Fire Safety Journal 156 (2025) 104457

Contents lists available at ScienceDirect

Fire Safety Journal

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

Early season wildfires pose the highest threat to buildings and people in Sweden

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ARTICLE INFO

Keywords:
Wildfire
Property
Building ignition
Injury
Wildland-urban interface
Traditional fire use

ABSTRACT

Wildfire damage to the built environment and people is typically understood through case studies of high-impact events, or from incident databases where the smallest wildfires are not always accounted for. We analyzed an exhaustive database of 131 040 reported fire service wildfire dispatches (1996–2022) in Sweden. There were on average per year 126 wildfires that threatened buildings, 22 that ignited buildings, 17.6 that injured people and 1.1 that led to a fatality. The analysis showed that building ignitions, human injuries as well as fatalities in this region were caused primarily by relatively small fires (90th percentile <10 ha) and that they occurred predominantly in the spring season. Untended grass litter near buildings constituted a much higher fire threat to the built environment than did forest vegetation, even when fire danger was relatively low. The source of the ignitions was 99 % anthropogenic and mostly connected with intentional fire use such as burning grass litter or garden debris. Our study highlights the need for improved fire statistics to cover the full extent of threats to life and property from wildfires. Further, it suggests that the potential for harm reduction through improved wildfire knowledge among the rural population should be large.

1. Introduction

The loss of human life and property due to both natural and human-caused wildfire is a mounting global challenge [1]. More frequent and prolonged dry spells, as well as altered land use, have increased the frequency and intensity of wildfires in many parts of the world [2]. Meanwhile, some regions experience increasing vulnerability at the Wildland-Urban Interface (WUI), stemming from decreasing rural populations and the dismantling of remote fire and rescue services (hereafter named fire services), making it harder to control and mitigate the impacts of wildfires [3–5].

Today, our understanding of the threat wildfires pose to human health and property is largely shaped by case studies of the most destructive events in fire-prone regions, such as western North America, Australia and southern Europe [6–13]. These studies typically highlight building and environmental vulnerabilities that contribute to loss. For instance, analyses of high impact incidents in Portugal [12], Spain [14] and Greece [10,15] show that most buildings are ignited by firebrand deposition on roofs [12], that the most vulnerable building elements are unprotected glazing and cladding materials, and that vegetation continuity contributes significantly to damage, even in high-intensity fires [10,14]. Similarly, a study of large forest fires in Sweden found that most buildings ignite through direct flame impingement, and that safeguarding the immediate zone around the building, such as keeping a managed lawn and removing combustible materials near façades, is crucial for improving survivability [16]. However, case studies do not capture the extent of the problem across wider regions, nor do they describe the ‘typical’ scenario in which a building is ignited or a person injured.

To arrive at a comprehensive picture of the wildfire threat to people and property, the analysis must rely on databases that include all wildfires. Within the European Union, there is no such database as of yet. Detailed national reports reside with the authorities of each member state [17], and there are no studies that analyze the full range of loss to wildfire in a European region.

A few North American studies analyzing fire incident databases suggest that small wildfires are substantial contributors to the annual amount of property lost. For instance, Miekiewicz et al. [18] combined the locations of settlements with fire locations from U.S. National Incident Management System [19], and concluded that small, human-caused fires within the WUI threaten more homes annually than large-area wildland fires. Likewise, Carlson et al. [20] used fire

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https://doi.org/10.1016/j.firesaf.2025.104457
Received 25 February 2025; Received in revised form 15 May 2025; Accepted 18 June 2025
Available online 20 June 2025
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occurrence data compiled by the US Forest Service [21] and found that including small wildfires is necessary to accurately assess fire hazards in the northeastern U.S., where fires are frequent but typically small. Since burned area does not directly correlate with property loss, analyses beyond case studies are needed in regions where large wildfires are less common.

Fatalities have been more thoroughly assessed than building loss in Europe. Molina-Terrén et al. [22] compiled fatalities in the Mediterranean region (Spain, Portugal, Greece, and Sardinia), between 1979 and 2016, by using data from several different sources such as civil protection agencies, fire services, forest services and news articles. They found 0.286 annual fatalities per million inhabitants for the whole region, with the lowest relative numbers in Spain (0.2) and the highest in Greece (0.5) and Sardinia (1.0). Despite large annual variations, the total number of fatalities appeared rather constant over this 36-yr-period [23]. Most of them occurred in high summer (late June and August) and involved just under 50 % civilians [22].

Data on wildfire fatalities in North America are scattered, and no comprehensive dataset exists [24]. It is estimated that, on average, at least 15 annual civilian and about 20 wildland firefighter fatalities occurred in the U.S. between 2002 and 2006, corresponding to 0.1 deaths per million inhabitants [25]. In Canada, a preliminary analysis reported an average about 2 firefighter fatalities per year between 1941 and 2010 [26]. The last few years of high-impact fires in the U.S., including the 2018 Camp Fire [27], 2023 Lahaina Fire [28], and 2025 Los Angeles fires [29], point toward higher civilian casualties during the recent decade in wildfires that developed into urban conflagrations.

An attempt at a global survey of wildfire fatalities [30] that was even more biased towards large and well-publicized incidents, estimated 79 global annual fatalities between 2000 and 2023. Studies on fatalities in highly fire-prone regions commonly find a high proportion of firefighters among the fatalities, and that fatalities occur during days with extreme fire danger. If civilians are harmed, it predominantly happens during evacuations that are carried out too late [22,24,31].

Here we explore the complete fire service dispatch database in Sweden to extract all wildfires (1996–2022) that injured or killed people (hereafter named WF-P) or that damaged or threatened to damage buildings (hereafter named WF-B). By assessing all wildfire dispatches in the database, which provides a nationwide coverage of all fire service dispatches, we aim to cover the complete range of wildfires that pose a threat to people or buildings. We analyze the prevalence, drivers and patterns of the wildfires starting in or entering areas with buildings or people, showing the circumstances under which people are injured, die or lose their homes in Sweden.

2. Methods

2.1. Material

The data used in this study was obtained from the Swedish Civil Contingencies Agency (MSB) fire database, in which all fire service dispatches are logged, from which we selected all wildfire incidents. The database was set up in 1996 and we used data from January 1, 1996, to December 31, 2022. The database includes information such as the location of ignition, date and time of the alarm call, burned area, cause of fire, land cover type (tree-covered or not), and free-text sections describing the incident [32].

Swedish fire services operate within a decentralized system where each municipality is responsible for its emergency response. All municipal fire services are organized into regional federations, which facilitate coordination and resource sharing. The Swedish incident command structure is escalation-tiered, where the command structure and resource mobilization scale up during large or rapidly developing incidents, to include regional coordination and national support. After each fire service dispatch, the incident commander on site fills in an incident report that is electronically transmitted to MSB.

Incident commanders are trained in standardized procedures for data reporting, to achieve nationwide consistency in how incidents are recorded and interpreted. MSB conducts annual validation checks and quality control of incident data entries before compilation to the national database.

