Wildland-Urban Interface Virtual Essays Workbench

WUIVIEW

GA number 826522

PBD Virtual Lab WUIVIEW

Funded by European Union Civil Protection

Technical Note TN 7.2.
Structure survivability in Swedish wildfires

WP - Task	WP7 T1	Version (1)	
File name	TN7_2 Structure survivability Sweden	Dissemination level (2)	Internal
Programmed delivery date	31/01/2021	Actual delivery date	31/01/2021

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Abstract	The past few years a number of wildfires in Sweden have spread to buildings that either survived or were damaged by the fire. This have led to hundreds of people having to evacuate and several buildings being destroyed. In the light of recent events it appears that Swedish communities are not adapted to deal with wildfires, and no guidelines or policies exist to aid land and homeowners in undertaking proactive measures. This study analyses recent wildfire events to understand area-specific variables that are important for structure survivability in Sweden. Results indicate that structures often are lost in low intensity fires, where ignition primarily occur by direct flame contact between the burning vegetation and the structure. However, buildings have also being destroyed in high intensity fires by ember ignition but these events are less common in the data at hand. The analysis reveals that the most important feature in the home ignition zone for prevention of structure loss is the presence of a managed lawn, a minimum defensible space of 10 m and the inclusion of broadleaves in the adjacent wildland.

(1) Draft / Final
(2) Public / Restricted / Internal

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1. Introduction

Property loss in wildland fire is an increasing problem globally, evident in the U.S. (Cohen, 2000), Southern Europe (Boschetti *et al.,* 2008) and Australia (Blanchi *et al.,* 2010). Northern countries such as Canada (Westhaver, 2017), Norway (Log *et al.*, 2017), Sweden (Schroeder & Wennerlund, 2016) and Russia (Earth Observatory, 2020), experience a similar trend and are expected, in a changing climate, to suffer from larger and more frequent wildfire incidents with even more extensive damage to urban developments.

However, not all structures are destroyed within a fire perimeter and the survivability of a structure is primarily governed by the characteristics of the structure and its immediate surrounding, such as façade material and garden fuels (Cohen, 2000). Alexandre *et al*. (2015) showed that the characteristics that can improve structure survivability in a wildfire varies across ecosystems and communities.

A substantial part of the Swedish building stock is located within the WUI (Vermina Plathner and Sjöström, 2021). Recent WUI fires have involved isolated structures and scattered hamlets within the forest, in locations were firefighting resources are low, but the possibility of a fire spreading into more densely populated areas cannot be discarded. Despite this, research on property loss in Swedish wildland-urban fires is scarce. The presence of a lawn for structure survivability was highlighted by Schroeder and Wennerlund (2016), but apart from their master's thesis, no efforts have been made to explore survivability of structures in wildfires in Sweden.

There are no statistics on how many wildfires that ignite structures in the Swedish WUI. What is known is that 71 buildings were completely or partially destroyed in the 2014 Västmanland fire, many of them outbuildings but also a number of summer houses in addition to permanent dwellings. During the summer of 2018 around 30 buildings were completely destroyed in the fires whereof a handful of high standard summer houses but no permanent dwellings. In April 2019 a residential building and a large horse stable were burnt in an unusually large grass fire in south of Sweden.

Apart from these large incidents, it is highly difficult to identify the frequency of structures ignited by wildfires. One reason is that a fire starting in the wild close to a building, eventually igniting the building, will in many cases be registered as a construction fire by the fire rescue service. However, 224 structure losses where the fire initiated outside of the building and where vegetation also burned have been identified between 1998 and 2018 in the database maintained by the Swedish Civil Contingency Agency (MSB). In these incidents, the Västmanland fire with 71 structures lost, is registered as one incident but the majority of incidents include only one building. Many of them are started by burning of vegetation fuel in or close to gardens.

The aim of this study is to determine why some structures survive in a wildfire whilst others are destroyed. The objective is to outline characteristics (in Swedish vegetation, housing, living conditions and gardens) that determine structure loss in a wildfire in Sweden. The study is limited to case studies on four large fires (Västmanland, 2014 and the three simultaneuous fires in Ljusdal, 2018) and does not consider smaller isolated fires from the dataset above.

2. Method

2.1. Selected cases

Two study areas including four large fires were selected to represent large wildfires in Sweden; the Västmanland fire that occurred in July/Aug, 2014, and the Ljusdal fire complex in July 2018, in which three fires burned simultaneously, and together surrounded the village Kårböle. Both study cases represent where wildfires affect intermix WUI, i.e. scattered settlements and buildings located within a vegetated area.

The Västmanland fire started on July 31st, 2014 by ignition from a scarifier machine in forestry site preparation activities (Sjöström *et al.*, 2019). preparing a clear-felled area for reforestation. The fire burned within an area of approximately 13 000 ha over several days but the majority of the area burnt during the afternoon of the 5th day since ignition. It took the fire rescue service over an hour to arrive at the scene, at which point it had spread beyond their control. The fire perimeter is illustrated in Figure 1. The wind direction was initially towards NE but switched to NW direction the third day. This change of direction gave rise to a wide fire front, seen in Figure 1. Strong winds at the fourth and fifth days enabled a fire spread of approximately 80 m/min during the worst afternoon. No significant spread occurred after that. During that time the fire had extended over an area of 13 100 ha, destroyed 71 structures, claimed one fatality and causing one person to be severely injured. Dominant vegetation within the Västmanland fire perimeter prior to the fire was pine (~50 % of the area) followed by spruce and conifer-dominated mixed forest (approx. 20 % of each).

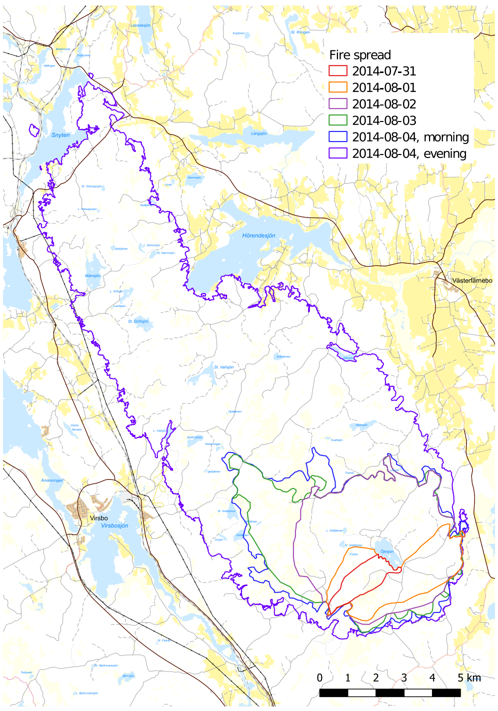

Figure 1. The 2014 Västmanland fire isochrones. Source, isochrones: Länsstyrelsen Västmanland. Source, background map: Lantmäteriet.

