to the probability that neighbouring building j burned. The feedback makes it difficult to infer the effects on structural survival from the estimated coefficients of Eqn 4 alone. To address the full effects of the diverse ecological and social attributes, we estimated total effect (LeSage and Pace 2009), which is the sum of two components: the direct effect of the parcel's attributes on building i's survival, $\beta x_i, +\gamma z_i$, and the indirect effects, which measure the feedback effect coming from nearby buildings included in the error term u_i.

Intense wildfire may exhibit locally chaotic behaviour, as it generates its own local weather. Evidence of the chaotic component may show up as random variation in observed burn severity. The noise of this inherently unpredictable component of burn severity may obscure the signals coming from the surrounding vegetation and property development characteristics that are more helpful to inform policy and planning to reduce wildfire risk to buildings. A simple strategy for keeping the focus on potentially policy-relevant characteristics is to ignore the burned status of neighbouring buildings and include the presence or absence of nearby buildings, regardless of their burn status. A more complex approach would be to estimate the degree to which burn status of a building might be correlated with the component of neighbourhood burn severity that is contributed by the characteristics of the local vegetation and built environment. To implement the latter strategy, we estimated an equation that estimates burn severity without the influence of surrounding buildings (x_{0i}) as a linear combination of exogenous ecological and development variables, x_i and z_i:

$$x_{0i} = \delta x_i, + \mu z_i + w_i, \tag{5}$$
$$w_i = \omega_i + \lambda \Sigma_j d_{ij} b_j$$

and ω_i is a normally distributed random error term.

We then estimated a version of Eqn 4 correcting for potential spatial elation, replacing measured burn severity with predicted burn severity, $\delta x_i, +\mu z_i$ from Eqn 5, using generalised spatial two-stage least squares instrumental variable regression (Drukker *et al.* 2013*a*).

The large number of potential explanatory variables for the small case study population requires a strategy for eliminating variables that are not associated with risk to buildings. Since the literature on wildfire in Alaska boreal forest ecosystems does not provide guidance for which spatial scale is most relevant for each particular characteristic of the site, we constructed ecological and some social variables with spatial buffers at varying scales. Measures of the same characteristic at different spatial scales are highly correlated. To determine the relevant set of explanatory variables, we tested potential effects with stepwise entry and removal, using $P < 0.2$ as a criterion for retention. For each characteristic that could be measured at multiple spatial scales, we examined spatial effects by starting with the smallest spatial scale for which a characteristic could be measured reliably. Then, we expanded to the next largest spatial scale. If a given characteristic met the $P < 0.2$ criterion at any spatial scale, we retained the one spatial scale for that characteristic that provided the best fit. We estimated variance inflation factors (VIF) to evaluate multi-collinearity among the remaining variable set. Strong winds spread the fire from north to south during the 2-day period when the fire burned out of control through the area, so we tested whether effects on the north side of buffers differed from effects coming from other directions.

After obtaining the preliminary set of regressors with the stepwise procedure, we tested the potential significance of every excluded variable again, including the different spatial scales, by entering the excluded variable again into the equation and testing for $P < 0.2$.

Results

Results from logistic regression (Eqn 4) estimated for the odds ratio that a building burned show that a nearby burned building was the most salient predictor of a building burning, followed by the 100-m exposure index measured within the 100-m building radius (Column 1 of Table 2). Vegetation cover within 100 m was negatively associated with a burned outcome, suggesting that vegetation such as deciduous trees may mitigate the effect of more flammable evergreen trees associated with higher exposure values. Burn severity, using the measure that attempted to exclude the building footprint, was also positively associated with burning, although the correlation is weaker ($P = 0.057$). Using the alternative measurement of burn severity that included all cells within the 30-m buffer provided a more significant correlation with burned status ($P = 0.048$); however, we cannot rule out that the variable was biased by, in some instances, measuring the burning building's contribution to burn severity.

Higher-valued buildings were more likely to survive, but controlling for value, larger buildings with more surface area were more prone to burning. Multiple buildings on the property reduced survival odds. These findings might be influenced by firefighting decisions favouring valuable properties and ensuring their safety. A junkyard near the building was not a significant predictor of building loss.