Updates to the incident report format were conducted in 1998, 2016, and 2022 (personal communication, Leif Sandahl, MSB). Although the format of free-text sections has remained relatively stable, the consistency and level of detail of the free-text sections has varied between users, with fire size, and over time. In our material, 98 % of all wildfire incidents contained free-text input, with an average of 36 $\pm$57 words per entry. The proportion of empty free-text entries was 8 % for the period 1996–1997, 2 % for 1998–2015, and 0 % for 2016–2022. The average word count per non-empty entry during these periods was 17, 38 and 63, respectively. These figures suggest that the risk of false negatives, meaning missed WF-B and WF-P fires due to data limitations, was generally low, although it cannot be ruled out, particularly during the initial years 1996–1997.

To extract all wildfire incidents that have caused harm (or have severely threatened to do so), the full corpus of incident reports was scanned for keywords in the free-text sections indicating threats to property (WF-B) (English translations: house*, barn, building*, dwelling*, storehouse*, cottage*, shed*, home*, garage*, stable*, façade*, eave*) and people (WF-P) (smoke, burned*, dea*, cough*, disease*, fatal*, inhal*, respirat*, breath*, oxygen).

This filtering generated over 5596 incidents which we then thoroughly read to select events that ignited buildings, or threatened to do so, or caused human injury or fatality. A number of smouldering fires that had started immediately adjacent to buildings, almost exclusively caused by discarded cigarettes, were rejected. Fires in gardens that did not spread beyond their point of origin were also discarded. These included self-ignited dung heaps or wood chip piles, arson in garbage cans or burning of garden debris without further spread (often during night when bypassing people called in the alarm). The rest of the incidents were selected for further analysis if the free-text stated explicitly that they:

- ignited or threatened a building, or
- injured a person, or
- were spreading, and explicitly described to have reached within 10 m or less from a building.

After this filtering, 3268 WF-B and 409 WF-P incidents remained, 150 of which were overlapping.

Additional data was summarized from the incident reports when possible, including the type of structure that was damaged or threatened, the number of structures damaged or threatened, whether civilian mitigation attempts were made and if they were successful, and which building element was first ignited (eave, façade, gutter, roof). Coordinates that were obviously faulty (e.g. outside of the nation borders) or completely missing were corrected based on the address column. In case of reported injuries and deaths we also recorded the victim's gender and age (if available) and the injury type: burn injury, respiratory distress or unknown/other. The injuries were classified as "severe" if transportation to the hospital was deemed necessary and otherwise as "mild".

The timing and location of each dispatch were used to match the data with hourly weather parameters such as global irradiance (I), temperature (T), relative humidity (RH), 10-m average wind speed (W) and gust (WG) from the European Space Agency (ESA) re-analysis data set (ERA5-Land) [33]. The data had a resolution of 0.1° $\times$ 0.1°, corresponding to approximately 9–11 km over Sweden. Weather parameters were taken at the point and time of alarm, regardless of any changes in weather over the course of the incident. In total, 3244 of the WF-B incidents could be matched to weather data. The remaining 24 incidents were located outside the geographical boundaries of ERA5-Land.

The incident dataset differentiates the area burned into forested land and land not covered by trees. The latter will typically be covered by grass/herb vegetation, often old-field successions and highly flammable in spring before green-up [34]. We defined each fire as either a grass- or a forest fire, depending on which of the two categories were the largest. We further defined land cover at each incident location as the dominant vegetation within a 100-m radius from the fire origin, using the 10 m resolution land cover map, issued by the Swedish Environmental Protection Agency [35]. The classes were reduced in number by collapsing them according to Table 1.

We defined the WUI category of each ignition point (the dominant category within a 100-m radius), from the global 10 m resolution map outlined by Schug et al. [36] (Table 2), in turn based on the ESA land cover map [37] and the building density map by Pesaresi and Politis [38]. We matched all incidents to population density statistics on a 1 km^2 grid [39].

2.2. Data preparation and analysis

For fire incidents involving more than one building (25 % of the fires), the incident characteristics were represented by the worst-case scenario. This was defined, for example, by the ignited building if a building was ignited, or by a dwelling if different types of buildings were involved, assuming that a dwelling represents a greater potential loss than e.g. a shed or a barn.

2.2.1. Types of fires threatening or damaging buildings

We described typical WF-B fires by separating them by their cause. The cross-comparison was based on all other variables, including vegetation type, time of day, and weather conditions at the time of ignition. This allowed us to identify patterns and differences in fire behaviour, risk context, and potential for spread or damage across fire types.

3. Results

3.1. Characteristics of WF-P incidents (human fatalities and injuries)

Between 1996 and 2022, 131 040 wildfires were reported by fire services in Sweden. Of these, we found a total of 30 fatalities, 62 cases of severely injured people and 395 cases of minor injuries among the reports. On average, Swedish wildfires caused 1.1 fatalities and 17.6 injuries per year. Less than a handful of firefighters were injured, according to the explicit statements in the WF-P dataset; most injuries that were described in detail concerned civilians. However, many reports (40 %) did not specify the identity or characteristics of the injured person at all.

The most common fatality victim was an older man (61 %) that fell due to fatigue or respiratory issues while attempting to extinguish a fire that he himself had started. One typical example from the incident reports reads:

> “An older man and his wife were burning last season’s grass by their summer house when he lost control of the fire and perished in the flames. The fire then spread to a shed where a barrel of kerosene exploded.”

Of the explicitly stated injury types in the database, smoke inhalation was more common (just over 60 % of the cases) than burn injuries (that accounted for around 40 %) (Table 3). However, 43 % were categorized as “unspecified/other”, which included fatigue, shock, cardiac distress and unknown injuries.

Although only 32 % of the injury-causing incidents (WF-P) belonged to the WF-B dataset (due to the narrow WF-B selection criterion of a threatened building), fires involving human injuries were almost exclusively started near buildings as shown in Fig. 1, regardless of the degree of injury (Table 3), and they were predominantly caused by

Table 1
Collapsed land cover classes [35].

Land cover category	Collapsed from
Conifer	Pine, mixed coniferous, spruce
Deciduous/mixed	Temperate hardwood, boreal hardwood, mixed hardwood, mixed
Open	Open vegetated land, clear-felled forest
Arable	Arable land
Urban	Building, road, railroad, non-vegetated open land
Water	Open wetland, inland water, marine water

Table 2
WUI classes as per Schug et al. [36].

WUI category	Aggregated land area that is covered by built-up[1] features, analyzed over a 500 m radius (%)	% wildland[2], and distance to 5 km^2 area with >75 % wildland
Non-WUI (vegetation)	<0.5 % built-up	–
Non-WUI (dense)	>15 % built-up	–
Interface (forest)	0.5–15 % built-up	<50 % wildland. <2.4 km
Interface (grass)	0.5–15 % built-up	<50 % wildland. <2.4 km
Intermix (forest)	0.5–15 % built-up	>50 % wildland
Intermix (grass)	0.5–15 % built-up	>50 % wildland

[1] Built-up surfaces are classified using a combination of sensors and satellites. It is interpreted in generic terms, where buildings, roads and other non-vegetated, non-water covered features are included.
[2] Non-wildland: crops, built-up area, bare soil, sparse veg., snow, ice, water. Wildland: Forest, shrubs, herbaceous wetland, moss, lichen. Grass is defined as wildland for the interface (grass) and intermix (grass) categories, but as non-wildland in remaining categories.

Table 3
Number of injuries and fatalities in Sweden 1996–2022[†].

