Safety Science 157 (2023) 105928

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Garden structure is critical for building survival in northern forest fires – An analysis using large Swedish wildfires

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ARTICLE INFO

Keywords:
Wildfire
Boreal
Wildland-urban interface
Scandinavia
Building loss

ABSTRACT

Despite increasing concern over wildfires in Fennoscandia, there are essentially no studies on the survivability of buildings within the wildland-urban interface of this region. We make use of four recent large-scale fires in Sweden to elucidate which factors are important for survival, using multiple logistic regression analysis of data collected at the sites. We obtained data on 187 buildings within the fire perimeters, nearly all with wood paneling and tile- or sheet metal roofing. 35 % of the buildings were lost or badly damaged. Results indicate that most buildings were approached by relatively low-intensity fire and that ignition primarily occurred through direct flame contact. The most important factor for survivability was the presence of a maintained lawn. The second most important was that no flammable material was present close to the building façade. Further, fire intensity often decreased close to buildings due to a larger portion of deciduous trees around gardens than in the surrounding forest. These factors were more important than specific features of the building itself, reflecting that the majority of buildings have combustible wooden façades. Our results suggest that the greatest potential for increasing building safety in the Swedish WUI is to keep the area immediately surrounding the building (~5 m) free from tree litter and other flammable material. Also, since fire intensities are generally low, buildings can in most cases be defended with simple tools without compromising personal safety.

1. Introduction

Loss of buildings in wildfires is an increasing problem globally (Caton et al., 2017) and has generated a large research interest, primarily in the US (Kramer et al., 2018), Canada (Westhaver, 2017), Southern Europe (Ganteaume et al., 2021) and Australia (Blanchi, et al., 2010; Gill et al., 2013; Collins et al., 2016). Many buildings are destroyed as large wildfires burn through the so-called wildland-urban interface (WUI), i.e., the area where wildland faces or intermixes with buildings (Radeloff et al., 2005, Kramer et al., 2018). However, not all buildings within a fire perimeter are destroyed and the survivability of a building is to a great extent governed by the characteristics of the building and its immediate surrounding, such as the building materials or the amount of garden fuel (Westhaver, 2017). Since Scandinavian architecture, landscapes and gardens differ from those of southern Europe or North America there are reasons to believe that conclusions drawn from studies in those areas are not directly applicable to Scandinavia. Here we aim to provide a first quantitative study of building loss and survivability in this region, using observations from large Swedish forest fires.

1.1. Previous research

In California, houses with flammable roofing material suffer from a significantly increased risk from airborne glowing or flaming embers leading to ignition (Foote 1994; Maranghides et al., 2013). Also, even nonflammable roofing such as weathered, curved ceramic tiles become vulnerable if tree litter accumulates (Manzello et al., 2010). Similar pathways to damage are untended gutters, leading to ignition of the roof assembly, as shown in both US case studies and lab tests (Cohen & Stratton, 2008; Manzello et al., 2008).

Combustible façade systems are susceptible to all types of ignition – direct flame contact (Grishin et al., 2014), embers (Manzello et al., 2012) and radiative exposure (Alexander et al., 1998). Further, lab studies show that windows can break due to thermal stress from the shaded frame and exposed center, although embers may also accumulate on the windowsill leading to an eventual window breakage (Manzello et al., 2012). But the most important building feature when surveying

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https://doi.org/10.1016/j.ssci.2022.105928
Received 9 December 2021; Received in revised form 24 August 2022; Accepted 7 September 2022
Available online 13 September 2022

building loss in Californian (Syphard & Keeley, 2019) as well as Spanish (Pastor et al., 2020) wildfires was the closure of eaves and vents, through which embers can otherwise enter.

A majority of building ignitions occur from fuels within their immediate surrounding (c.f. review of US incidents, Kramer et al., 2018). Experimental data suggest that coniferous garden vegetation generally infers a higher risk to nearby buildings than typical broadleaved vegetation (Riberio et al., 2020). The presence of non-vegetative fuels, for instance, household LPG tanks (Scarponi et al., 2019) or wooden fences (Maranghides et al., 2013) elevates the risk of building ignition. Additionally, attached or detached constructs such as sheds, decks and porches can increase risk (Quarles et al., 2012).

Vegetation touching or overhanging the building was identified by Syphard et al. (2012) as a risk factor in the USA. To counter this, a common protection strategy is to clear or prune vegetation in the immediate surrounding of homes, to create a 'defensible space' (Cohen, 2000; Winter et al., 2009). Syphard et al. (2014) found that a defensible space of 5 to 20 m significantly increased the chances of surviving, whilst cleared vegetation beyond a 30 m radius around the building did not further improve fire protection.

Fire intensity and rate of spread are determined by fuel structure, fuel moisture content, wind and slope, and should be critical for the exposure of a building to the approaching fire. Somewhat surprisingly Syphard et al. (2012) found that building destruction in California was more likely for buildings located in herbaceous-type terrain than in fuel-rich woody ones. This was hypothesized to depend on the rapid drying of herbaceous fuel and its relatively higher ignition propensity, as well as the increased local wind speeds. The same study showed that building destruction due to wildfire was more likely in isolated communities with low housing density than in larger settlements, due to the reduced access to firefighting.

Alexandre et al. (2015) highlighted that the determining features for building survival in wildfires vary across both ecoregions and types of settlement. The reason why and how buildings are ignited and destroyed within a fire perimeter will thus vary geographically. The bulk of research on building ignitions by wildfire has been done in North America, Australia, and southern Europe. For Northern Europe, there is hardly any information, although a number of catastrophic wildfires in recent years have highlighted the risk for buildings and other infrastructure (Grishin et al., 2014; Log, 2015; Log et al., 2017; Gustafsson et al., 2019; Granström, 2020).

In Sweden, a large part of the rural building stock is located within the WUI, (Vermina Plathner & Sjöström, 2021a) although the small area burnt in wildfires in recent decades have kept overall risks low. This might change with the prospect of increasing wildfire season length and severity in the future (Flannigan et al., 2013; Yang et al., 2015). The forests in rural Sweden are largely conifer-dominated with typical boreal surface fuel beds of porous moss/litter that can generate high fire intensity and spread rates.

1.2. Aim

Here we make use of four recent large (+1000 ha) wildfires in Sweden that in total had 187 buildings within their perimeters, to find the most important physical features of the buildings and their surroundings that influenced the risk of destruction. Data from the destroyed and undamaged buildings and their surroundings were collected from aerial photos and field observations forming the basis to multiple linear regression analyses and characterizations of the buildings, gardens, landscapes and fire intensity. We aim to find the most important building-, garden- or landscape-features that increases building survivability in northern forests.

Table 1
Buildings within the four analyzed wildfires.

Ignition location (WGS 84)	Fire	Burned area (ha)	Buildings (total)	Destroyed buildings
59.840912, 16.203869	Västmanland	13 100	130	40
61.95236, 15.489852	Enskogen	4 326	41	16
62.000868, 15.264378	Nötberget	872	3	3
61.925689, 15.425239	Ängra	3 797	13	7
	Total	**22 000**	**187**	**66**

2. Methods

2.1. Study areas

Four large fires with a substantial number of buildings within their perimeters were selected: (1) the Västmanland fire that occurred in south-central Sweden in 2014, and (2) three fires that burned in 2018, 230 km further north in the country, see Table 1.

2.1.1. The 2014 Västmanland fire

The Västmanland fire (Fig. 1) started 31st of July 2014 by ignition from a mechanical scarifier (cf. Sjöström et al., 2019). The fire burned an area of approximately 13 000 ha over five days, of which around 75 % burned during the afternoon of the 5th day when strong winds and very low relative humidity resulted in a high-intensity crown fire. Over three-hours in the afternoon spread rates of approximately 80 m/min were logged (Granström, unpublished). The fire damaged 71 buildings, claimed one life, and caused one severe injury. Dominant vegetation within the Västmanland fire perimeter before the fire was pine forest (~50 % of the area) followed by spruce forest and conifer-dominated mixed forest (approx. 20 % each) with only a small portion of clear-felled land (2 %) (MSB, 2015; Nilsson et al., 2014). The rate of spread and final size of the fire was unprecedented for the last 100 years. Residents in the area were therefore not ordered to evacuate by authorities in time but did so spontaneously when the fire approached. Mostly, this was done hastily, and few mitigation attempts were performed by either residents or rescue services.