Table 2. Statistical results of logistic regression equations and generalised spatial two-stage least squares (GLS) regression equations explain which homes burned and which survived the McKinley wildfire.

Equation	(1) Eqn 3	(2) Eqn 3	(3) Eqns 2, 4	(4) Eqn 5	(5) Eqns 2, 4, 5
Dependent variable, specification	Probabilty that a building burned, controlling for nearby burned buildings	Probability that a building burned, ignoring burn status of nearby buildings	Probability that a building burned, same as Column 2 adjusting for spatial auto-correlation	Burn severity without the influence of buildings	Probability that a building burned, including burn severity without the influence of buildings
Estimation method	Logistic regression	Logistic regression	Spatial GLS regression	Least squares regression	Spatial IV GLS regression
Average burn severity in a 30 m buffer, excluding building footprint	0.00282 (1.90)*	0.00537 (4.48)***	0.000721 (3.49)***		
Predicted average burn severity in 30 m buffer, excluding building footprint					0.000620 (2.27)**
Percent of tree cover within 100 m	−0.0411 (−2.91)***	−0.0503 (−4.53)***	−0.00700 (−3.79)***	1.500 (2.76)***	−0.00619 (−3.66)***
Undetectable vegetation within 10 m of building				−42.3 (−1.87)	
Average 100 m wildfire exposure value within 100 m buffer	0.0567 (2.96)***	0.0396 (2.67)***	0.00696 (2.54)**		0.00587 (2.38)**
Maximum 100 m wildfire exposure value within a 100 m buffer				2.90 (2.88)***	
Average 100 m hazardous vegetation value within a 30 m buffer				2.12 (2.19)**	

(*Continued on next page*)

Table 2. (*Continued*)

	(1)	(2)	(3)	(4)	(5)
Equation	Eqn 3	Eqn 3	Eqns 2, 4	Eqn 5	Eqns 2, 4, 5
Maximum 500 m hazardous vegetation value within a 100 m buffer				-2.87 (-4.03)***	
Distance to fire starting point				-0.0101 (-4.71)***	
Building value (000s)	-0.0105 (-2.74)***	-0.0135 (-4.64)***	-0.00200 (-4.23)***		-0.00210 (-5.24)***
Total buildings on parcel	0.551 (2.50)**	0.737 (4.21)***	0.112 (3.34)***		0.116 (4.04)***
Building wall perimeter	0.0364 (1.88)*	0.0179 (1.30)	0.0391 (1.83)*		0.00387 (2.06)**
Parcel lot size (acres)	-0.0128 (-1.45)	-0.0182 (-2.31)***	-0.00232 (-1.87)*		
Burned building within 30 m	3.75 (9.77)***				
Building within 30 m	0.743 (2.33)**	0.105 (1.98)**	-22.7 (-1.43)		0.108 (1.91)*
Number of buildings within 30 m		0.260 (2.79)***		-16.0 (-3.60)***	
Constant term	-1.51 (-1.61)	-3.15 (-3.62)***	-0.202 (-1.31)	295 (5.55)***	-0.0725 (-0.51)
Spatial lag (λ)			0.882 (4.18)***		1.12 (7.05)***
Spatial error (ρ)			0.676 (1.53)		
Observations	325	325	325	325	325
Log likelihood	-113.0		-173.5		-168.2
Wald/*F*	223.8***	102.8***	61.45***	30.31***	52.09***
d.f.	8	9	8	8, 316	8
R^2/Pseudo R^2	0.498	0.229	0.286	0.43	0.255

A negative sign indicates an increased probability of building survival. Figures enclosed in parentheses below coefficients represent coefficient *z* or *t* statistics.
*$P < 0.10$
**$P < 0.05$
***$P < 0.001$

Although the wind came from the north on the day of the fire, burn severity on that side, or any side, of a building was not as good a predictor as burn severity around the entire building, suggesting that radiative heat was more likely to drive building ignition than wind-driven flames.