	Minor	Severe	Fatal	Total
	(N = 395)	(N = 62)	(N = 30)	(N = 464)
All (%)	85.1	13.4	6.5	100
Gender				
Men	116	34	22	172
Women	33	5	1	39
Unspecified	246	23	7	276
Total	395	62	30	487
Age				
Older	26	8	8	42
Child	40	0	0	40
Unspecified	329	54	22	405
Total	395	62	30	487
Injury type*				
Burn	75	28	*	103
Smoke	135	22	*	157
Unspecified/other	185	12	*	197
Total	395	62	*	457
Distance to closest building				
0–100 m	224	40	18	268
>100 m	71	13	8	85
Total	295	53	26	353

* excl. fatalities.
† Based on what is specified in the free-text of the incident reports.

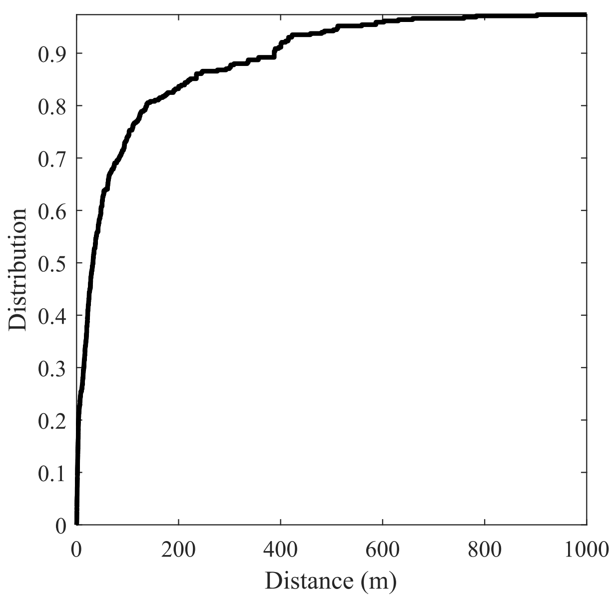

Fig. 1. Cumulative distribution of the distance between ignition points and closest buildings, for all wildfires 1996–2022 that led to human injuries.

grass- and debris burning. And similar to the WF-B data, 67 % of the fatalities in the WF-P dataset occurred in small (<0.5 ha) fires.

3.2. Characteristics of WF-B incidents (buildings threatened or ignited)

We identified 3268 fires that posed a threat to 4785 buildings. A total of 777 structures were eventually ignited during 559 fire events. Nearly half of the threatened buildings were residential while only 25 % of those that did ignite were residential; the rest were barns, sheds, garages, and other outbuildings.

Of all ignited buildings for which it was known where the fire first took hold, 88 % were ignited in the lower façade, indicating direct flame impingement, whilst 12 % were ignited in the roof or attic, suggesting ember ignition. However, these reports only comprise 24 % of all building ignitions in the dataset.

3.2.1. Population density and fire area

The WF-B incidents occurred across the country and largely reflect the population distribution (Fig. 2).

However, a closer look at the data revealed that 46 % of WF-B, both with and without subsequent building ignition, occurred in areas populated by less than 20 people/km^2 (Fig. 3a). Ignitions typically occurred outside of villages and towns, as exemplified in Fig. 3b.

Despite locally low population densities at the points of ignition, fire service response times were short (median time of 15 min) (Fig. 4a), and the resulting fire areas small. Of all buildings in the WF-B dataset, 65 % were exposed to fires smaller than 0.5 ha (Fig. 4b). Of the ignited buildings, about half (54 %) were ignited in fires smaller than 0.5 ha.

3.2.2. Seasonality and vegetation cover

Over 80 % of all WF-B occurred during the spring period March/April/May (Fig. 5a). The seasonal distribution was similar regardless of the area burnt; 81 %, 87 %, and 76 % occurred during spring for fires of sizes <0.5 ha, 0.5–10 ha, and >10 ha, respectively. Most fires (68 %) started in tree-less areas, particularly on open vegetation, comprising grass, herbs and/or shrubs [35], and arable land but also on clear-felled forest land (Fig. 5b) In comparison, only 24 % of all WF-B were ignited on tree-covered land, with deciduous forest being most prevalent.

Over the period 1996–2022 there was no clear trend in building-exposure from grass fires (Fig. 6), but as for forest fires there was a significant ($p = 0.003$) positive trend, although with a high variability between the years.

Extracted weather distributions from ERA5-Land were indicative of generally low forest fire danger for both grass fires and forest fires (Fig. 7). For instance, according to the weather data for the hour of ignition, WF-B occurred in low/moderate wind speeds, with a median of 2.8 m/s.

Most incidents (60 %) occurred between 12:00 and 16:00 Central European (Summer) Time (CE(S)T) (Fig. 8b).

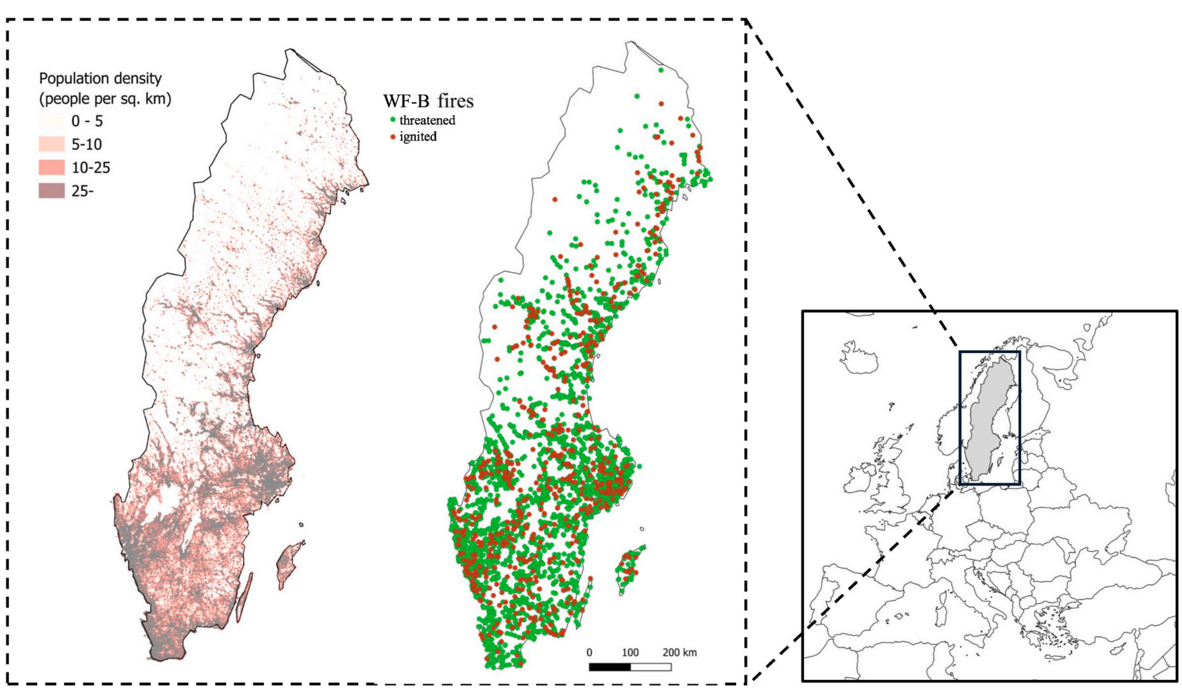

Fig. 2. Spatial distribution of population and WF-B in Sweden. Documented incidents between 1996 and 2022 mirror the population distribution at national scale.