2.1.2. The 2018 Ljusdal fires

The three fires within Ljusdal (referred to as Enskogen, Ängra and Nötberget in Table 1) were all ignited by lightning on the afternoon of the 14th of July 2018 and were not fully controlled until July 28th (Fig. 1). In comparison with the Västmanland fire, the rate of spread and fire intensity were generally lower, with only small sections of crown fire. Dominant vegetation was pine forest (~35 %) and recently clear-felled land (~25 %). A total of 57 buildings were located within the fire areas, of which 26 were destroyed (Granström, 2020). Most residents within and around the fire perimeter were evacuated and not let back to their homes until long after the fires were controlled. Due to the generally lower rate of spread compared to the Västmanland fire, more fire suppression efforts were undertaken at the Ljusdal fires. However, the extreme resource scarcity limited attempts to salvage buildings and the degree to which these attempts influenced the outcome for buildings in the area is unknown.

2.2. Data collection

Data was collected for all 187 buildings located within the fire perimeters (Table 1) of which 66 were destroyed and 121 survived. In this study, smoke-damaged buildings or buildings with only minor damage are referred to as *survived buildings*.

For the Västmanland fire, observations of fire characteristics,

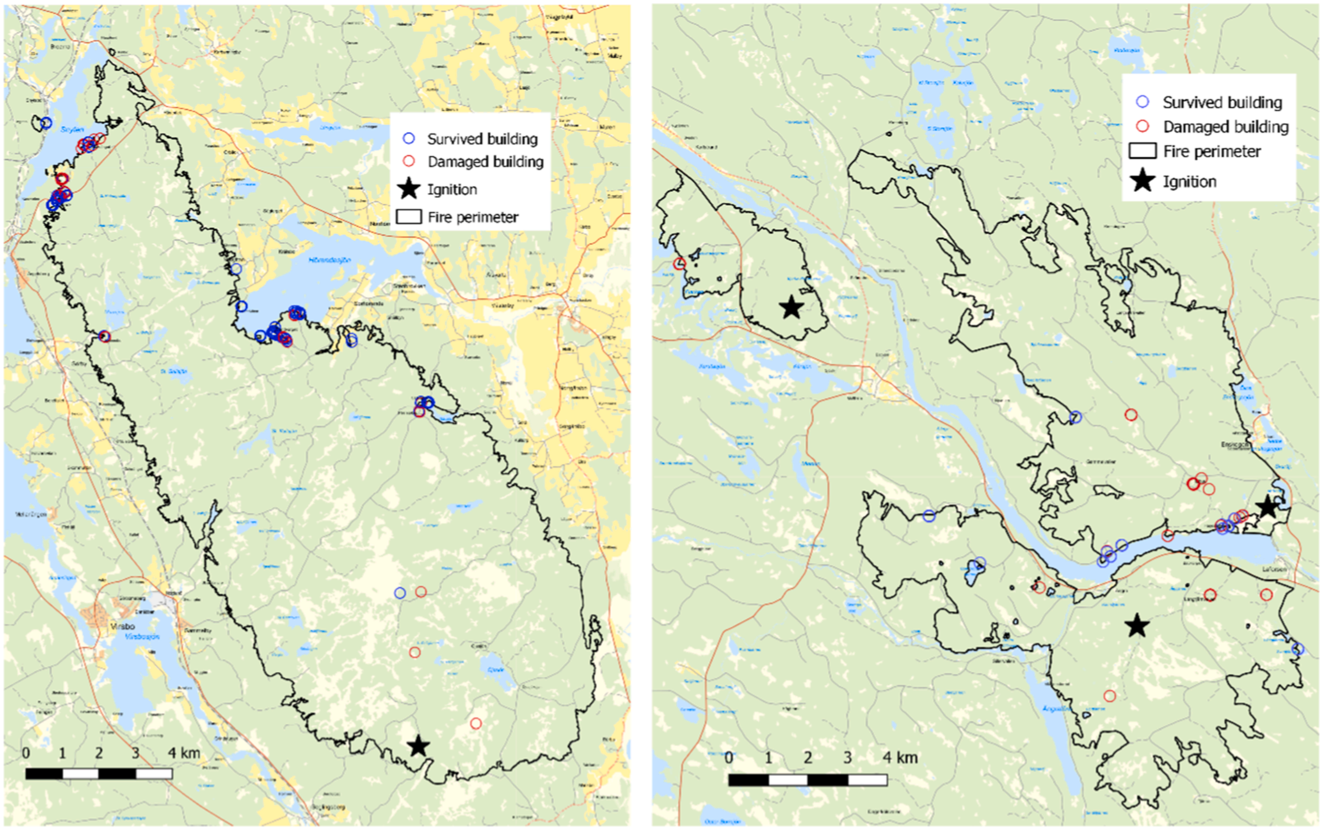

Fig. 1. Final fire perimeter for (a) Västmanland fire, and (b) Ljusdal fires. All 187 buildings within the perimeters are identified with a circle, although many overlap on this large scale. Sources: (a) MSB (2015), (b) Granström (2020). Background map ©Lantmäteriet.

buildings and their surroundings were obtained both by analysis of high-resolution photos from the Swedish armed forces' helicopter wing, taken immediately after the fire and post-fire field observations directly after the incident. For the other three fires, we obtained such data primarily by field observations during and directly after the events. Some complementary observations were done 12 months after the fires.

The direction from which the fire approached the building was obtained from reconstructions of fire progression built on aerial observations (MSB 2015, Granström 2020). Fire intensity in the vicinity of buildings was deduced by observing char height and aspect on nearby tree stems or by observing fire patterns from aerial photos. The criterion for a low-intensity fire was a char height of less than 2 m.

Wildland is here defined as any land outside of gardens or roads. A *garden* is defined as all land within the obvious garden area. While vegetation types of gardens were assessed using photos and site observations, the landscape characteristics in the vicinity of the building were additionally analyzed in Quantum Geographical Information Systems (QGIS, 2022). The dominant fuel type surrounding each building was, for fires within the Ljusdal fire complex, analyzed with the zonal histogram tool in buffered half-circles ($r = 40$ m) from each building in the upwind direction at the time of the fire, overlaying a vegetation map (10 m × 10 m resolution) produced by the Environmental Protection Agency (2020). The vegetation map had not been constructed at the time of the 2014 Västmanland fire, so the dominant vegetation type in that fire was instead obtained by examining the post-fire photos from the Swedish armed forces' helicopter wing and high-resolution (0.25 m) orthophotos taken by the Swedish Mapping, Cadastral, and Land Registration Authority (Lantmäteriet) before the fire.

Housing density was obtained by creating a buffer ($r = 40$ m, (Cohen, 2000)) around each building and thereafter calculating the number of buildings within that area. The presence of potential fuel breaks in the vicinity of each building was obtained by mapping roads, lakes and watercourses between buildings in the direction from which the fire approached. Topographical features (slope and aspect) were obtained from the Swedish Mapping, Cadastral, and Land Registration Authority (2021).

To gain relevant information that could not be observed by us on-site, we contacted homeowners, on-site or by phone. We then asked about the status of the building and garden at the time of the fire and whether or not any pre-fire mitigation activities had been done, such as cleaning of gutters. Observations were also collected from three first responders active in the suppression efforts.