Four years later, the entire country experienced severe draught in the summer of 2018. The Ljusdal complex fires (referred to as Enskogen, Ängra and Nötberget in Table 1), all ignited by lightning, burned simultaneously in the Ljusdal municipality from July 14th to August 9th, 2018. In comparison to the Västmanland fire, the fire had no distinct propagation direction, as seen in Figure 2. Production pine stands (~35 %) and clear-felled land (~25 %) dominated the area.

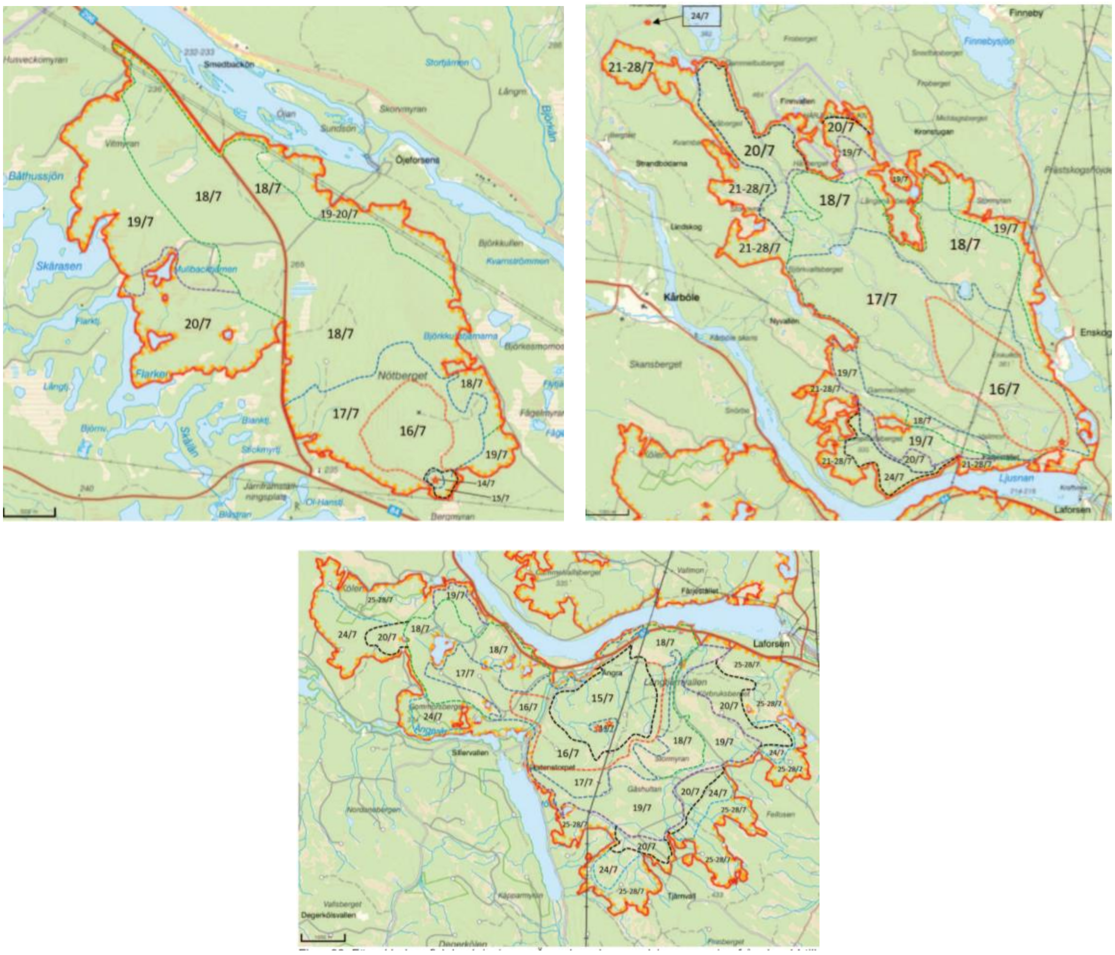

Figure 2. The 2018 Ljusdal fire isochrones. Source: Granström (2020)

2.2. Structures lost in wildfires

Table 1 lists the number of structures involved in the selected cases. Of the selected cases, all buildings related to the Ljusdal fires (Enskogen, Nötberget and Ängra) have been included in the analysis. However, due to unconfirmed data 43 of the buildings in Västmanland, these have been removed from the analysis.

Table 1. Burned area and structures in the analysis

Location	Burned area (ha)	Structures (total)	Destroyed structures
Västmanland	13 100	71 (156)	39 (71)
Enskogen	4 326	39 (41)	15 (16)
Nötberget	872	3 (3)	3 (3)
Ängra	3 797	13 (13)	7 (7)
Total	**22 095**	**126 (213)**	**64 (97)**

2.3. Collection and analysis of sample data

Data was gathered about the structures within the fire perimeters, based on a combination of an inventory of the fire sites, interviews with and photos from house owners, orthophotos taken by the Swedish Forest Agency and high-resolution photos from the Swedish armed force's helicopter fleet, and satellite images from Sentinel-2. Also, vegetation is described by a terrestrial raster map (grid cell size of 10x10 m^2) produced by the Swedish Environmental Protection Agency (2020) based on the CORINE land cover European classification system. The variables of interest and their origin of data are summarized in Table 2.