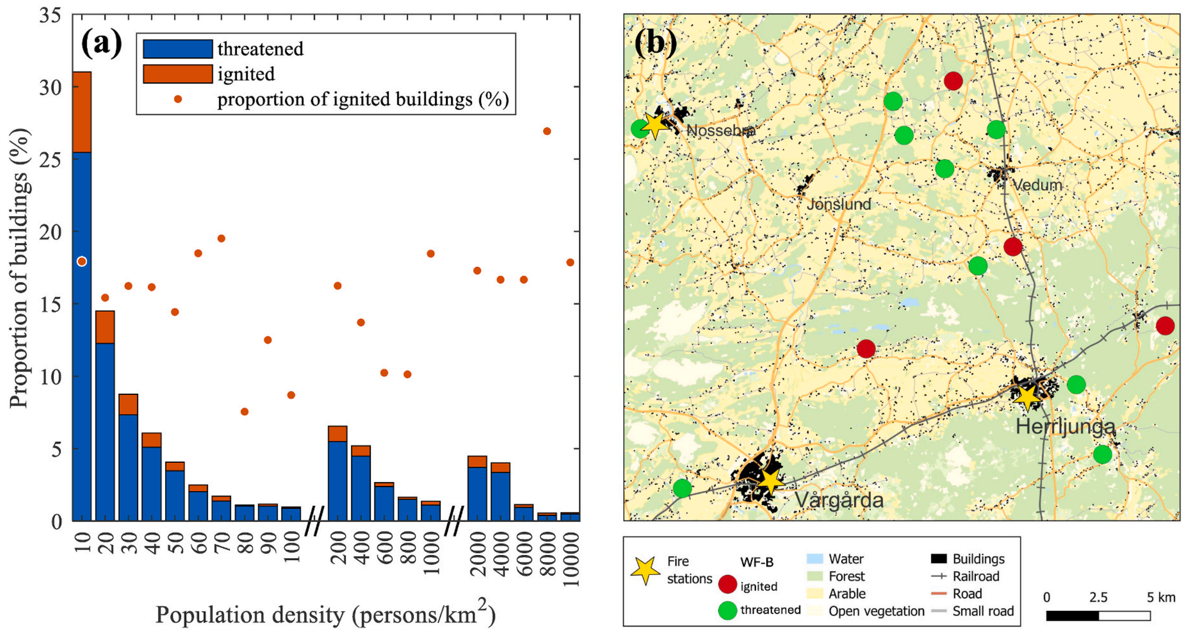

Fig. 3. (a) Distribution of WF-B incidents in relation to population density (extracted from a 1 km^2 grid). Statistics for all incidents in Sweden 1996–2022, stacked as buildings that were ignited or not. The dots indicate the proportion (%) of the fires in each population-density category that resulted in building ignition. (b) Example of the geographic distribution of WF-B incidents, dispersed countryside houses, villages and small towns. Yellow stars show fire stations in the area. Background map ©Lantmäteriet. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

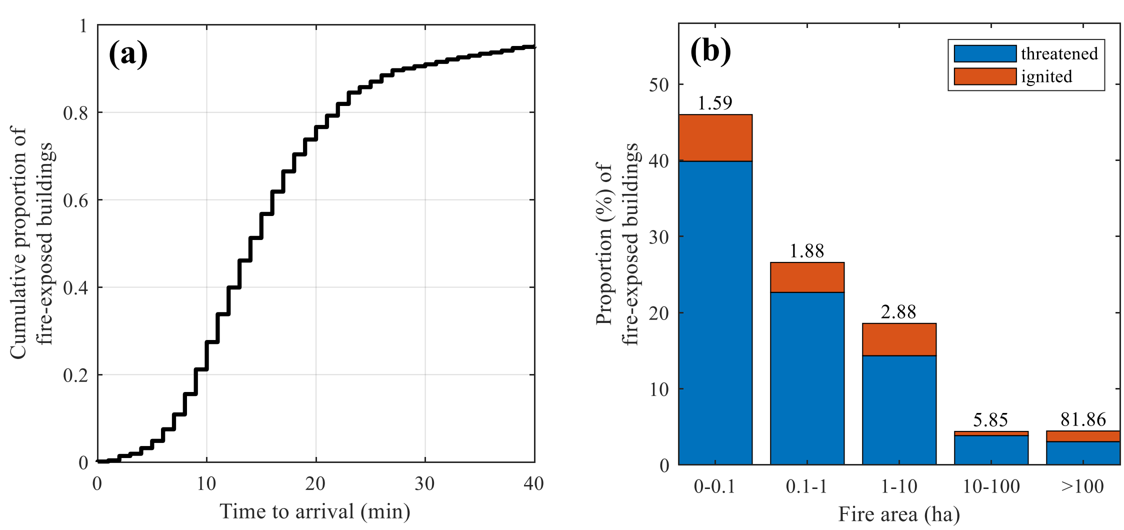

Fig. 4. (a) Cumulative distribution of fire service response time to WF-B fires in Sweden. (b) Distribution of area burned for WF-B fires, stacked as buildings that were ignited or not. Numbers above the bars indicate the mean number of buildings threatened per fire in the respective size category.

3.2.3. *Ignition cause*

Of all incidents with an established cause, over 99 % were due to anthropogenic factors (Table 4). The dominant fire causes were deliberate burning of grass and garden debris, such as leaves, branches or other combustibles (Fig. 8a). Together, these two causes accounted for over half of all WF-B incidents. There was also a large proportion of fires for which the cause was unknown or not stated, accounting for approximately one-fifth of the incidents. Only 2 % of all WF-B were started by arson.

Cross-comparison of WF-B incidents by cause reveals commonalities and differences among ignition types (Fig. 9). Most fires occurred during spring (March–May), in low-populated areas ($<$100 people/km^2) and involved fires that remained below 1 ha in size. A notable exception was lightning-ignited WF-B, which occurred predominantly in summer under distinct meteorological conditions. While the other causes to 60–70 % occurred during spring, grass- and debris burning incidents were to 94 % concentrated to the spring months of March to May.

Tables 5 and 6 in the Appendix provides a more detailed overview of the cross-comparison.

3.2.3.1. Grass burning. Grass burning was one of two leading ignition causes for WF-B (29 %) and the most common cause for WF-P (35 %) incidents. Most of these fires originated in non-WUI areas (sparsely populated) (70 %) and typically started on open vegetation (39 %) such