2.3. Data analysis

The response variable, i.e. whether a building survived the fire or not, was collected from the four different fire events. However, three of these occurred simultaneously in time and in relative proximity to each other. We therefore treated the three Ljusdal fires as a single *fire id* in a generalized linear mixed model (GLMM). We based the analysis on *fire id* as a random intercept along with a set of fixed effects estimates relating to the building itself and its surroundings. The complete dataset of fixed effects included 24 features of the building, the garden, the fire behavior, and the surrounding landscape. A list of all variables is presented in the appendix (Table A1).

All variables were first univariately analyzed but if the occurrence (N) for any category and outcome was below 10 it was, for the multivariate analysis, either collapsed into combined categories or excluded from the regression analysis (such variables are labeled with a superscripted '1′ in Table A1) (Moineddin et al., 2007). An example of exclusion is the *façade material* variable for which all except nine buildings had wood exterior paneling. An example of a variable with combined categories is *wildland fuel type*, describing the vegetation around the gardens, where spruce, pine and clear-felled area were

Table 2
Results of the logistic regression model using the hypothesis-based selection method. OR and CI are the odds ratios and their 95 % confidence intervals. p represents the significance level of the variable to be compared with the chosen level $p < 0.1$, indicated by (*).

Variable	Category	Reference category	Multivariate analysis		
			OR	CI (95 %)	*p*
Intercept					0.386
Defensible space	1–4 m	0 m	1.49	(0.60; 3.81)	0.398
	5- m		2.85	(1.24; 6.91)	0.017*
Wildland	Mixed	Coniferous	1.00	(0.45; 2.24)	0.999
	Deciduous		2.18	(0.90; 5.54)	0.091*
Fuel break	Yes	No	1.57	(0.75; 3.29)	0.226
Type of building	Main building	Outbuilding	1.19	(0.59; 2.40)	0.624
Housing density	300–400 units/km^2	200–300 units/km^2	1.10	(0.51; 2.42)	0.809
	greater than400 units/km^2		1.08	(0.42; 2.83)	0.876

Random effects variance: 0.

combined to represent a category where high fire intensity or rapid fire spread could occur. The three new categories for this variable became (1) *coniferous and clear-felled land*, (2) *mixed* and (3) *deciduous*, see Table A.1 for details. The data was thereafter cross-tabulated (Table A1).

Initial removal of a few parameters with known collinearity was also made (labeled '2' in Table A1). For example, *fire intensity* is dependent on topography (*aspect* and *slope*) and fuel characteristics (i.e *wildland fuel type*) and was therefore removed from the data set for the GLMM models, while *slope, aspect* and *wildland fuel type* were kept. *Vegetation fuel in the garden* was similarly removed due to its correlation with *defensible space* (by definition, there is no defensible space when there is a high degree of garden fuel). Collinearity was also tested with the variance inflation factor model in R car package (Fox & Weisberg, 2022) where all building variables aligned with the variable *building type*. We therefore chose to use the *building type* variable as a proxy for all building features. Thus, an *outbuilding* represents a building with wooden exterior paneling, corrugated metal sheet roofing, no gutters, and an open crawlspace foundation. The *main building* similarly represents a building with wooden exterior paneling, a tiled roof, gutters, and a closed foundation.

The one-in-ten rule of thumb for logistic regression (Peduzzi et al., 1996) and the 66 destroyed buildings in the data set implies that a maximum of six predictor variables should be used to avoid the risk of overfitting, although a smaller number is preferable. Two different models were produced using different methods to select the variables; one hypothesis-based and one significance-based selection.

First, we employed a hypothesis-based selection procedure, whereby variables were chosen based on our own observations and previous research. These were: *building type*, *defensible space*, *wildland fuel type*, *fuel break* and *housing density*. Most destroyed buildings in the investigated fires were outbuildings (63 %), i.e. garages, barns or sheds. Although these buildings have less economic value than main buildings, they may pose an additional threat to the main building by adding ember- and radiative exposure for a longer time duration. Outbuildings were often located closer to (or even within) the wildland and had therefore both a higher degree of vegetation fuel touching or overhanging the roof and usually forest floor stretching to the façade. *Defensible space* was selected due to its frequent use as an indicator in previous research (Syphard et al., 2014). Due to their covariance, we decided to keep *defensible space* and ignore the *presence of a lawn*. *Wildland fuel type* was selected since broadleaves are known to have a dampening effect on the fire intensity (van Wagner, 1977). *Fuel break* (linear breaks such as roads or streams) may, at least for low-intensity fires, stop or delay fire propagation and was selected based on site observations.

Second, we employed a significance-based selection procedure where the variables were instead reduced by an automatic procedure in which they are ranked and selected by a stepwise procedure (both forward and backward directions), selecting the model combined with the smallest Akaike's Information Criterion (AIC) (Akaike, 1973).

The variables that were not selected for the regression analysis in either case, as well as supporting variables, are briefly discussed separately in the results section. The selected variables were in both cases fitted with multiple logistic regression, using the *Generalized Linear Mixed Model* (Stroup, 2012) in the statistical software R with a logit link function, to indicate variables that had a major effect on the building survivability. *Fire id* was modelled as a random intercept and all other selected variables as fixed effects. Thus, both selection methods provide a multiple logistic model of survivability based on the chosen variables for the method.

The modelled effects of the selected variables relate the odds of survival in one category to a chosen reference category (Table 2). The odds ratio (OR) describes by what factor the odds for survival change when one variable changes from a reference category to another (all other variables equal) for the fitted model. For univariate analysis, this is simply the arithmetic ratio of survived and destroyed buildings of the two categories, but in the multiple logistic regression analysis the effect of dependencies between variables are also taken into account.

3. Results

The statistical analyses (Section 3.3) describe the correlations between survivability and the different variables but not the actual mechanisms involved. Here we describe the characteristic landscape, gardens and fire behavior and the outcome for buildings, based on observations from ground and air.

3.1. Field observations

3.1.1. Fire intensity and ignition mechanism

Houses and gardens that were approached by high-intensity surface fires or crown fires were exposed to numerous airborne embers, according to homeowners and aerial photo evidence (e.g. the isolated spot fires in Figs. 2 and 4). An obvious example of ember ignition of a building is the isolated garage in Fig. 2b, in which the house owner also testified on embers falling frequently on the garden before evacuation. However, most destroyed buildings were approached by low-intensity fires moving uninterrupted toward the house and ignition was likely by direct flame impingement rather than by embers or radiation. Char heights of only a few decimetres on the tree stems around many of the destroyed houses support this assumption (Fig. 2a). One direct observation was also made of a low-intensity fire (estimated flame length 30 cm) approaching a timber-framed building and igniting it, leading to destruction (Fig. 3). Such low-intensity fires hardly produce any embers and since most facades were wooden (thus igniting if subject to flaming) we judge direct flame contact to be the cause for most of the destroyed buildings.

3.1.2. Decks and porches

It is difficult to ascertain whether or not external features such as wooden decks and porches contributed to the eventual destruction of a building since they were often destroyed together. We observed several cases where glowing embers had made only deep char marks on wooden decks without leading to sustained ignition. Also, in one case a low-intensity fire had burned the fine fuel all the way to the house without igniting the façade, due to a 40 cm high foundation of asbestos cement boards. However the horizontal steps of the wooden porch (the only

Fig. 2. Indicators of building ignition pathways: (a) Remnants of a building most likely ignited by flame impingement. Low scorching of the vegetation in the background suggests that a low-intensity fire has burned through the fine fuel up to the building, subsequently igniting it. (b) A high-intensity fire in the nearby forest spread to a garden. Burning embers fell on the garden igniting the garage to the right. Flames also spread in the more natural fuel under the planted Thuja array where some of the trees torched completely. No flames could however spread across the lawn. Photos: (a) Johan Sjöström, (b) Swedish armed forces' helicopter wing (with permission).

combustible housing material at ground level) initially ignited from below but could not sustain further fire spread.