Table 2. Variables included in the study

Category	Variable	Type	Description
Structure	Type	Nominal	- main building - outbuilding - industrial
	Façade	Dichotomous	- combustible (timber) - non- or low combustible
	Roofing	Dichotomous	- combustible (hay, grass) - non- or low combustible
	Foundation	Dichotomous	- open - closed
	Gutters	Dichotomous	- yes - no
		Dichotomous	- recently cleaned (less than 1 yr ago) - not recently cleaned
	Deck, porch, patio, balcony	Dichotomous	- yes - no
	Windows	Dichotomous	- opened - closed
Garden	Lawn	Dichotomous	- yes - no
		Dichotomous	- mowed - not mowed
		Dichotomous	- surrounding the entire building - surrounding parts of the building
	Vegetation fuel load in garden	Ordinal	- low - medium - high
	Vegetation fuel load against the façade	Ordinal	- low - medium - high
	Other fuel load in garden	Ordinal	- low - medium - high
	Other fuel load against the façade	Ordinal	- low - medium - high
	Garden boundary	Nominal	- none - fence - hedge - non-combustible border
	Defensible space	Continuous	- The distance between wildland and structure in the direction against the fire
Wildland	Fuel type	Nominal	- pine - spruce - mixed - clear-felled land - deciduous
	Fire break between structure and fire front (within 100 m from the structure)	Nominal	- none - road - watercourse - lake
Fire	Fire intensity	Ordinal	- low - medium - high
	Probable structure ignition	Nominal	- radiant - flame impingement - firebrands
	Mitigation efforts by residents	Dichotomous	- yes - no

In cases of unknown data, fields have been left blank.

2.3.1. Characteristics of the fire

Isochrones from satellite images provide time stamps for the extending fire area, as well as indications of location of the fire front, flanks and backing fire at community level. Characteristics at the property level is indicated by local fire patterns. Fire intensity approaching a construction is e.g. suggested by scorch height in the adjoining wildland (Figure 3). In a similar manner is local fire direction indicated by soot and char angles on boles.

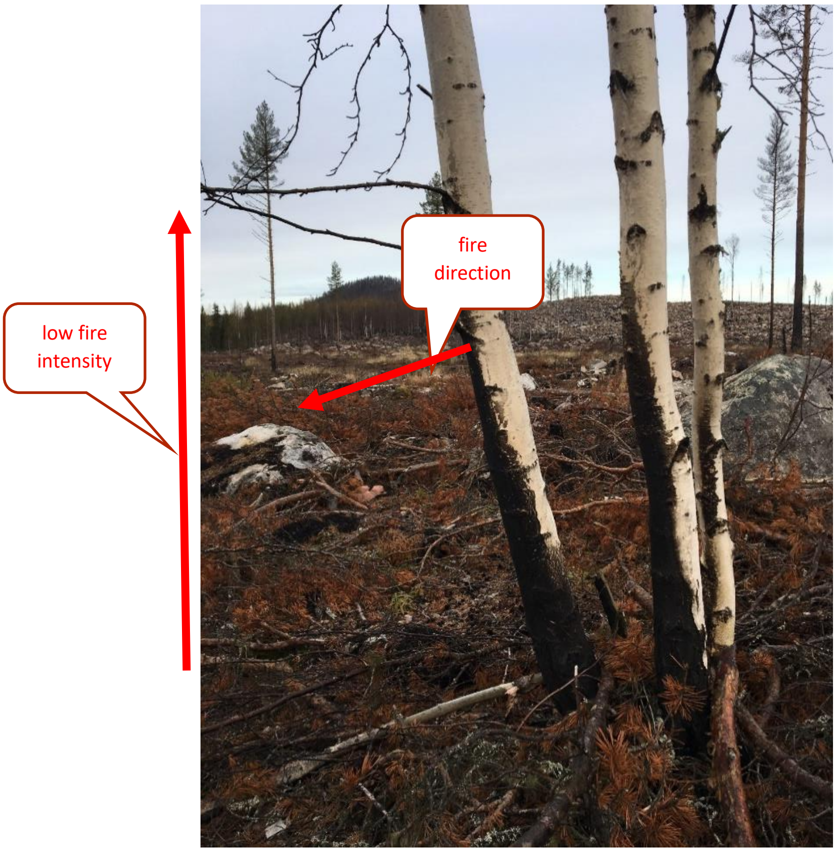

Figure 3. Indications of local fire intensity and fire direction

The most likely cause of ignition of structures has been assessed by analyzing destruction patterns in the surrounding area of each building. Unconsumed vegetation and unburned structures nearby indicate firebrands as a likely ignition source, whilst low fire intensity in combination with a fully consumed surface vegetation indicate ignition by flame contact (Cohen, 2000).

2.3.2. Characteristics of structures

Information about the structures are obtained in a combination of an inventory at the fire sites (Figure 4), interviews with and photos from house owners and personnel working during the incidents. Uncertainties (e.g. lack of remains) are as far as possible double-checked with the house owners.

Figure 4. Example of the Inventory of destroyed structures

2.3.3. Characteristics of gardens

Each garden is analyzed primarily by the presence of a defensible space, such as a lawn or other open surface with sparse or no vegetation. The structures in the Ljusdal fires were almost exclusively summer houses, hunting cabins and sheds, many which did not have a garden at all but were intermingled with the forest vegetation. Less than 60 % of the structures in total had a traditional garden (i.e. a lawn). The "forest gardens" without lawn have 0 m stated as distance between façade and wildland, and the vegetation fuel load for these "gardens" is not specified.

2.3.4. Characteristics of the wildland

The Ljusdal fire area consisted mainly of pine (Figure 5), but to a large extent also of clear-felled area. Wetland (open and vegetated) make up approx. 1/20 of the land types.