Significant variables appeared to be relatively robust with respect to the different specifications of Eqn 1. The parallel linear regression (Eqn 5, results not shown) showed very similar results. Multi-collinearity among remaining explanatory variables in Eqn 5 was modest (VIF mean 1.56, maximum of 2.15). The Moran global I test reported no significant spatial auto-correlation ($\chi^2 = 0.257$, $P = 0.61$). Including a nearby burned building in the list of explanatory variables essentially specifies a spatial lag model, complicating attribution. Column 2 of Table 2 shows results from estimating Eqn 3 but replacing a burned building as an explanatory variable with any building, burned or not, within the 30-m buffer. These results showed that nearby buildings were a highly significant predictor of the risk of loss, although the equation explained less than half as much of the likelihood of a building burning. Without the direct spatial lag in the equation, the Moran I test reported that the residuals were highly spatially correlated ($\chi^2 = 39.47$, $P < 0.001$).

The high degree of spatial auto-correlation in the equation could theoretically be due to the fact that the nearby building is a risk factor for direct ignition, implying a spatial lag model, or that the spatial scale of the ecological risk; i.e. exposure to radiative heat from burning vegetation is larger than the distance between buildings, generating a spatial error. The results of estimating Eqn 5 with both a spatial lag and spatial error terms, displayed in Column 3 of Table 2, show a highly significant spatial lag (λ) ($P < 0.001$), but the spatial error was not significant (ρ) ($P = 0.13$). One should note that the ecological variables are constructed from gridded data by drawing spatial buffers ranging from 30 to 100 m around the building. The data, therefore, build in and account for spatial error in the form of contiguity matrices with distances to neighbours corresponding to buffer radii in the variable definitions.

We do not have measurements of fire intensity at the relevant scales; however, burn severity within 30 m of the building footprint represents evidence for fire intensity and is, not surprisingly, a positive and significant explanatory variable for the probability that the building survives the wildfire. It is possible that a burning building may have ignited the surrounding vegetation and, therefore, increased the fire intensity in nearby vegetation. We addressed that potential feedback by estimating Eqn 5 as a spatially auto-correlated equation with burn intensity as an endogenous variable (Drukker *et al.* 2013*a*). In this case, the spatial error was not significant ($P = 0.2$), so we show the results in Column 5 of Table 2, which includes only the spatial lag (λ). The equation shown in Column 5 includes the predicted values of the equation for burn severity without the influence of buildings from the equation shown in Column 4 rather than the measured values of burn severity. The results are very similar to those of Column 3. The only real difference is that the coefficient for burn severity has a larger standard error.

The equation for burn severity (Column 4 of Table 2) reveals additional factors relevant to building survival that were not visible directly but appear to affect building survival indirectly through their impact on burn severity. First, the nearby building has a negative sign (although not statistically significant, $P = 0.15$). These results suggest that a building within 30 m ignites nearby buildings with radiant heat rather than by igniting vegetation. Although many of the same vegetation characteristics are the same as those directly affecting survival, they are significant at smaller spatial scales. Additional significant factors associated with burn severity include distance to the fire start location and absence of vegetation in the immediate 10 m around the building. The negative coefficient on the distance to the fire start location likely indicates the ramping up of the fire suppression effort, including aerial water drops to reduce the intensity (Gabbert 2019). The lack of observed vegetation around the building represents efforts of homeowners to protect the building by clearing brush near the building. Although clearing brush around the house did not make the $P = 0.2$ cut-off for inclusion in the equations for building survival, it was marginally significant in reducing fire intensity around the home ($P = 0.07$).

The way the effects from the variety of social and ecological variables interact to predict the probability of a structure burning, after adjusting for spatial auto-correlation, is spatially complex. Fig. 2 illustrates two important contributing factors that interact to predict burn probability: (1) social, the spatial clustering of buildings; and (2) ecological, the exposure. The figure overlays the estimated probability of burning and actual burn status with wildfire exposure, an important contributing factor to building ignition directly, as well as indirectly through its impact on burn severity. The estimated probability of burning, calculated from the coefficients in Column 5 of Table 2 is higher in areas with high exposure values (lighter colours). Supplementary Appendix S4 shows the logistic curve fit between predicted burn probabilities and burn status.