3.1.3. *Garden fuels*

Typically, the fuel structure within gardens was spatially very heterogeneous. Most often there were at least some non-flammable areas, such as gravel paths and stone walls but we also observed several cases where managed lawns did not burn (see e.g. Fig. 2b and Fig. 4). Instead, flames often spread through areas of more natural vegetation, with or without overarching shrubs or trees. One such example is the sparsely planted array of *Thuja occidentalis* in Fig. 2b, where the surface fuels carried the fire all along the hedgerow. Thus, although fire intensity was high in the nearby forest, throwing embers into the garden, within the garden itself fire could only spread through less managed vegetation and not across the lawn.

High-resolution aerial photography provide further evidence that a maintained lawn can offer protection (Fig. 4). In this particular case, the fire approached from the lower side of the photo with high intensity, ignited and destroyed two buildings located in proximity to the spruce forest but failed to carry over the mowed grass surrounding the other buildings.

3.1.4. *The landscape*

Fire intensity decreased in areas with deciduous trees that often surrounded the gardens. An example is illustrated in Fig. 5. Here a high-intensity head fire approached through old coniferous stands and a recent clear-felled area. The residents described numerous embers landing in the lawn as they fled to safety. But then fire intensity decreased within a ~ 20 m wide strip of mainly deciduous trees around the garden: birch (*Betula pendula*), sallow (*Salix caprea*), and aspen (*Populus tremula*). The fire finally stopped when it reached the lawn that surrounded the house (Fig. 5).

3.2. *Univariate analysis*

Building survival was analyzed for a total of 18 variables, 6 of which were related to the building itself, 10 to the surrounding environment, and 2 to the behavior of the fire (Fig. 6). The univariate analysis accounts for each variable separately without considering interdependencies between them. The odds ratio for each category/

Fig. 3. Photo from across the river Ljusnan showing tall flames from a building just ignited by an approaching low-intensity fire. The photo was taken at 22:15 on July 27, 2018. The Enskogen fire was started by a lightning strike 13 days earlier. Photo: Anders Granström.

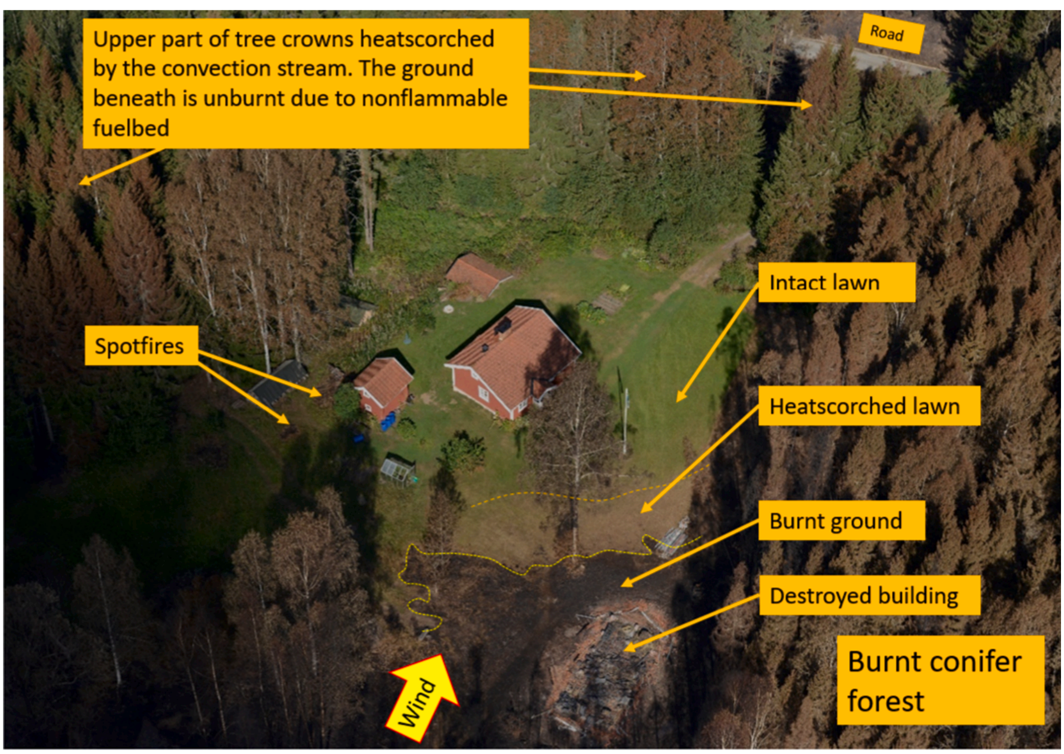

Fig. 4. An example from the Västmanland fire in which the maintained lawn prevented the fire to be carried to the buildings. The fire, traveling upwards in the figure, had a moderate to high intensity as it reached the property. It destroyed two buildings, of which the remains of one is seen in the low, center part of the figure. Hot convection streams scorched the upper parts of the spruce and birch trees in the background. However, the lawn and everything located on the lawn, such as buildings, plastic water barrels and woodpiles, were unaffected by the fire. Photo: Swedish armed forces' helicopter wing (with permission).

reference category is shown in the appendix (Table A.1).

Most variables (13 of 18) follow expected trends (blue lines in Fig. 6). There was a strong (OR > 3.5, Table A1) positive effect in survival with the presence of a *lawn*, low amount of *vegetation fuel in the garden*, or *touching/overhanging the building*, a *defensible space* larger than 5 m and low *fire intensity*.

Expected but weaker trends (OR < 3.5) were found for *building type*, *foundation type*, amount of *non-vegetation fuels in garden* or *touching the façade*, *wildland fuel type, housing density,* the presence of *fuel breaks* and fire approaching the building on a downward *slope*.

Some variables (red lines in Fig. 6) exhibit trends that are opposite to the expected. For instance, a larger fraction of buildings with *tile roofing* survived than those with other roofing types, which is rather unexpected given that most other roofs were sheet metal types and that previous studies show increased risk associated with fuel accumulation on curved tiles (Manzello et al., 2010). However, roofing type covaries with

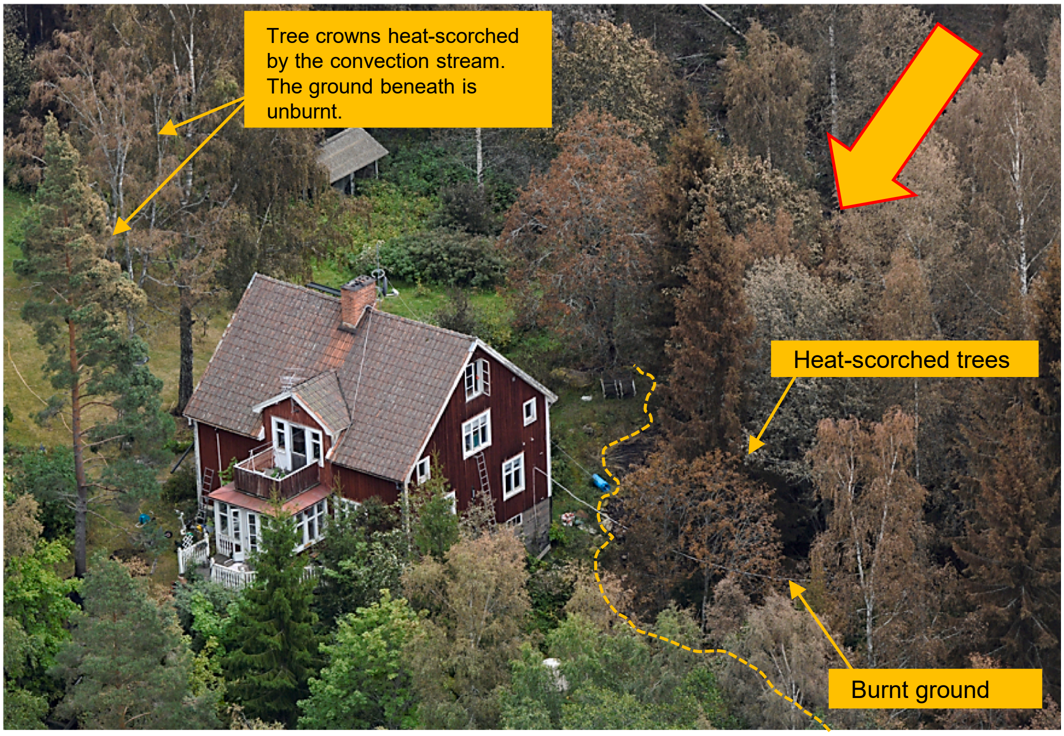

Fig. 5. A house surviving the Västmanland fire. A high-intensity fire travelled with wind from the upper right-hand side in the figure, before reaching the deciduous forest strip containing birch, sallow, and aspen. Hot convection streams from high-intensity fire (mainly crownfire) up-wind of this scene scorched the trees on both sides of the building. However, the fuels under deciduous trees reduced fire-intensity and the fire finally stopped against the lawn, preventing the fire from reaching the house. Photo: Swedish armed forces' helicopter wing (with permission).