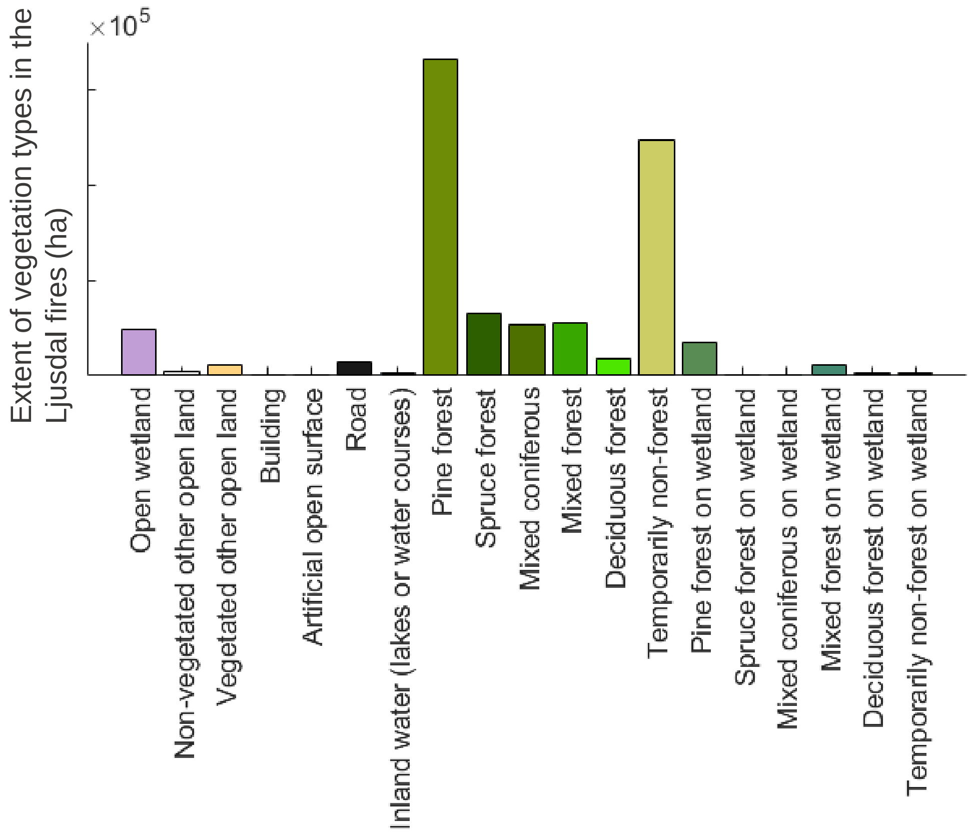

Figure 5. Vegetation types in the Ljusdal fire area prior to the fires

The vegetation before the Västmanland fire was also dominated by pine, with elements of birch and spruce. The vegetation close to buildings was obtained from aerial photography. Characteristics of the wildland was obtained by analyzing vegetation and elevation maps, in combination with the inventory.

The presence of firebreaks was also obtained from maps. A firebreak is here defined as a land type (natural or artificial) that has the possibility of lowering the fire intensity so that structure loss is mitigated, or to contain the wildfire on one side of the break. Fire breaks are e.g. lakes, water courses, roads and open wetlands.

2.4. Statistical analysis

The importance of each feature within the home ignition zone for structure survival is evaluated by a Pearson's chi square test and a bagged decision analysis.

The data set of structures that have been involved in wildfires consists of mixed-type data with continuous (e.g. distance), ordinal (e.g. scales such as low-medium-high), nominal (non-ordered categories such as vegetation type) and binary (e.g. existence of a lawn) are combined. There are also missing values, where the features are not known. This type of data can be handled by supervised learning techniques in order to find safety factors and indicate differences in damage-no damage of structures. One such technique is called bagged (bootstrap aggregation) decision tree. The bagged tree analysis consists of predicting 'destroyed' and 'survived' returns by using a set of N observations (number of structures) described by F number of features (predictors). The program randomly selects subsets of the observational data (called bootstraps) to build decision trees, Figure 6. The observational data which is not selected by a bootstrap replica is referred to as out-of-bag data. These observations are subsequently used to calculate the prediction accuracy of the built model.

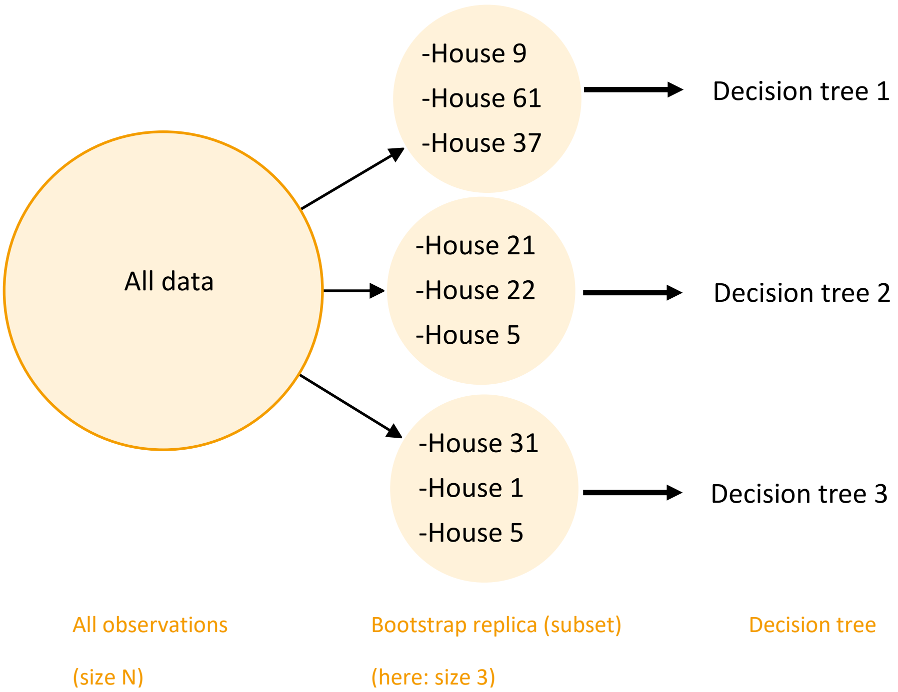

Figure 6. Generation of bootstrap samples

From the bagged decision tree it is possible to determine which factors that are contributing most to a structure survivability outcome. The feature importance measure is the resulting error that the variable would have if it was permuted for the out-of-bag observations in every tree. It is found that a threshold of 0.3 gives a sufficiently accurate result, Figure 7 (left).

The performance of the decision tree can be explored with a receiver operating characteristic (ROC) curve, Figure 7. The shape of the curve indicates that the model is predicting structure survivability reasonably well. For a perfect prediction the area under the curve would be unity.