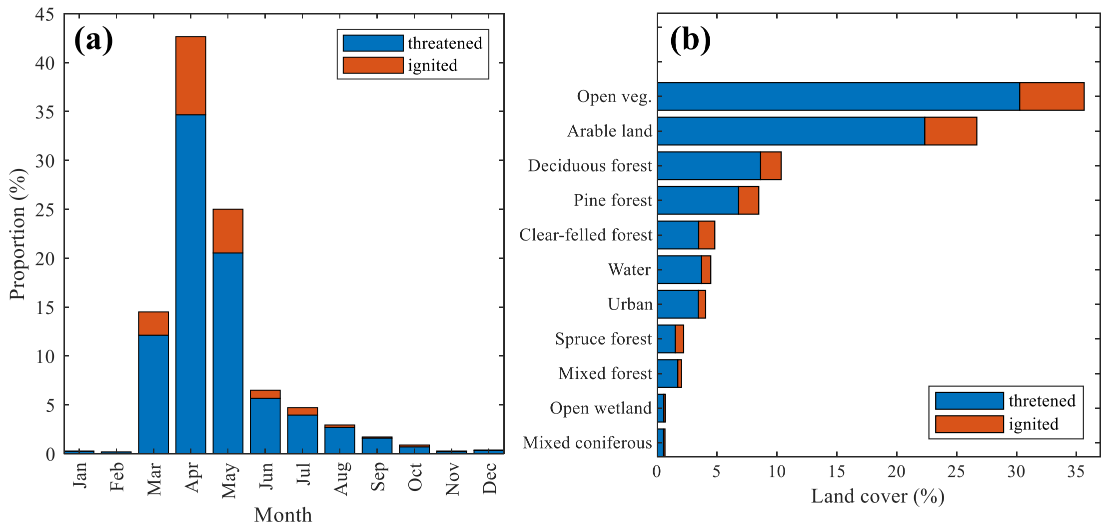

Fig. 5. (a) Seasonal distribution of WF-B. (b) Dominant land cover in the area surrounding each point of ignition, as classified in the national vegetation cover map [35].

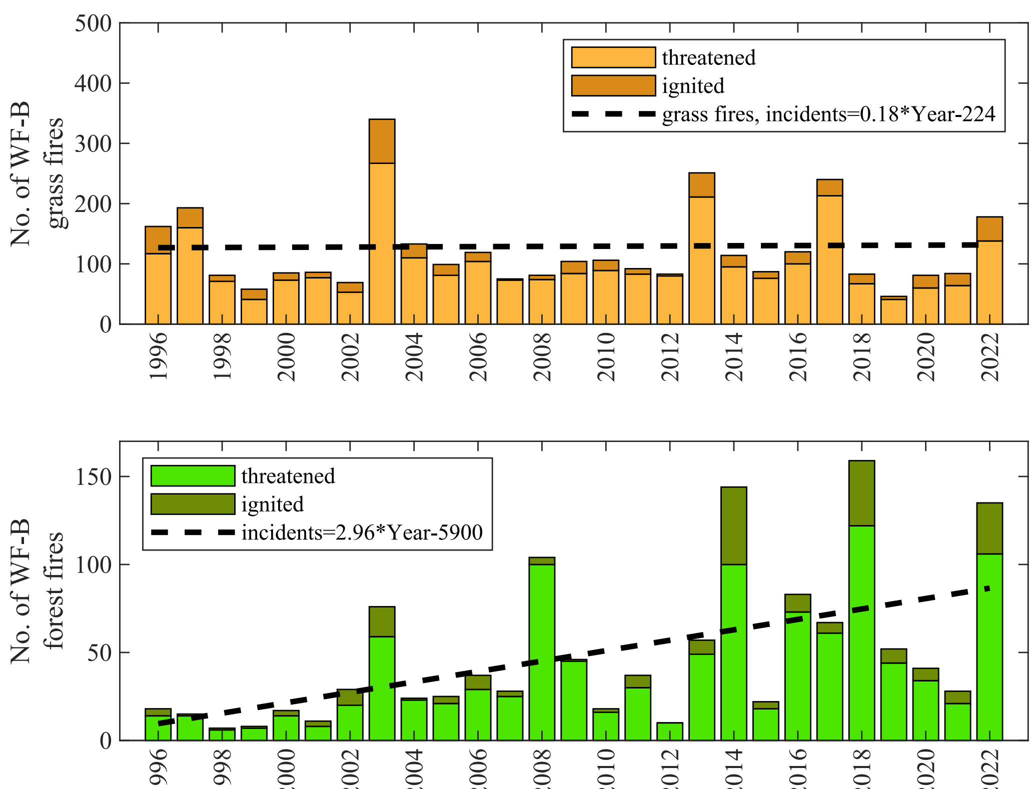

Fig. 6. Annual number of WF-B fires, with and without subsequent building ignition (stacked), separated into grass fires (upper panel) and forest fires (lower panel). The stippled lines show linear regressions.

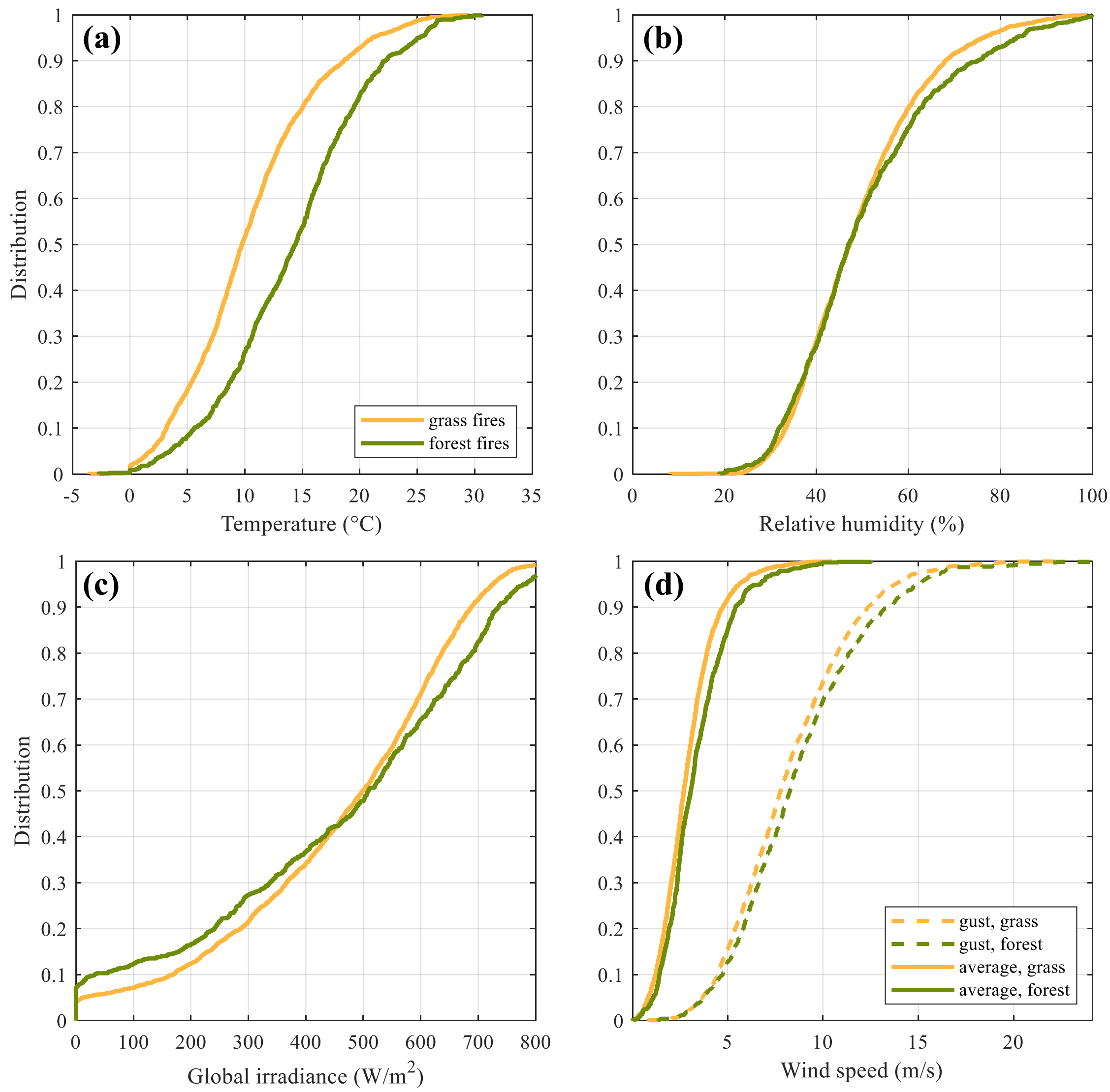

Fig. 7. Cumulative distributions of weather parameters at the time of the emergency call for WF-B fires: Temperature, relative humidity, global irradiance and wind speed for grass and forest fires respectively. Wind speeds are presented for both averages and gusts.