building type, where main buildings more often have tiled roofing than outbuildings and are often more isolated from the surrounding fuel than are outbuildings. Surprisingly, buildings with *combustible façades* survived to a higher degree than those with incombustible ones. However, only 9 buildings had incombustible façades, rendering this result uncertain. While the presence of *gutters*, *wooden decks*, or *hedges/fences* are expected to decrease the likelihood of survival the opposite was observed, most probably also due to the covariance with *building type* and hence a long distance to the wildland and presence of *defensible space*.

In the Ljusdal data set, for which we had access to vegetation type maps, we assessed the vegetation from each building in a 40 m radius semi-circle in the direction from where the fire approached (Fig. 7). This analysis enables us to describe how different vegetation types affect the building outcome in more detail, compared to the few variables that can be included in a GLMM. There were relatively small differences between destroyed and survived buildings in the proportion of the nearby area covered by different substrates/vegetation. The most abundant cover was pine forest for both destroyed and survived buildings (Fig. 7). However, destroyed buildings had notably higher proportion of clear-felled land. On the other hand, destroyed buildings had a lower proportion of mixed forests, lawns or roads (Fig. 7).

3.3. Multiple logistic regression

3.3.1. Hypothesis-based model

In the hypothesis-based model, a *defensible space* of 5 m or more provided the most important factor for building protection. It is also one of only two statistically significant (significance threshold of $p \leq 0.1$) variables in the model that incorporated a total of 5 fixed variables (Table 2).

The other significant outcome was that buildings surrounded by deciduous *wildland vegetation* had higher survivability compared to those surrounded by coniferous or clear-felled land. There was however no statistically significant difference between coniferous/clear-felled land and mixed forest (Table 2).

3.3.2. Significance-based model

Variables that were related to survivability at a significance level of ≤ 0.1 in the automatic selection procedure (Appendix Table A2) were selected for the 2nd logistic regression. Four variables, with four non-reference categories fulfilled this criterion (Table 3).

The *presence of a lawn* had the largest survivability odds (Table 3). All else being equal, buildings with a lawn had an almost fourfold higher chance of surviving than buildings without.

Topography played an important role for survivability. If the fire approached the building on a downward slope the chances of survival increased significantly compared to when the fire approached via flat ground or an upward slope.

Likewise, the absence of non-vegetation fuel (typically firewood, furniture, wood pallets, car tires, and plastic barrels) touching the building was associated with significantly higher survival. In case there was a fuel break (watercourse, asphalt, or road) within 100 m from the building in the direction of the approaching fire the survivability odds doubled (Table 3).

4. Discussion

This study is the first analysis of building survivability in forest fires in northern Europe. Although drawn from only four different fires, the analysis comprised a total of 187 buildings, 66 of which were destroyed. Both the statistical analyses and the field observations point to several critical factors for survival, relating primarily to features in the garden surrounding the building, but also to the building itself, and to some extent the fire behavior.

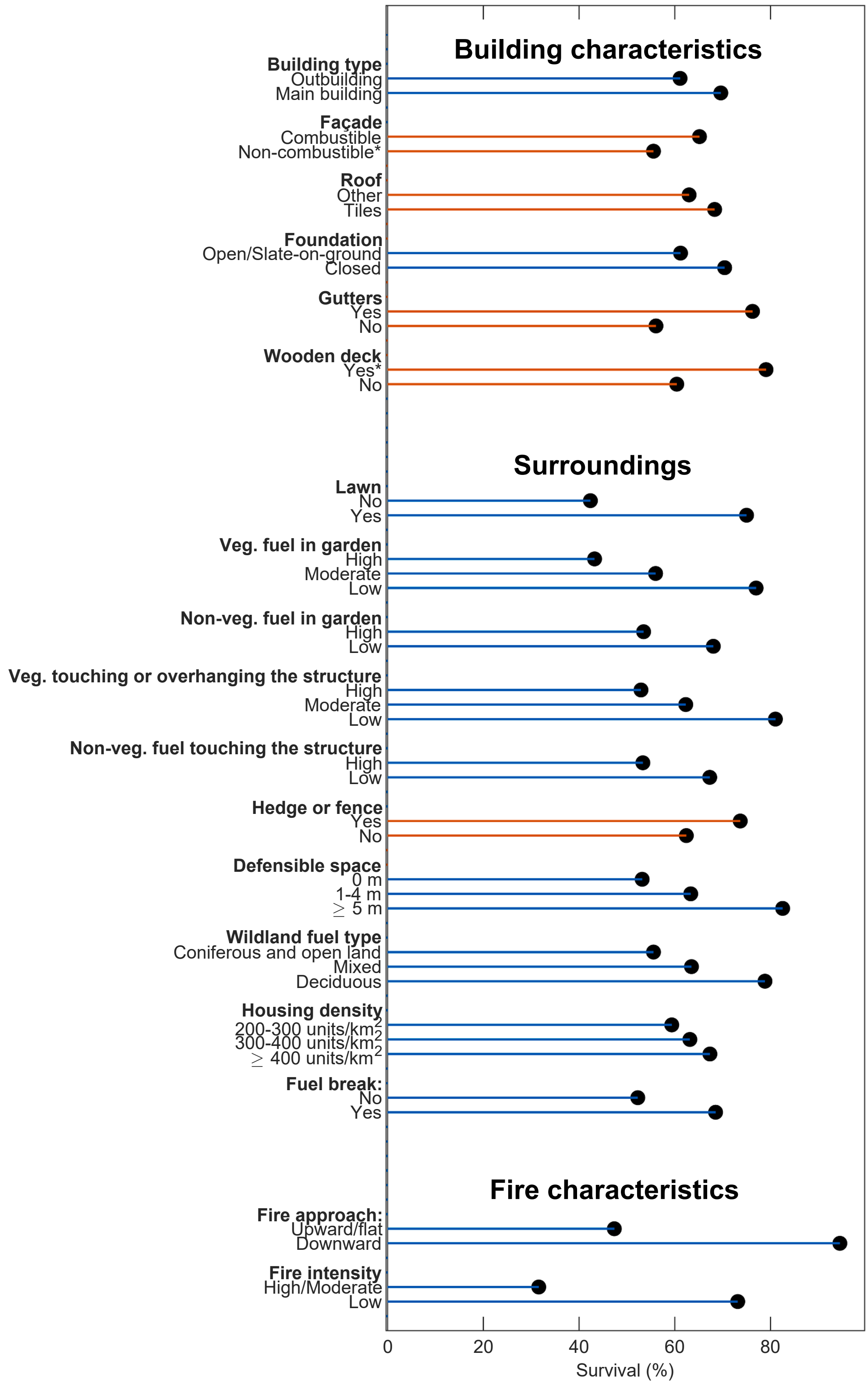

Fig. 6. Univariate analysis of variables with regard to the fraction of survived buildings within each category. Blue lines signify variables with an expected outcome trend whereas red signify an unexpected trend. Asterisk (*) denotes categories with less than 10 buildings. See Table A1 (Appendix) for full cross tabulation of the variables collected in the inventory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Surrounding fuel structure