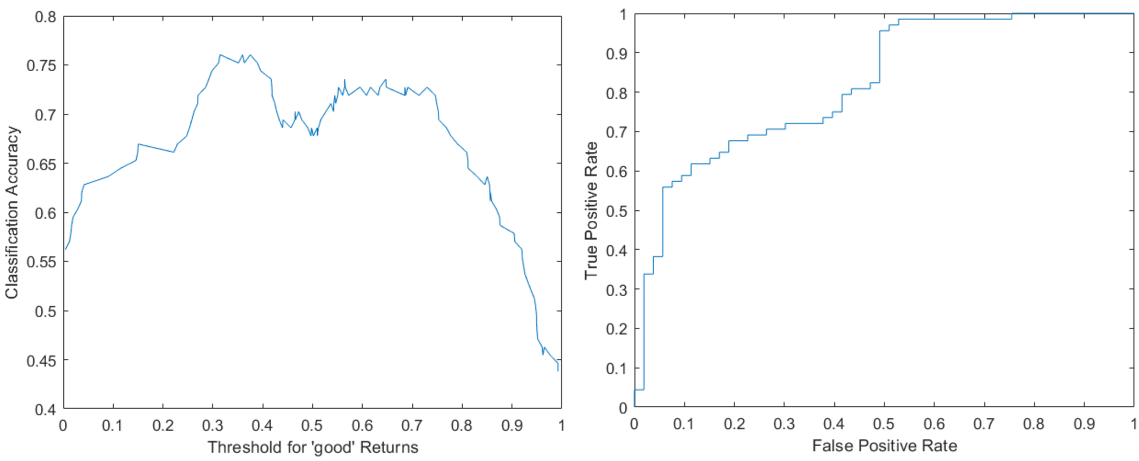

Figure 7. Model accuracy vs. different possible thresholds (left) and receiver operating characteristic (ROC) (right)

3. Results

3.1. Feature importance

A Pearson's chi-square test is performed with results presented in Table 3. The test provides information on whether the feature has a significant influence on the survivability of the structure. A test for "other" fuels cannot be performed due to too small groups. The last column of the table answers if the parameter has a significant effect on structure loss based on a significance level of $\alpha > .001$. The presence of a lawn and fire intensity are both significant features.

Table 3. Chi-square test of HIZ features

Category	Parameter	X^2	Significant at $\alpha > .001$?
Structure	Façade material	$X^2(1, N = 129) = 0.0065, p = .936$	No
	Roofing material	$X^2(3, N = 128) = 4.30, p = .117$	No
	Foundation type	$X^2(1, N = 122) = 0.302, p = .583$	No
	Gutters	$X^2(1, N = 119) = 3.33, p = .068$	No
	Cleaned gutters	$X^2(1, N = 36) = 1.20, p = .274$	No
	Wooden deck, balcony or porch	$X^2(1, N = 78) = 5.14, p = .023$	No
Garden	Lawn	$X^2(1, N = 129) = 16.5, p = .00005$	Yes
	Maintained lawn	$X^2(1, N = 116) = 16.9, p = .00004$	Yes
	Maintained lawn surrounding the structure	$X^2(1, N = 116) = 10.8, p = .001$	Yes
	Vegetation fuel load in garden	$X^2(1, N =) = 5.96, p = .051$	No
	Vegetation fuel load against the façade	$X^2(1, N =) = 7.44, p = .024$	No
Wildland	Wildland type	$X^2(2, N = 129) = 5.03, p = .285$	No
	Wildland type (coniferous/clear-felled vs. deciduous)	$X^2(1, N = 121) = 2.99, p = .084$	No
	Presence of fire break	$X^2(1, N = 124) = 0.66, p = .417$	No
	Slope (up/flat vs. down)	$X^2(1, N = 115) = 5.23, p = .022$	No
Fire	Fire intensity	$X^2(1, N = 116) = 14.28, p = .0002$	Yes

The relative importance of each structure-, garden- and wildland-feature is also analysed with a bagged decision tree to account for combined effects; results are presented in Figure 8.

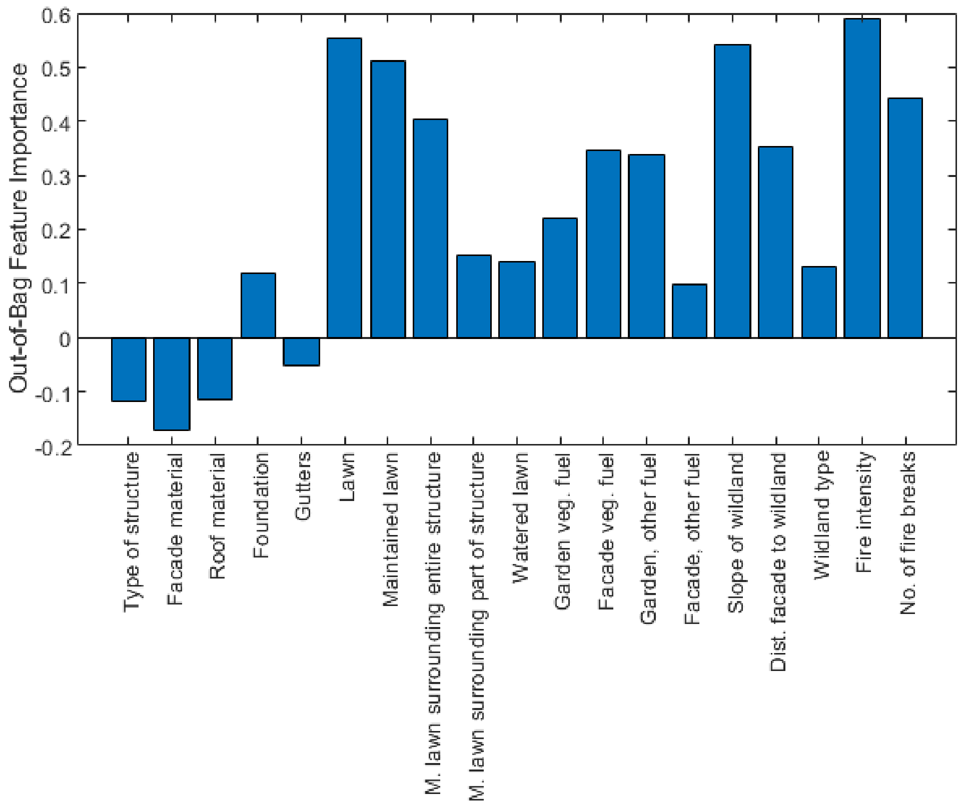

Figure 8. Feature importance for each variable

From Figure 8 the most important features for whether or not a structure will be lost in a wildfire can be selected. An arbitrarily selected threshold of 0.3 on the y-axis yields the most important features; lawn (presence of, if the lawn is maintained and if it surrounds the structure), vegetation fuel adjacent to the façade, other fuel in the garden, slope of and distance to wildland, fire intensity and firebreaks. A more detailed analysis of each category is given in subsequent paragraphs.