As described in the Materials and Methods section, the full effect of each explanatory variable in the regression equation with spatial auto-correlation includes a direct effect and an indirect effect (LeSage and Pace 2009). The direct effect represents the effect of a characteristic of a given building on that building's burn probability. That same characteristic also affects the potential ignition of nearby buildings. That effect coming through ignition from nearby buildings is included in the indirect effects. The total effect is the sum of direct and indirect effects. Table 3 shows the direct, indirect, and total effects of a one-unit change in each characteristic derived from the equation in Column 3 of Table 2. The results show that indirect effects are broadly similar to the direct effects, although somewhat smaller. The total effects are generally more statistically significant than the regression coefficients in this case. The pattern of burned buildings is spatially clustered, reflecting the spatial clustering of development in the region (Fig. 2). However, the characteristics of those buildings within the burn perimeter of the McKinley wildfire are locally spatially diverse. Some properties contain homes with non-residential outbuildings, while neighbours may include only a single building; small recreational cabins may be adjacent to large homes, commercial buildings, or mobile homes. Such diversity at local spatial scales causes the spatial errors to be uncorrelated with the spatial lags, contributing to the lack of difference between the relative strength of direct and indirect effects.

Fig. 3 illustrates the relative magnitude of the direct and indirect effects of the various ecological and social characteristics. They show the effect of a 1% change in each characteristic on building survival. The direct effect represents the effect of that characteristic on the probability that buildings burn. In contrast, the indirect effect represents the effect of the characteristic of a building on the sum of the changes in probabilities of loss of nearby buildings, considering the effect of the building burning on the loss of its neighbours. For example, Fig. 3 indicates that a 1% increase in burn severity around a building increases the probability that it burns by about 0.3%, and it increases the sum of the