All properties (building plus garden) we examined were, at a larger scale, embedded within forest vegetation, most often stands of coniferous tree species. Such stands typically have a highly flammable surface fuel bed of moss/litter below a field layer of ericaceous dwarf-shrubs (Schimmel & Granström, 1997). Between the forest and the buildings (here defined as '*gardens*'), various plant assemblies and non-

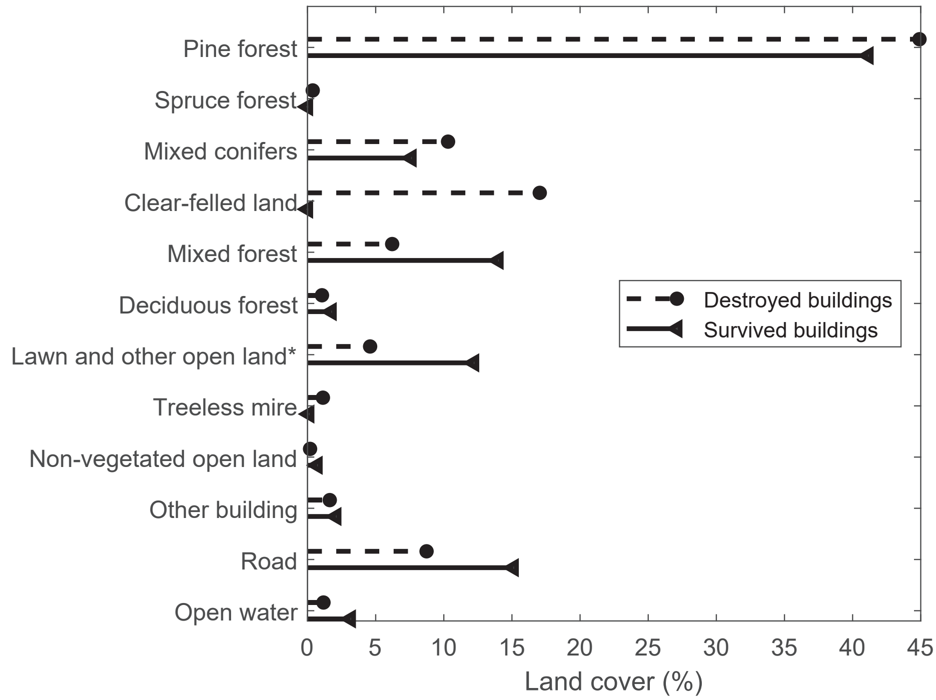

Fig. 7. The proportion of land cover types in buffered half-circles extending 40 m from each building centroid, in the direction towards the approaching fire (Ljusdal fires only). (*) 'Other open land' is defined as land that is not wetland, arable land or exploited vegetation-free surfaces, but with >10 % vegetation coverage.

Table 3
Results of the logistic regression model using the significance-based selection method. OR and CI are the odds ratios and their 95 % confidence intervals. p represents the significance level of the variable to be compared with the chosen level $p < 0.1$, indicated by (*).

Variable	Category	Reference category	Multivariate analysis		
			OR	CI (95 %)	*p*
Intercept					0.0008*
Lawn	Yes	No	3.82	(1.93; 7.73)	0.0001*
Fire approach	Downwards	Upward/flat	2.61	(1.18; 8.98)	0.0187*
Non-veg. fuel touching the building	Low	High	2.80	(1.22; 7.03)	0.0271*
Fuel break	Yes	No	1.99	(0.94; 4.30)	0.0772*

vegetation covers were present, with distinctly different capacities to carry fire. Direct photo evidence, the multiple regression analysis, and the univariate analysis all suggest that the presence of a lawn was the most important factor for survivability (Table 3). When the lawn variable was excluded from the regression model the highest odds ratio was for *defensible space*, which largely co-varies with the presence of a lawn.

A maintained lawn has short green grasses and herbs as the main fuel component, often with a subcomponent of thin mosses. As such, it can hardly sustain fire spread both due to short stature and to the high moisture content within the live fuel bed (NWCG, 2014). In case of severe drought, the lawn is often watered to keep it green, which is very favorable from a fire protection perspective. Further, homeowners tend to keep the lawn free from other fuel such as tree litter, by raking in the fall. The flammability of taller uncut "meadow" vegetation is more complicated to assess. It cures during winter and is highly flammable in spring until green-up (Granström et al., 2000; Sjöström et al., 2021). The investigated fires occurred well into summer but in severe drought and some of the taller herb/grass vegetation may have cured enough to carry fire. There were frequent observations (as in Fig. 2b) that uncut grass/herb vegetation did indeed burn, e.g. around garden bushes, likely helped by additional litter from trees and shrubs.

Although a lawn is typically part of the residential garden in this region (Ignatieva et al., 2017) not all buildings have lawns. Many summerhouses and outbuildings are instead surrounded by trampled, more or less non-vegetated ground, covered by various amounts of needles, leaves and other tree litter. Even though such a fuel bed is more flammable than a typical lawn, provided the litter quantity is high enough, it still would yield a lower rate of spread and fire intensity than the characteristic surface fuel under an intact conifer forest (Vermina Plathner et al., 2022). The logistic regression shows that such defensible spaces, if more than 5 m wide, increase the chance of building survival, in accordance with earlier research (Syphard et al., 2014).

In contrast to observations at e.g. the Camp fire in California (Knapp et al., 2021), housing density had only a marginal and non-significant effect on the outcome in the hypothesis-based model. There was however little variation in housing density for both survived and destroyed buildings and for most sites, only 2 buildings (one main- and one outbuilding) were present within a 40 m radius.

During the 2018 Ljusdal fires, the authorities issued an evacuation of the residents who almost exclusively complied. Residents were not allowed back to their properties until the operation was fully completed. Since many of the buildings ignited from fire approaching with relatively low intensity, they could have been saved if people had been present and able to take action. One example is the completely unprotected house we saw being ignited and destroyed (Fig. 3). That fire should presumably have been easy to control around the house, even with simple hand tools, had the residents only been permitted access back to their house.

4.2. Building characteristics

We find no significant results with regard to the building's features. However, the quantitative data indicate that *building type* could be used as a proxy for building features since it co-varied with many of them.

The characteristics for the *main building* on the property were wooden exterior panelling, tile roofing, closed foundation and gutters that had not been cleaned recently, while the characteristics for an *outbuilding* were instead wooden exterior panelling, corrugated metal sheet roofing, open foundation, and no gutters. Even though these potentially important features are hidden within our proxy variable *building type*, there was no significant correlation between *building type* and survivability. This may be due to the fact that nearly all (95 %) of the *façade* claddings were comprised of wood, and the buildings were thereby vulnerable by default, regardless of what other features they had.

A relatively recent study estimated that 80 % of single dwellings in Sweden had wooden façades (Molnár, 2003) and outbuildings are, to an even larger extent than dwellings, completely built of wood. For newly constructed houses, wooden façades are increasingly dominant (TMF, 2022) and is therefore also what would be expected in future wildfire scenarios.

Combustible façade claddings can be ignited through direct flame contact, ember showers, radiation, or combinations of those. Ignition solely by radiation from fire in natural fuel beds is unlikely, as indicated in crown fire experiments by Cohen (2000), in large part due to the short flame residence time, characteristically around 2 min, following Anderson (1969) for fuels between 1-h and 10-h time lag (Andrews, 1986). The combination of exposure time and radiation pressure sufficient to ignite a wood surface is not easily reached (e.g. 15 min at 15 kW/m^2 or 4 min at 20 kW/m^2, following Babrauskas (2002)). Artificial fuels stored close to a building on the other hand, such as stacks of firewood, can potentially burn long enough to cause ignition by radiation to the façade. However, any degree of radiation from an advancing fire will help the preheating needed for subsequent ignition through flame contact.