3.2. The fire

The rapid spread and high intensity of the 2014 fire resulted in fast and unprepared evacuation and little or no chance for mitigating actions. In the 2018 fires the spread was continuous over a longer period and aid from the rescue service was more common.

Whilst the closer investigated fires partly burned with high intensity, most of the fire patterns in the vicinity of structures indicate a primarily low intensity (79 % of the cases, compared to 11 % medium and 11 % high). An example of low fire intensity in Ljusdal is seen in in the left of Figure 9

Figure 9. Ängra fire. Photo by Marco Hassoldt.

However, the availability of a continuous fuel bed from wildland (sometimes via garden) to the façade was characteristic of the fires, in many cases carrying the low-intensity fire all the way to the building foundation. Structures are mainly ignited due to flame impingement rather than glowing embers or sparks carried by wind. The phenomenon is exemplified in Figure 10 and Figure 11.

Figure 10. Example of low-intensity fire ignition by flame impingement of a wooden deck, in this case followed by extinction.

Figure 11. Example of low-intensity fire ignition by flame impingement of the façade, in this case followed by extinction. The vegetation around the structure (below the cover of pine needles) is fully consumed.

However, in some cases in the Västmanland fire (17 % of the burned structures), unconsumed surface vegetation and shrubs, indicates ignition by embers.

3.3. The structure

Typical isolated structures within the Swedish wildland comprise of timber façades, tile or metal roofing and an open or closed crawlspace foundation. It is difficult to draw conclusions on structure material from the gathered data, since almost exclusively all (94 %) of the structures in the selected cases had timber façades.

In the investigated fires, the characteristics of the structure does not have any significant influence on housing loss. Neither façade material (combustible vs. non-combustible, roofing material, nor foundation type (open vs. closed) are significant factors for structure survivability. There is also no significant association between structure survivability and presence of gutters, nor the presence of *cleaned* gutters. The presence of a wooden deck, balcony or porch is not a factor that is indicated to determine structure loss, based on a significance level of $\alpha > .001$. The number of structures nearby did not have any effect on the outcome.

Schroeder and Wennerlund (2016) found no examples of fire entering a structure due to open/broken windows, and this has not been obtained from the interviews in this study either.

However, the three non-timber buildings in the study were located close to other buildings that had timber facades. It is possible that these structures ignited due to a spill-over effect in which firebrands were transported from the burning timber buildings.

3.4. The fire

Only a rough estimation can be given of the fire intensity, as no such measures have been conducted for the fire. Qualitative measurements of scorch height etc., together with testimonies from residents provides indications that the majority of structures, especially in the Ljusdal area, were ignited by a low intensity fire, where the fire traveled all the way to the house. However, photos from the helicopter fleet provide evidence that a few buildings located within the forest were facing a crowning fire.

3.5. The garden

Of all structures in the analysis 57 % had a lawn. Structure survival correlates to the presence of a lawn, and in particular to a maintained lawn that surrounds the entire structure as seen in Figure 13 and exemplified by Figure 13. In the analysis, a few occurrences of pebbled ground with little vegetation has been binned into the “lawn” groups.

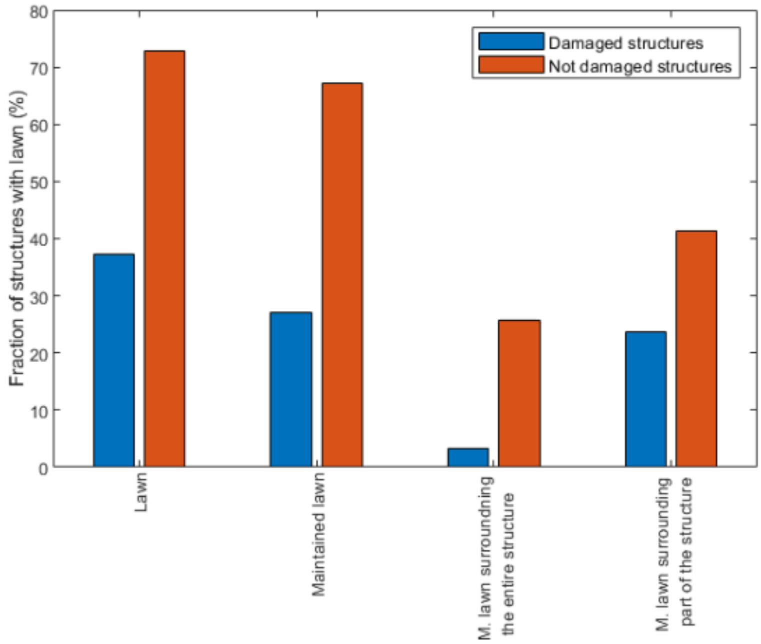

Figure 12. Fraction of all damaged (blue) or survived (red) structures that had a law, a maintained lawn and a maintained lawn surrounding part or the entire building.

Figure 13. An example in which a low-intensity fire in a maintained lawn has carried the fire to the dwelling without subsequent ignition. The maintained lawn has prevented the fire to be carried to the outbuilding. Photo: Anders Granström.

Furthermore, the size of a maintained garden has an influence on the survival of structures. In Figure 14 the wildland is viewed as the closest end of a maintained garden, regardless of where property borders are located. The proportion of structure survivability goes from ~50 % for building-wildland distances of less than 10 m, to reach 100 % at distances over 10 m. It is however important to note that the dataset at larger distances is small and that exhaustive conclusions regarding relative risks are improved with a larger data set.