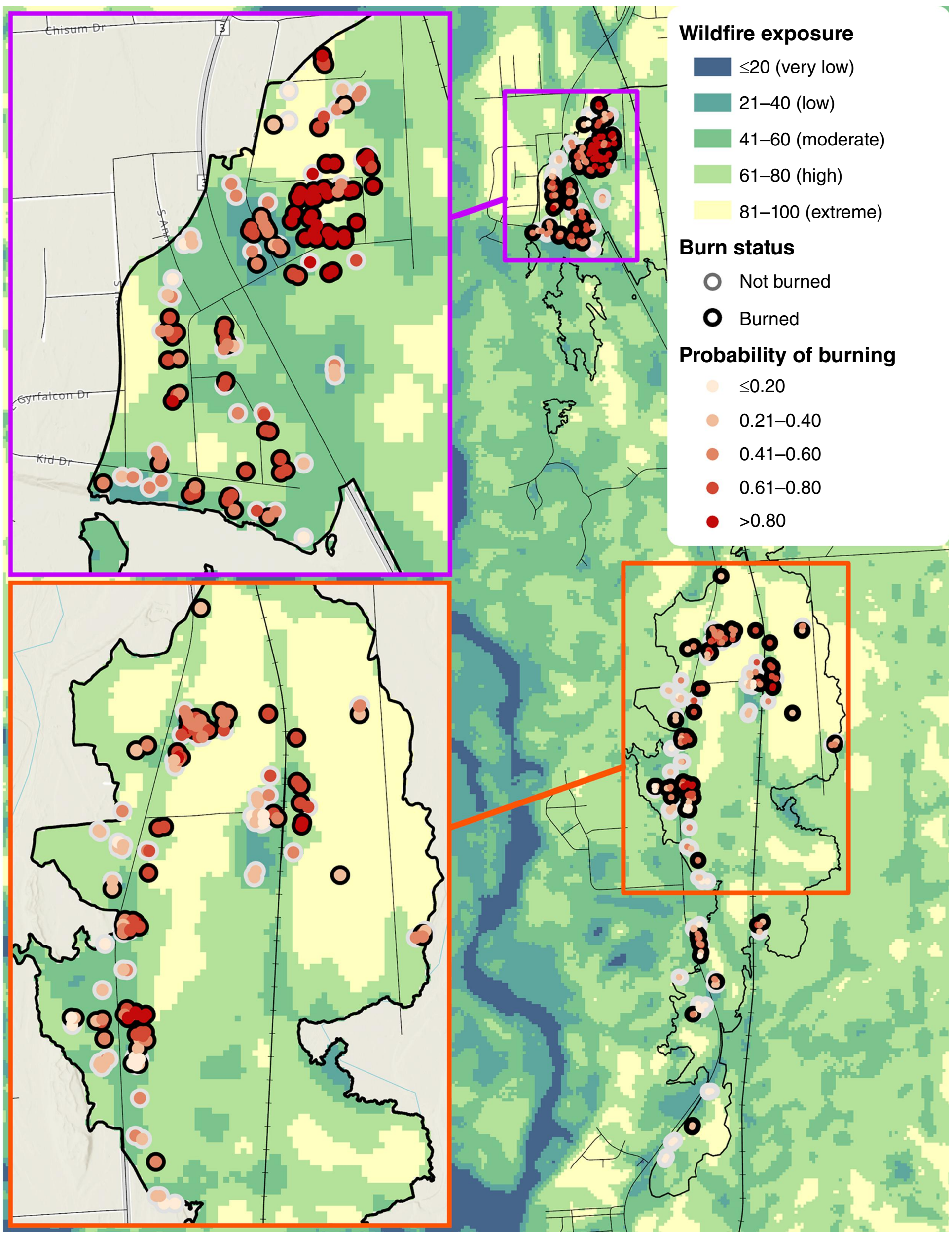

Fig. 2. Location of buildings, with predicted probability of burning (dot interior colour) and burn status (dot boundary colour), overlaid on wildfire exposure. Predicted probability of burning is derived from coefficients in Column 5 of Table 2. Lighter exposure colours represent higher exposure.

Table 3. Estimated direct, indirect, and total effect of a one-unit change in each explanatory variable in the spatial regression equation (Column 3 of Table (2) explaining which homes burned and which survived the McKinley wildfire.

Explanatory variable	Direct effect (z statistic)	Indirect effect (z statistic)	Total effect (z statistic)
Burn severity (30 m)	0.000729 (3.51)***	0.000565 (2.73)***	0.00129 (4.41)***
Percent of tree cover within 100 m	-0.00707 (-3.80)***	-0.00548 (-2.73)***	-0.0125 (-4.58)***
Average 100 m wildfire exposure value within 100 m buffer	0.00703 (2.55)**	0.00545 (2.11)**	0.0125 (3.31)***
Value of improvements (000s)	-0.00202 (-4.23)***	-0.00158 (-2.80)***	-0.00360 (-4.87)***
Total buildings on parcel	0.113 (3.35)***	0.0873 (2.35)**	0.200 (3.99)***
Building wall surface area length	0.0395 (1.84)*	0.0306 (1.39)	0.0702 (2.28)**
Parcel lot size (acres)	-0.00234 (-1.88)*	-0.00182 (-1.60)	-0.00416 (-2.47)**
Number of buildings within 30 m	0.106 (1.99)**	0.0825 (1.82)*	0.189 (2.70)***

A negative sign indicates an increased probability of building survival. Figures in parentheses below coefficients represent coefficient *z* or *t* statistics.
*P < 0.10.
**P < 0.05.
***P < 0.001.

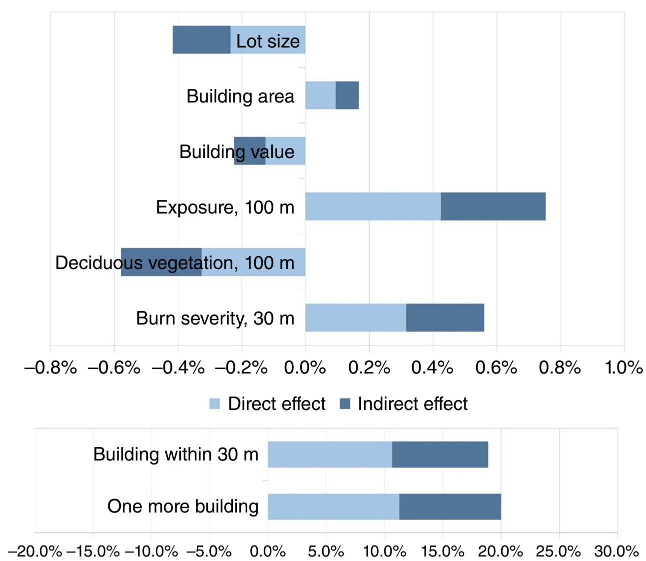

Fig. 3. The relative direct and indirect effects of different explanatory factors in the spatial regression equation for the probability that a building burned are derived from Table 3 and measured as the effect of a 1% increase in each explanatory variable.