as meadows and roadsides, or on arable land (31 %). Grass burning activities were initiated on sunny days in spring, under relatively low humidity (47 %), light wind conditions (2.6 m/s), and following minimal precipitation (0.3 mm in 24 h). Their occurrence in dry, sunny conditions increased the potential for fire escape, especially under gusty winds. Civil mitigation measures prior to fire service arrival were typically carried out by the individuals conducting the burning and/or by neighbours. A representative case describes a fire escaping control following a sudden gust:

> ”A person was burning last year’s grass in a meadow when a gust of wind caused the fire to spread out of control. Fortunately, neighbours helped contain the flames until we arrived. Without their efforts, three barns and one summer cottage would likely have burned down.” (May 8th)

3.2.3.2. Debris burning. Debris burning accounted for a nearly equal share of WF-B incidents (28 %). Like grass burning, these fires were most common in non-WUI areas (73 %) and frequently involved arable land (33 %). The environmental conditions closely mirrored those of grass burning, including low humidity, minimal precipitation, and high solar irradiance. A typical incident report states:

> ”A couple was burning garden debris on a small field, at a day with strong winds (5 m/s with 11 m/s gusts), when the fire escaped over the dry grass litter and approached the neighbouring homestead. They called the fire service. The wind still blew against the neighbour’s property upon our arrival, with less than 10 m before flames would impinge on the closest outbuilding, why we directed our initial efforts to save that building.” (April 19th)

One nationally recognized [40] incident is the 2022 Sörvattnet fire (Fig. 10), which started during a day of reported high grass danger (RH = 20 %, W = 2–4 m/s, FFMC = 90), but with no fire ban in place. The fire started by an escape from a controlled burning of debris in a barrel, about 20 m from the nearest house. Several precautionary measures had been taken, including cutting of the tall grass litter around the barrel. The person burning had also water available in two buckets and had brought a rake. Following a wind gust, the grass outside the protected perimeter caught fire, whereupon the two people present tried to extinguish the fire, without success due to increasing wind speeds. The

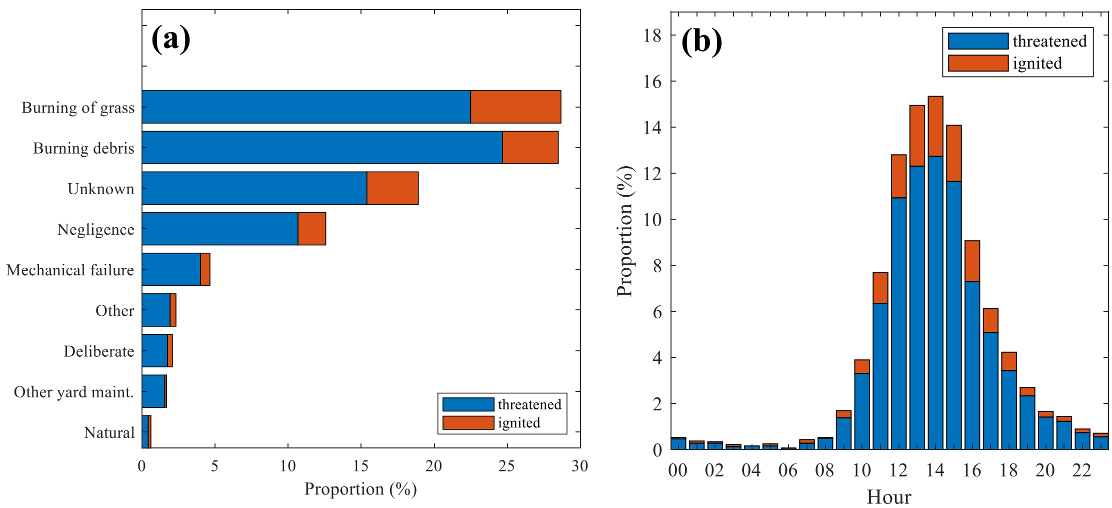

Fig. 8. (a) Distribution (%) of WF-B causes in Sweden 1996–2022. (b) Hour of ignition (CET/CEST).

Table 4
Distribution of fire causes for WF-B and WF-P fires.

Category	Sub-category	Definition/example	Number of incidents	% of WF-B incidents	% of building ignitions	% of WF-P
Burning of grass	Burning of grass	The burning of last season's dead grass over an area	937	28.7	36.2	35.3
Burning debris	Burning debris	Includes the point burning of leaves, pruned twigs, and branches and other organic and inorganic yard waste.	931	28.5	22.4	25.5
Unknown	Unknown	Unknown	618	18.9	20.6	13.8
Neglect	Ash from fireplace	Discarded hot ash in vegetated places, where re-ignition can occur	115	3.5	3.0	0.4
	Unsupervised children	Ignition by children playing with fire	112	3.4	2.7	4.9
	Unattended campfire	Ignition or re-ignition due to campfires or barbeques	91	2.8	3.2	5.5
	Fireworks	Ignition by fire work, firecrackers or guns	50	1.5	0.7	2.3
	Discarded cigarette	Discarded cigarettes in flower beds that has not led to flaming ignition have been removed from the data set.	43	1.3	1.4	1.2
Deliberate	Arson	Arson	68	2.1	2.0	1.8
Mechanical failure	Railroad	Sparks by e.g. faulty breaks	52	1.6	1.1	0.6
	Machinery	Includes both large machines for e.g. forestry and arable harvesting and miscellaneous power tools	45	1.4	0.7	4.1
	Power line	Electrical arcs or failure by breaking powerlines	35	1.1	1.1	1
	Vehicle	Burning vehicles	20	0.6	0.9	0.2
Other yard maintenance	Hot works	Sparks from welding etc.	30	0.9	0.4	0.2
	Weed burner	Accidental ignition during weed removal	25	0.8	0.4	0.4
Other	Ember from chimney	Ember from chimney	20	0.6	0.2	0.4
	Building fire	Ignition by fire spread from a burning building	14	0.4	0.9	0.8
	Other sparks	An umbrella term for unknown causes presumed being caused by sparks	14	0.4	0.4	0
	Rekindle	Reignition after insufficient mop-up	13	0.4	0.2	0.2
	Self-ignition	Ignition e.g. by focused sunlight through glass shards etc.	10	0.3	0.2	0.4
	Heat transfer	E.g. overheating of electrical equipment	5	0.2	0.5	0
Natural	Lightning	Lightning	20	0.6	0.9	0.8

first responders – a part-time firefighting crew 19 km from the incident - arrived 36 min after the emergency call. At this point four buildings had already been ignited. The other stations that took part in the operation were located 57 and 88 km away, respectively. During the rapid spread of the fire nine buildings on three properties were ignited, three of which were main buildings. Two firefighters were injured during the incident; one obtained a burn injury from the radiative heat when protecting an unignited building in the wind direction, and another experienced respiratory issues during the following night due to lengthy exposure of smoke without having any respiratory protection [41].