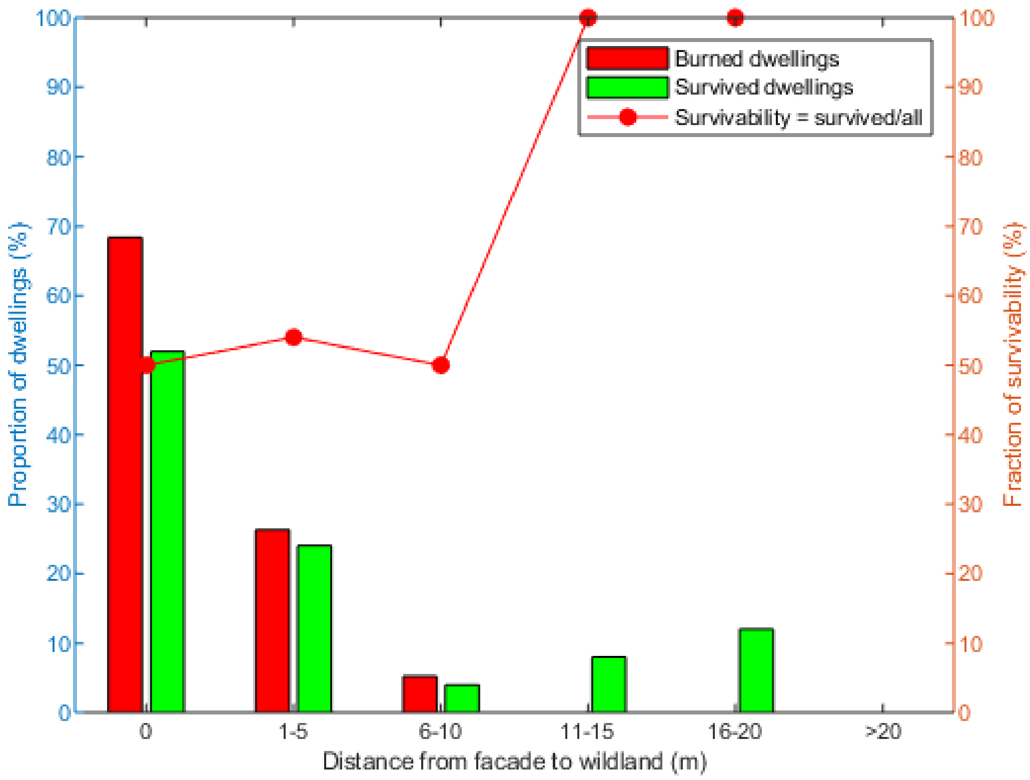

Figure 14. Distance building façade to wildland for dwellings and summer houses

Fuel load within gardens and adjacent to the façades are either vegetation or non-vegetation. Non-vegetation fuel loads are typically stacks of fire wood, but can also be garden furniture or occasionally car tires. Since several of the “gardens” that were analyzed consist of a forest floor, where the wildland reaches all the way to the structure, the analysis of vegetation fuel load is limited to gardens with a lawn. Few of the structures had a physical garden border towards the wildland, such as a hedge or a fence. None of the gardens in the study had an incombustible physical garden border.

An example of a forest garden for a summer house is seen in Figure 15.

Figure 15. Summer house with a sauna and an outbuilding: (upper) prior to the fire, and (lower) one year after the fire. Upper photo by Johan Molarin.

Little is known about mitigation efforts in these fires. Schroeder and Wennerlund (2016) analysed aerial photos taken by the helicopter fleet in the Västmanland fire and concluded that survivability of structures was increased if a garden hose was unravelled (i.e. that preventive watering of lawn and/or façade had been conducted).

3.6. The wildland between structure and fire

Many of the buildings that have been affected by the four wildland fires are isolated dwellings, intermixed with the forest. Dividing into broad categories, without regarding fire intensity or whether a lawn exist, the wildland type does not significantly correlate with structure loss in the chi square test. However, a graphical illustration of the three fires in the Ljusdal municipality provides insight into the differences in structure loss with respect to vegetation type. The data in Figure 16 is retrieved from analysing a 10 m by 10 m raster map of vegetation types prior to the fire. Buffered half-circles with 40 m radius in the direction towards the fire are drawn in Quantum geographical information system (QGIS) to retrieve a more detailed picture of the various types of vegetation in that area. The same analysis is not possible to retrieve from the Västmanland fire, since no detailed vegetation map from 2013 – 2014 is available.

The surviving structures had a lower degree of pine and mixed coniferous forest in the direction of the fire than did the damaged ones. Even more explicit, 18 % of the vegetation type in the fire direction of damaged structures was clear felled areas (Temporarily non-forest) whereas the surviving structures had no cleared areas within 40 m in the fire direction. On the other hand, vegetation types relatively more common for the surviving structures were vegetated open land as well as mixed and deciduous forest, Figure 16.

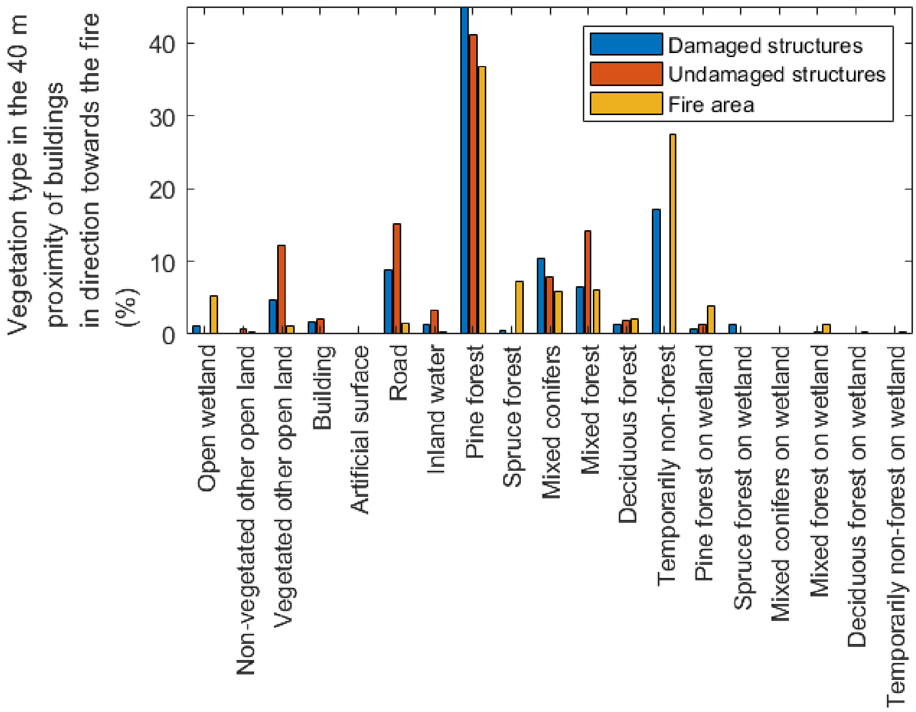

Figure 16. The Ljusdal fires: Vegetation type adjacent to burned and unburned structures.