Even if sections of these fires burnt as crown fire or high-intensity surface fire, most of the buildings were reached by lower-intensity fire, based on the low char height in the most nearby trees. Although difficult to conclusively prove, we judge that direct flame impingement to the façade was the most common mechanism for ignition.

Ignition of a standing wood surface through flame contact depends on several different mechanisms: (1) Increasing flame length yields larger exposed surface areas and higher gas temperatures in the plume (Pastor, 2020). (2) Longer residence time next to the façade (determined by the fuel structure) will increase the likelihood of ignition (Babrauskas, 2003). (3) Rugged panel surfaces with imperfectly covering boards or poor tongue/groove structure yield small cavities where the heat release and flame spread can accelerate (Urban & Fernandez-Pello, 2020). (4) Height of an incombustible foundation which reduces the area exposed to direct flame contact (Babrauskas, 2003).

Although fire intensity was generally low close to buildings, we had ample evidence (e.g. Fig. 2b, 4 and 5) that many of these properties received numerous glowing and flaming embers, most of which are likely to have originated from torching trees in the nearby coniferous forest (Koo et al., 2010). A vertical façade of sawn timber should not be susceptible to embers due to its orientation, but other parts, such as wooden decks and porches are more exposed. We cannot categorically state that attached wooden structures facilitated ignition of buildings, whether by embers or flame contact, due to its covariance with *building type*. However, certain characteristics need to be highlighted. First, it is difficult for a horizontal wood surface to be ignited by a burning ember landing on top (Manzello et al., 2009). We observed several examples that flames had self-extinguished on clean and horizontal wooden surfaces of a deck or porch. Successful ignition then usually requires an assembly of dry litter or non-vegetation fuels like plastics or textiles laying on the wood (Kramer et al., 2019; Pastor et al., 2020). Second, sawn wood and other flammable material are frequently stored under decks and porches, which can potentially allow an approaching fire to enter stepwise from below, involving first the stored material, then the deck, and finally the main building.

Vents and eave-ventilations are often cited as dangerous entry-points for fire (Quarles & TenWolde, 2004; Manzello et al., 2012). Here however, these structures are usually covered with a metal mesh net primarily intended for mosquito protection, which would also restrict entry by even small embers. Another phenomenon often reported in the literature is the breakage of windows, but we found no evidence that windows were important entry points for fire. The requirements for window breakage due to thermal radiation is high, although pane and framing characteristics significantly influence the results (Debuyser et al., 2017). Irradiance above 16 – 18 kW/m^2 for more than 1 – 2 min is needed (Mowrer, 1998; Ismael & Heymes, 2020) and these conditions were unlikely reached on building façades given the generally low fire intensity close to the buildings we observed. We even observed several surviving buildings where windows had been left open, testifying to the hasty, spontaneous evacuation (see e.g. Fig. 5).

Since façades in the Swedish WUI are nearly all combustible, the role of the windows should be subordinate even in case of high-intense fire. This contrasts with the situation in southern Europe, where combustible hedges close to the façade are common and the façade material is masonry or concrete, thus rendering windows the weak points.

4.3. Swedish rural garden ideals vis-á-vis wildfire

Although we find no published evidence to the fact, we believe that the commonly desired garden structure in rural Sweden is favorable in case of fire, relative to that in e.g. Southern Europe or California. At these northern latitudes, with low sun angles and relatively cool temperatures, there is little need for shading and most people want the sun to reach the house and large parts of the garden. Thus, overhanging or nearby trees are routinely removed. Further, most buildings in rural Sweden are sparsely distributed and there is rarely a need for using tall hedges to keep privacy. All this facilitates creation of defensible spaces with relatively little fuel. Also, since the most common building material for single dwellings is timber, ornamental plants are often placed at some distance from the house, to increase ventilation and reduce the risk of mould and rot in the wooden façade. Likewise, roofs are regularly cleaned from tree litter to avoid the growth of moss. Thus, even though most of Sweden is dominated by conifer forests with fuels that can easily support high-intensity fire, the traditional characteristics of gardens in rural Sweden mitigate the risk that the buildings will be ignited.

In contrast to the forest proper, the immediate surroundings of gardens were often dominated by deciduous trees such as *Betula pendula*, *Populus tremula,* and *Sorbus aucuparia* (e.g. Fig. 5). Reasons for this are likely aesthetic (Hulmes, 2009), but incidentally, it should also offer considerable fire protection, not least by prohibiting high-intensity crown-fire close to the buildings. Although few studies have directly analyzed the net effect of broadleaved species on fire intensity in the boreal (Alexander, 2010), the notion that they are beneficial has been the received wisdom for long. In fact, after a series of devastating fires in the wooden towns of northern Sweden in the 1800 s, it became common to establish birch-lined avenues, to reduce the risk of fire spread between buildings (Palmgren, 2006).

5. Conclusions

The majority of buildings in rural Sweden have exterior wood paneling and are thus inherently vulnerable if the fire can reach the façade, even if fire intensity by then is low. Our results identified the presence of a maintained non-flammable lawn around the building as the most important factor for survival since it can isolate the building completely from the advancing fire. Absence of fuels around the façades was also beneficial.

Whether or not the buildings survived, fire intensity was generally low within their vicinity, often reduced by deciduous trees that are favoured over conifers around the gardens. Thus, it should be possible to reduce the ignition risk of buildings within the Swedish WUI with comparatively small efforts. The most effective preventive action would

Table A1
Cross tabulation of the variables in the inventory. The first row in each variable is the selected reference variable. The odds ratio (OR), and its 95 % confidence interval (CI), describes the odds for survival relative to the reference category.

Variable	Survived	Destroyed	Total	Univariable analysis OR	CI	
BUILDING						
Building type						
Outbuilding	66 [0.55]	41 [0.62]	108 (58 %)			Outbuildings include e.g. sheds, barns & garages. Main buildings are dwellings and summer houses.
Main building	55 [0.45]	25 [0.38]	79 (42 %)	1.37	(0.74;2.52)	
Façade[1]						
Combustible	116 [-]	62 [-]	178 (-)			Combustible = wood siding
Non-combustible	5 [-]	4 [-]	9 (-)	0.67	(0.17;2.58)	
Roof[2]						
Other	80 [0.66]	47 [0.71]	127 (68 %)			'Other' is mainly metal, but also paper and plastic
Tiles	41 [0.34]	19 [0.29]	60 (32 %)	1.27	(0.66;2.43)	
Foundation[2]						
Open/Slate-on-ground	71 [0.59]	45 [0.68]	116 (62 %)			Open foundations include. 'slate-on-ground'
Closed	50 [0.41]	21 [0.32]	71 (38 %)	1.51	(0.80;2.84)	
Gutters[2]						
Yes	61 [0.50]	19 [0.29]	80 (43 %)			Presence of gutters
No	60 [0.50]	47 [0.71]	107 (57 %)	0.40	(0.21;0.75)	
Cleaned gutters[*]						
Not cleaned	43 [0.75]	18 [-]	61 (80 %)			Whether or not the gutters were cleaned any time the year of the fire, before the fire occurred.
Cleaned	14 [0.25]	1 [-]	15 (20 %)	–	–	
Wooden deck[2]						
Yes	35 [0.29]	9 [-]	43 (23 %)			Presence of a wooden deck anywhere in the garden
No	86 [0.71]	57 [-]	144 (77 %)	0.39	(0.17;0.87)	
Windows and doors[1]						
Open/broken	6 [-]	0 [-]	6 (-)			Were windows and doors open/broken or were they whole/closed
Closed	115 [-]	66 [-]	181 (-)	–	–	
GARDEN						
Lawn[4]						
No	25 [0.21]	34 [0.52]	59 (32 %)			Does the garden floor consist of a lawn or a forest floor?
Yes	96 [0.79]	32 [0.48]	128 (68 %)	4.08	(2.12;7.84)	
Maintained lawn[*]						
No	6 [-]	0 [-]	6 (-)			Has the lawn been recently mowed?
Yes	77 [-]	26 [-]	103 (-)	–	–	
M. lawn surrounds the entire building[*]						
No	39 [0.47]	17 [-]	56 (51 %)			Does a lawn enclose the entire building or is one or more sides of the building in direct proximity to wildland?
Yes	44 [0.53]	9 [-]	53 (49 %)	2.13	(0.85;5.32)	
Vegetation fuel in garden[2]						
High	16 [0.13]	21 [0.32]	37 (20 %)			Evaluation of veg. fuel load from photos. The degree of the categories is described in Vermina Plathner & Sjöström (2021b)
Moderate	28 [0.23]	22 [0.33]	50 (27 %)	1.67	(0.71;3.94)	
Low	77 [0.64]	23 [0.35]	100 (53 %)	4.39	(1.97;9.78)	
Non-vegetation fuel in garden[2]						
Moderate/High	23 [0.19]	20 [0.30]	44 (24 %)			Evaluation of non-veg fuel load from interviews, site visits and photos. The most frequent non-vegetation fuel are stacks of firewood.
Low	98 [0.81]	46 [0.70]	143 (76 %)	1.85	(0.93;3.71)	
Vegetation touching or overhanging the building						
High	36 [0.30]	32 [0.48]	68 (36 %)			Evaluation from orthophotos. High refers to veg. that surrounds or overhangs the building, moderate if trees overhang more than ¼ or if there is a large fuel load touching the building
Moderate	38 [0.31]	23 [0.35]	61 (33 %)	1.47	(0.73;2.97)	