3.2.3.3. Unknown. Fires with unknown causes (19 %) showed higher-than-average occurrence in intermix (forest) zones (33 %), close to built-up land (7 %). These fires occurred during warmer days than the overall mean (14 °*C*), and with higher population density than the

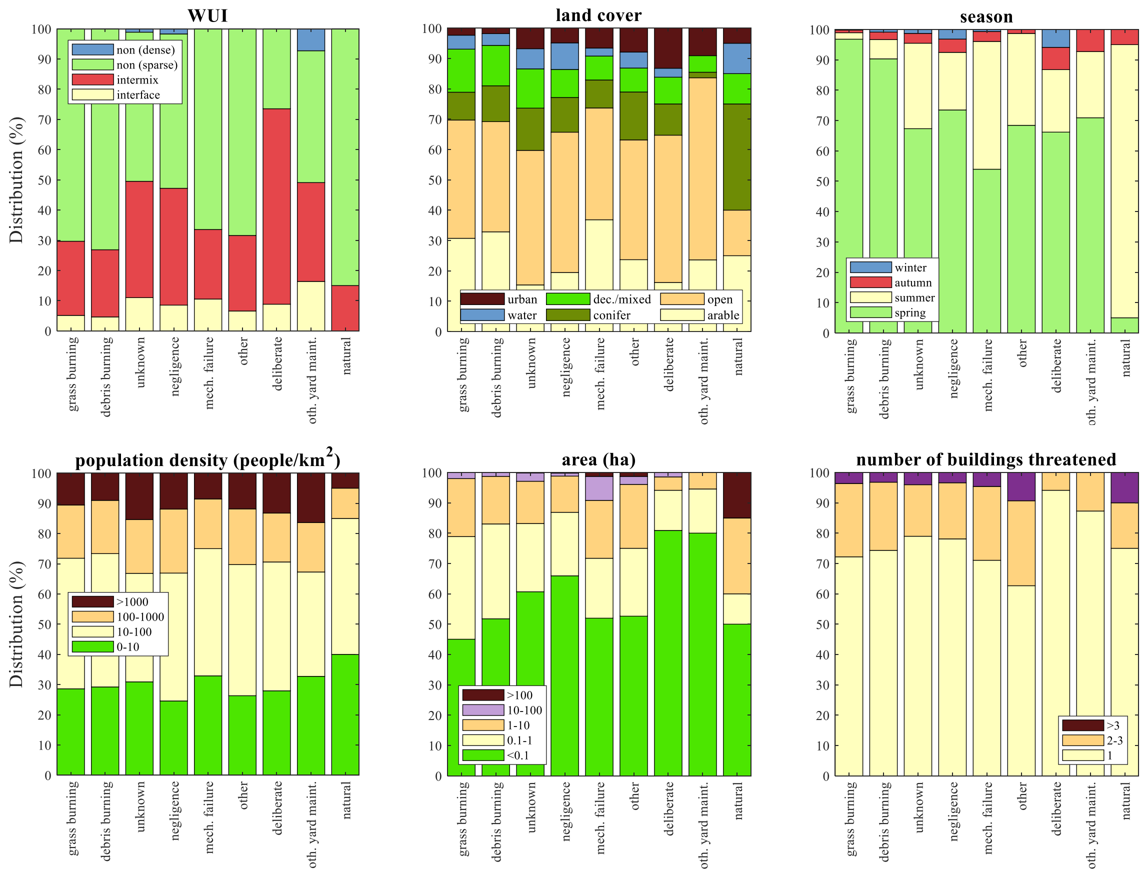

Fig. 9. Distribution of variables within each cause: WUI type, land cover, season, population density and area burned.

overall mean (521 pers/km^2). An example reads:

> ”This was a small forest fire on the slope, just behind a couple of garages. We saw the smoke plume from a kilometre away. It’s dry now with good conditions for spread. […] I couldn’t find an obvious cause of ignition, but we found some glass shards in the scorched grass.” (April 24th)

3.2.3.4. Neglect. Negligent ignitions (13 %) included improper disposal of ash from the fireplace onto combustible garden litter/vegetation, discarded cigarettes, fireworks or insufficiently extinguished campfires. These fires occurred across all seasons but were concentrated to spring (70 %). Common for most negligent ignitions is that they started by a smoldering object and on slightly windier days (3.4 m/s) than the overall mean of WF-B fires. A typical example reads:

> ”The most likely fire origin is a bucket of ash and glowing embers that was carried out earlier during the day, which ignited the surrounding grass and spread towards the house. We extinguished the flames at the building’s foundation, but since the façade cladding had charred, we checked it with a thermal camera and stayed put to ensure there was no remaining smouldering.” (May 2nd)

3.2.3.5. Mechanical failure. Fires caused by mechanical failure (5 %) occurred in both spring and summer, including sparks from faulty train brakes, forestry machinery, or power lines. These fires were larger on average (88 ha) and ignited more buildings (2.5) compared to other ignition causes. Most mechanical ignitions occurred in sparsely populated, non-WUI areas, along with a higher-than-average proportion in interface (grass) zones (7 %). The high number of buildings ignited is partly due to the multiple ignitions that can be caused by trains, and partly due to the relative remoteness associated with power lines and forestry operations:

> “We found several fires spreading along the railroad tracks. Residents tried to mitigate where fires approached buildings. Everything ran smoothly. The incident commander decided that we would prioritize those fires that could spread into gardens.“ (June 1st)

3.2.3.6. Other. This category (2 %) included individually infrequent, diverse ignition sources, such as embers from chimneys, building fires spreading into vegetation, self-ignition in stacks of organic material and rekindling fires. Due to this diversity, these fires occurred under varied circumstances and across all land cover types, rendering few characteristics by which to describe them. However, they stand out for being skewed to the eastern part of Sweden, but also by occurring in relatively windy, warm and dry conditions. In this they resemble WF-B caused by neglect. One example states:

> “Fire spread from a burning barn into the surrounding vegetation. The residential house was threatened, with flames on the porch when we arrived. Several nearby cottages were also at risk. We extinguished fires in surrounding buildings with powder extinguishers. The fire had spread across the road to a clear-cut, threatening more cottages. With several units on site, firefighting efforts were carried out on three fronts simultaneously.” (May 30th)

Fig. 10. Situation at the Sörvattnet fire incident, 5 h after the alarm call on May 17th, 2022. One of the homeowners burned garden debris in a barrel placed in the field (marked with a red x). A wind gust lofted embers over the barrel and ignited the continuous cover of highly flammable grass litter outside of the protected perimeter, leading to the loss of nine buildings, of which three were dwellings. The approximate fire perimeter is marked with a yellow line. The fire covered approx. 5 ha. Photo: Nisse Schmidt (with permission). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.3.7. Deliberate (arson). Deliberately ignited fires accounted for a minor share of WF-B incidents (2 %), but were disproportionally located in the WUI, particularly in the intermix zones. These fires occurred across all seasons but with 2/3rd during spring. Together with fires caused by other yard maintenance, it was characterized by the smallest burned area, compared to other fire causes.