Figure 17. After the Västmanland fire, April 2015. The foreground shows what previously was a vegetated clear-felled area. The trees on the clear-felled area as well as surrounding coniferous forest burned with crown fire. However, the deciduous forest strip containing birch, sallow and aspen stopped the fire before it reached the structure in the background. Photo by Kenneth Risberg.

Even though firebreaks, such as roads, is not statistically significant for survivability in this data we also see a that roads between building and fire is more common for the surviving structures. Two examples of functioning firebreaks are given in Figure 18 and Figure 19.

Figure 18. Forestry road as a functioning firebreak, where the fire did not carry over. Photo: Marco Hassoldt.

Figure 19. Watercourse as a functioning firebreak. Photo: Marco Hassoldt.

4. Discussion

Structure loss in large Swedish wildfires has so far concerned isolated buildings within the forest. Although none of the largest wildfires in Sweden has directly threatened larger settlements, the possibility of a wildfire spreading to a more densely populated area cannot be discarded. The WUI is present all over Sweden, from isolated houses to the suburbs of Stockholm. A rapidly spreading fire into a densely populated area would provide different results, with possible spillover effects due to burning structures.

This study has utilized a few large wildfires to gain results on structure survivability. It is important to acknowledge that the resulting fire size may have an impact on the conclusions drawn in this study. Large wildfires occur in low population density areas, mainly in mid and north Sweden, in contrast to small wildfires, that mostly occur close to populated areas. It cannot be excluded that a data set based on small wildfires could provide a different set of features that are important for the survivability of a structure. Ongoing research is looking into the damages of structures in small wildfires in Sweden during a 25 years period.

There has not been any data collection on where mitigation efforts by the rescue service may have saved structures, since there is uncertainty of whether and when such actions would have been conducted. In the Ljusdal fires, two cases are found; one where water bombing was evidenced by structure damage, and one structure where there is photographic evidence of preventive actions (Figure 20), although this was the only case that the interviewed fire fighter knew about.

Figure 20. Preventive foam deflection of a structure. Photo by Anna Eriksson Swenne.

Aerial suppression arrived too late to the Västmanland fire to have any significant impact on the data, but no data is available for preventive or suppressive work by ground forces.

Most buildings seem to have been ignited by direct flame impingement to the façade. Thus, the local fuel load, in the direct vicinity of the façade, plays a major role. The single most important factor for survivability is a managed lawn. Other contributing factors are (however obvious they may seem) occurrence of fire barriers of fuel breaks in the near vicinity and inclusion of broadleaves in the close proximity of the building.

Occurrence of open windows do not represent an important factor in the material for this study. Neither does fire entrance in houses due to thermal breakage of windows from the radiant heat of the fire. Such thermal impact would instead have an immediate effect on ignition of combustible façades. Ignition of structures from spotting appears to be of low occurrence material. This is most likely due to the scarcity of crown fires in Swedish wildfires. Having said that, a rare event like the 2014 Västmanland fire could potentially threaten many homes, other buildings or infrastructure through spotting. Also, a few examples of spot ignition is found in the data and for the farm burnt down in 2019 as described in chapter 1. Some, but not all, of these are spotting from fires in flashover fires of neighbouring buildings

Evacuation of people due to wildland fires occurred on large scale in Västmanland 2014. In larger fires this is now routine. In retrospect it could potentially have increased the vulnerability of structures. House owners, if not evacuated, will take preventive measures, such as watering the lawn and the façade, removing some of the fuel load in the garden etc. Many structures in especially Ljusdal were burned in low intensity fires. Some of these could have been saved with low resources, and in some cases by the house owners themselves.

5. Concluding remarks

Three fires in Ljusdal 2018 as well as the 2014 Västmanland fire have been analysed in terms of structure survivability. The fire direction and intensity in the close vicinity, the vegetation type and characteristics of the building such as distances to the wildland, façade materials, open windows, existence of a managed lawn and existing fire barriers were all collected for each building. All structures in these incidents were isolated buildings surrounded by wildland or located in small hamlets.

The rapid spread and high intensity of the 2014 fire resulted in fast and unprepared evacuation and little or no chance for mitigating actions. In the 2018 fires the spread was continuous over a longer period and aid from the rescue service was more common. Many of the structures burnt in 2018 were ignited by low intensity fires. Some of these could have been saved with very low resources but since residents were evacuated, and extinguishing resources operated elsewhere, the buildings were left to ignite.

Generally, analysing the burnt structures from 2014 and -18, it appears as if structures most often have been ignited by fires continuously burning up to the façade, which very often is combustible, and not as much by burning embers finding their way into the building through windows or other cavities. Thus, direct flame impingement seems to be a common mechanism for ignition. The most important factor for survivability of a structure, in these studied cases, is the presence of a managed lawn and that this lawn is surrounding the whole building. Distance to wildland is also relevant. It should be noted, however, that none of the structures, survived or burnt, had as much as 40 meters to wildland which is an important limit identified by Cohen (2000).

Preventive actions seem to have an effect. Garden hoses were unravelled over the lawn for some of the structures that survived the 2014 fire. The effective cases are hypothesized to include watering the façades and the surrounding. A non-effective measure, at least from the data at hand in the present study, is closing windows. Likewise, no examples of fire entering a house due to thermal breakage of windows have been found.

Another obvious important factor is the intensity of fire close the building. Very few buildings with crown fires in surrounding trees have survived but some exceptions occur, and those cases are characterized by a managed lawn. Most buildings were, however, burnt in low intensity fires.

Vegetation and land type surrounding the building can be shown to play a role for survivability. The vegetation type in a semi-circle of 40 m radius in the direction towards fire are shown in Figure 17 for the structures in the Ljusdal fires. The close presence of roads increases survivability as does a surrounding forest with inclusion of broadleaves compared to only pine or mixed conifers. Buildings close to a clear-felled area (temporarily non forest in Figure 17) were all destroyed in the fires.

Ignition of structures from spotting appears to be of low occurrence. This is most likely due to the scarcity of crown fires in Swedish wildfires. Having said that, an unlikely event like the 2014 Västmanland fire could potentially threaten many homes, other buildings or infrastructure through spotting.

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