changes in probabilities that neighbouring buildings burn by 0.28%. Among all the significant predictors of building loss, the exposure index has the largest percentage effect, with a 1% increase associated with a direct effect of about 0.4% and an indirect effect of about 0.35%.

The bottom panel of Fig. 3 shows that adding one more building to a parcel increases the probability of burning by 20%. Additionally, placing another building within 30 m of another adds a 10% increase in burn probability for each additional building. The mean number of nearby buildings is relatively small (2.32). The indirect effect (i.e. the sum effects on all the other nearby buildings) is only a little smaller than the direct effect.

Discussion

Statistical results consistently showed that the presence of nearby buildings significantly predicted building loss. Additionally, the indirect effects of a building on its neighbours were nearly as important as the direct effects (Table 3 and Fig. 3). These findings support the view that neighbourhood efforts are part of the solution to improving wildfire preparedness and reducing vulnerability (Cohen 2008; Paveglio *et al.* 2012). Despite the rapid spread of the McKinley wildfire, the absence of fatalities in this rural area indicates the effectiveness of community networks. Post-wildfire discussions revealed the use of communication networks for evacuation, emphasising their importance for adaptive capacity (Byrd and Schmidt 2020; Schmidt 2020). Paveglio *et al.* (2016*a*) and Lambrou *et al.* (2023) showed that neighbourhood efforts and good communication are important for adaptive capacity toward wildfire. Steffey *et al.* (2020) also noted that community groups, communication networks, and local firefighters play vital roles in shaping attitudes and reducing building vulnerability in rural areas. Bringing like-minded individuals together as a collective group with positive risk reduction attitudes has been shown to reduce building loss to wildfire in these areas (Lucas *et al.* 2022).

Our results underscore the significance of policy-related factors such as zoning, lot size, and building codes. Building spacing and density have been identified as important factors influencing building vulnerability in other studies (Alexandre *et al.* 2016; Knapp *et al.* 2021; Mockrin *et al.*

2023). Despite rural areas being inherently sparsely populated, clustering occurs, and our findings indicate that placing buildings within 30 m of each other increases vulnerability. When buildings are in lower densities, the risk depends on the exposure to hazardous vegetation surrounding the buildings, not how far they are from another house. Crafting policies that balance affordable housing needs with wildfire risk reduction is a top priority for many WUI communities.

Information about the exterior characteristics of buildings, such as roofing materials and siding used in Alaska, which might explain more of the variation in ignition (see Meldrum *et al.* 2022), was unfortunately unavailable for the study and is a relevant topic for future research. Even with our limited data, building characteristics such as value and age are more important than demographic characteristics (Paveglio *et al.* 2016*b*, 2018). Better construction may help explain why more expensive homes were less likely to burn. However, it could also be that firefighting crews prioritised saving more expensive homes during suppression efforts.

Wildfire impact on buildings depends on the fire's ability to reach them, influenced by factors like flammable vegetation and fire intensity. Wildfire exposure measures how capable the flammability hazards surrounding a specific location are to reach and impact that location. A 10% increase in wildfire exposure values at the 100-m scale (short-distance ember dispersal) within 100 m of a building resulted in nearly a 4% increase in the probability of building loss, both for the building itself (directly) and for nearby buildings (indirectly; Fig. 3). Burn severity, rather than the direction of fire spread, highlighted the increased vulnerability generated by flammable vegetation near homes. Practices like Firewise and Firesmart suggest removal of flammable vegetation, which homeowners may avoid undertaking, thinking it implies a total loss of vegetation (Nelson *et al.* 2005; Paveglio and Kelly 2018). However, this drastic approach is neither necessary nor in alignment with Firewise. Like others (Gibbons *et al.* 2018), our results show that leaving deciduous trees on the property (although not abutting the house) can decrease loss.