(continued on next page)

Table A1 (*continued*)

Variable	Survived	Destroyed	Total	Univariable analysis OR	CI	
None/Low	47 [0.39]	11 [0.17]	58 (31 %)	3.80	(1.68;8.55)	
Non-vegetation fuel touching the building						
Moderate/High	16 [0.13]	14 [0.21]	30 (16 %)			The most frequent non-vegetation fuel are stacks of firewood.
Low	105 [0.87]	52 [0.79]	156 (84 %)	1.77	(0.80;3.90)	
Hedge or fence[2]						
Yes	28 [0.23]	10 [0.15]	38 (20 %)			Presence of a hedge or a wooden fence
No	93 [0.77]	56 [0.85]	149 (80 %)	0.59	(0.27;1.31)	
Defensible space						
0 *m*	50 [0.41]	44 [0.66]	94 (51 %)			The minimum distance of a pruned garden.
1–4 *m*	24 [0.20]	11 [0.17]	30 (16 %)	1.92	(0.85;4.36)	
>=5 *m*	47 [0.39]	11 [0.17]	63 (34 %)	3.76	(1.74;8.13)	
LANDSCAPE						
Wildland fuel type						
Coniferous and clear-felled land	40 [0.33]	32 [0.48]	72 (38 %)			The type of wildland outside any garden space. ‘Coniferous and clear-felled land’ includes pine, spruce, open land and clear-felled land, i.e. vegetation that may either burn with high intensity or allow for fast spread. The fraction between these is 80 % conifers, 10 % open and 10 % clear-felled.
Mixed	40 [0.33]	23 [0.35]	63 (34 %)	1.39	(0.70;2.78)	
Deciduous	41 [0.34]	11 [0.17]	52 (28 %)	2.98	(1.32;6.71)	
Housing density (units/km[2])						
200–300	19 [0.16]	13 [0.20]	32 (17 %)			No. of buildings within a merged buffer zone, where individual buffers extend r = 40 m from each building / merged area
300–400	36 [0.30]	21 [0.32]	57 (30 %)	0.83	(0.42;1.65)	
>=400	66 [0.54]	32 [0.48]	98 (52 %)	0.71	(0.31;1.61)	
Fuel break						
No	23 [0.19]	21 [0.32]	44 (24 %)			“Yes” if a road (80), watercourse (12) or lake (16) is within 100 m from the building, between building and fire
Yes	98 [0.81]	45 [0.68]	143 (76 %)	1.99	(1.00;3.96)	
Fire approach						
Upward/Flat	18 [0.15]	21 [0.32]	39 (21 %)			Categorized slope, from a calculated percentage slope based on a distance of 100 m from each building in the direction towards the fire
Downward	103 [0.85]	45 [0.68]	148 (79 %)	2.67	(1.30;5.49)	
Aspect[1]						
S	39 [0.32]	20 [-]	59 (32 %)			The compass direction that the slope faces in the location of buildings
E	22 [0.18]	6 [-]	28 (15 %)	1.88	(0.66;5.38)	
W	37 [0.31]	20 [-]	57 (30 %)	0.95	(0.44;2.04)	
N	23 [0.19]	20 [-]	43 (23 %)	0.59	(0.26;1.32)	
FIRE						
Fire intensity[2]						
Moderate/High	12 [0.10]	26 [0.39]	38 (20 %)			Indicated by bole char height and interviews. Low intensity is indicated by a char height of<2 m.
Low	109 [0.90]	40 [0.61]	149 (80 %)	5.90	(2.72;12.8)	
Irrigation efforts[3]						
No	60 [0.50]	36 [0.54]	96 (51 %)			Indicated by interviews with houseowners and first responders, as well as if extended garden houses are visible in the post-fire photos.
Yes	24 [0.20]	7 [0.11]	31 (17 %)	2.06	(0.81;5.25)	
Unknown	37 [0.30]	23 [0.35]	60 (32 %)	0.97	(0.50;1.88)	

* denotes supporting variables, that do not have a total of 187 buildings.
[1] denotes excluded variables in the multiple regression analysis, for which (N_category < 10).
[2] denotes variables excluded in the multiple regression analysis, due to collinearity.
[3] denotes variables excluded due to multiple unknowns.
[4] a few occurrences of pebbled ground with little vegetation have been binned into the *lawn* group.

Table A2
Results from the stepwise variable selection. df is the degrees of freedom, AIC is the Akaike's Information Criterion, LRT denotes Likelihood Ratio Test and p refers to the p-value.

Variable	df	Deviance	AIC	LRT	p (>Chi)
'none'		212.27	222.27		
Fuel break	1	215.48	223.48	3.2128	0.073063*
Type	1	211.66	223.66	0.6078	0.435616
Veg. touching or overhanging the building	2	209.66	223.66	2.6005	0.272462
Housing density	1	212.26	224.26	0.0043	0.947987
Defensible space (categorized)	2	210.28	224.28	1.9831	0.370999
Wildland	2	211.72	225.72	0.5429	0.762257
Non-veg. fuel touching the building	1	217.95	225.95	5.6816	0.017143*
Slope	1	218.00	226.00	5.7388	0.016594*
Lawn	1	227.38	235.38	15.1171	0.000101*

be to cut open grass/herb vegetation short, regularly remove litter such as needles and leaves, and keep the vicinity of the building free of artificial fuel assemblies. Even a 5 m defensible space will significantly increase the likelihood of survival.

Further, because of the typically open space around houses in this region and low fire intensity, most houses can be easily defended using simple tools, without compromising personal safety. However, this requires basic fire knowledge by the owners and good communication between the residents and the fire suppression crews.

CRediT authorship contribution statement

Frida Vermina Plathner: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Johan Sjöström:** Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Anders Granström:** Conceptualization, Investigation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was funded by the European Commission jointly by DG ECHO, project WUIVIEW (grant agreement number 826522) and REA project FirEUrisk (grant agreement number 101003890). Contributions of photographic material from various sources are gratefully acknowledged. A special thanks go to Schroeder and Wennerlund who performed a preliminary study on the Swedish WUI in their BSc thesis in 2016.

Appendix A

See Tables A1 and A2.

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