Diverse weather conditions, terrain, vegetation, and suppression actions all contribute to variability in individual wildfires (Finney 2005; Carmel *et al.* 2009). Previous studies that linked vegetation characteristics to building loss emphasised the role of weather on wildfire characteristics (Finney *et al.* 2010; Maranghides *et al.* 2013; Prichard and Kennedy 2014; Stevens *et al.* 2014; Johnson *et al.* 2019). Weather conditions varied little during the brief 2-day period when the McKinley wildfire spread uncontained, and the relatively flat terrain precluded consideration of topographical variations (Haire and McGarigal 2009).

The McKinley wildfire underscores the need to reassess WUI definitions (Radeloff *et al.* 2005, 2018; Carlson *et al.* 2022). The minimum development threshold for the WUI definition poses challenges for Alaska and rural areas, where people and property remain at risk, despite lower development densities (Cottrell 2005). The formulaic approach to defining the WUI may exclude these areas from mitigation funding (CWSF 2023; FEMA 2023). Small communities or states with limited resources may struggle to determine effective approaches. Collaboration between academia, agencies, and communities in community-driven research to understand vulnerability would promote wildfire-adapted communities.

Conclusion

This research adds to the growing body of work highlighting the complexity of building vulnerability to wildfire in the WUI. The statistical findings on building loss provide policy suggestions to reduce wildfire vulnerability in the boreal forest region and potentially globally in the WUI, especially in areas with relatively low population density. Significantly, the spatial arrangement of buildings underscores the importance of land-use codes, such as building setbacks, in mitigating wildfire vulnerability during initial development stages. Fundamental Firewise and FireSmart principles, including vegetation management around buildings and on the property level, remain crucial, even in forest-dominated areas. Recommendations include avoiding buildings within 30 m of another building to prevent radiant heat spread and discouraging construction in high wildfire exposure areas. If buildings are constructed in such areas, fuel management actions to clear flammable vegetation to reduce wildfire exposure would decrease building loss during wildfires.

Our findings emphasise the importance of a comprehensive SES approach that integrates social and ecological factors to understand building loss to wildfire in the WUI. As (Calkin *et al.* 2023) noted, WUI fires are not solely a wildfire problem but are closely tied to buildings and their surroundings. We found that wildfire may still spread from building to building in sparsely populated areas. Storage sheds and other outbuildings, popular in more sparsely populated areas where self-sufficiency and identity are valued, pose a risk to residences. Instead of creating WUI building codes, which may face resistance, empowering people through knowledge and awareness initiatives, such as outreach at home builder conferences or outdoor symposiums/shows, may be more effective in reducing wildfire risk by making residents aware of the hazards from outbuildings near their homes.

Many WUI residents, especially in Alaska, enjoy living in the forest and value the ecosystem services they provide (Hansen and Naughton 2013; Little *et al.* 2018). Work in Alaska showed that shaded and thinned fuel treatments were more acceptable than cleared treatments (Hansen and Naughton 2013; Little *et al.* 2018). Our finding that deciduous trees reduce the likelihood of building loss provides a potential pathway for living with forests in a fire-safe manner. Property owners should still heed Firewise recommendations regarding the placement of trees and removal of debris, but this could be an acceptable trade-off for mitigating wildfire risk.

Supplementary material

Supplementary material is available online.

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Data availability. After acceptance, the dataset used for the modelling will be archived with the NSF Arctic data centre.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. Funding for this work was provided by the US National Science Foundation, Award No. 1927563/1927537: NNA: Arctic Urban Risks and Adaptations (AURA): a co-production framework for addressing multiple changing environmental hazards and the Alaska EPSCoR and the state of Alaska provided funds for this project (NSF award #OIA- 1757348).

Author contributions. J.S.: Conceptualisation, methodology, data collection and curation, writing. M.B.: Methodology, formal analysis, and writing. C.W.: Conceptualisation, methodology.

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