> ”Probably arson on the municipality's storage yard. A grass area was burning. Two separate fires, about 5 m from the tool shed. The police and security company were informed about the event.” (March 31st)

3.2.3.8. Other yard maintenance. Fires that were initiated by garden/home maintenance equipment (2 %) mostly occurred in highly populated urban areas (610 people/km^2), under dry, warm conditions. Though typically small in area (0.2 ha) and with a swift fire service response (13 min), the proximity to buildings rendered an immediate threat to buildings. A typical case involved the use of a weed burner that ignited grass adjacent to a residence:

> “According to the owner, an electric weed burner ignited last season's grass between the garden tiles by the entrance to the house. The fire spread quickly to surrounding surfaces with dry grass, eventually reaching their home and two garages. The owner discovers that the façade has caught fire and extinguishes it by removing bits of the façade.” (May 4th)

Apart from grass, incident reports frequently mentioned ornamental garden plants such as Northern white-cedar (*Thuja occidentalis*), Port Orford cedar (*Chamaecyparis lawsoniana*) or Norway spruce (*Picea abies*) fuelling the fire.

3.2.3.9. Natural (lightning). Ignitions caused by lightning were rare, accounting for 0.6 % (N = 20) of all WF-B, but stood out in terms of both timing and fire behaviour. Unlike anthropogenic ignitions, peaking in early spring, lightning-ignited fires occurred almost exclusively during summer, coinciding with the seasonal peak in convective storm activity. The mean day of the year was 195, corresponding to mid-July. Therefore, these fires were also meteorologically different from the global mean in that they occurred under higher ambient temperatures, typical of thunderstorm conditions.

These fires tended to ignite in sparsely populated regions (85 % in non-WUI), dominated by coniferous forests (35 %). Such environments, with fire-prone fuel and low accessibility, likely contributed to their relatively large burnt areas (479 ha), and the high number of buildings ignited per fire (3.8), highlighting the potential threat of delayed detection and challenging access. An excerpt from one of the fires reads:

> “Fire hose layout and mitigation starts as soon as the staff arrives. The fire overpowers the firefighters, and they retreat. The village must be immediately evacuated. Aerial resources and ground staff with a pumper engine try to restrict spread and protect houses. The fire is gaining a furious momentum, and more villages must be evacuated. More attempts are made to stop its growth, but winds and smoke interfere, and the situation is sometimes on the verge of life-threatening.” (July 16th)

4. Discussion

This study describes wildfires that either injured people (WF-P) or threatened/damaged buildings (WF-B) in Sweden between 1996 and 2022. It is likely the most complete analysis of WF-P and WF-B fires so far as it builds on the entire corpus of firefighting dispatches, in contrast to other studies where the data originates from a number of high-consequence fires, or fires above some area threshold. Our results identify that loss of life and property are notable risks also for small wildfires. Although occasional large wildfires in the region cause substantial damage in the WUI or rural areas, small wildfires dominate as to the total number of damaged buildings and injured humans.

The average number of wildfire fatalities in Sweden was 1.1 per year during the study period, normalized to 0.11 annual fatalities per million inhabitants. This represents 54 % of the reported fatality rate in Spain, and 37 % of that of the Mediterranean region as a whole (for the time period 1979–2016) [22]. Even though this surprisingly large number might be partially related to undocumented cases in the South European statistics, it also shows that the risk of loss from wildfires is not solely dependent on the occurrence of high-consequence fires. On the contrary, in humid or cold climates, hazards are more related to phenology [42] and the presence of fast-drying litter fuels that become flammable even during short dry spells [34]. Thus, they become more sensitive to human activity than to climate conditions [43], which is, in turn, associated with proximity to the built environment [44].

Another noteworthy difference from the situation in highly fire-prone regions is that all casualties were civilian rather than firefighters and that civilian fatalities did not occur during evacuation but during suppression attempts of small fires [22,24,31]. The victims were therefore found very close to what was often their homes.

Building loss in these small-area wildfires is, as extracted from the dispatch reports, highly connected to the availability of fuel in immediate contact with the structures. In fact, this is also a trait of most building losses during large forest fires [16]. The amount and continuity of 'wildland' fuels is typically low in an urban/WUI setting, but evergreen and highly flammable ornamental species such as such as Norway Spruce or Northern Cedar, can be both plentiful and often located right next to façades. Whilst these are flammable all year round, another common feature is tall, cured grass, which is highly flammable during spring, but considerably less so after green-up [34]. This pattern is likely applicable to a broader region within northern Europe, as indicated by a study from Norway, limited to 74 incidents, which similarly found that spring fires and direct flame contact were the main contributors to building ignitions in WUI areas [45].

Both human injuries and building ignitions in small wildfires are linked to the traditional use of fire during spring. Most small wildfires were caused by yard maintenance activities, such as the burning of grass litter or other debris. The general public seem to underestimate the drying rate and/or the spread potential in grass litter, since we found many accounts of inadequate safety measures, such as having water buckets instead of watering cans and hoses, and a high proportion of building ignitions related to land-management fires. This indicates a poor understanding of safe burning practices, despite the fact that an hourly grassfire warning system [34] is freely available to the Swedish public on a mobile app (*Brandrisk Ute)*. Underestimation of the intensity of grass fires may also be a reason for the surprisingly high number of burn injuries compared to smoke-related injuries.

The abundance of yard-maintenance related WF-B causes reflects grass- and debris burning traditions in Sweden. Once necessary for cattle herding, grass burning is steeped in history and traditions [46,47] and transformed during the end on the 20th century to a pastime [48], and a way to tidy up gardens and nearby land patches in spring. One incident report exemplifies this as: *"The sun is shining, spring is in the air. It is time to BURN GRASS!"*.

Beyond cultural practices, the prevalence of grass burning incidents may also be attributed to the fire-prone nature of grass litter, which supports rapid flame spread even at moderate wind speeds and responds almost instantaneously to gusts and shifting wind directions. Weather distributions in WF-B fires were, in fact, highly similar to those of wildfire dispatches in general [49]. However, incidence reports often described sudden local wind gusts as the reason for fire escapes, phenomena that are not satisfactorily captured by ERA5-Land data (using a $0.1^\circ \times 0.1^\circ$ grid).

Although building ignition from grass fires have not increased over the years studied, there is a noteworthy positive trend of building ignition from forest fires, even if omitting the large 2014 Västmanland fire and the plentiful forest fires of 2018 (Fig. 6). We cannot find a clear reason behind this increase. The number of forest fires have not increased during the same period, but changes in demography, such as a declining rural population, have reduced availability of fire service personnel in remote areas [50]. Another contributing factor may be improvements in fire incident reporting over time, which could have led to more consistent detection and recording of building ignitions.

Our findings highlight the need for detailed WUI fire statistics. Without complete datasets, including very small fires, preparedness and prevention strategies may be misdirected. Information on e.g. ignition cause, vegetation, and suppression attempts reveals how and where people use fire, under what conditions they attempt mitigation, and when they take excessive risks. This knowledge can support targeted and timely safety campaigns, such as promoting safe debris burning in spring. Patterns with respect to building ignitions can also inform building codes and resource allocation.

5. Conclusions

Unlike the situation in western or boreal North America and southern Europe, most building ignitions, injuries and fatalities in this part of boreal Europe occur in spring, during relatively small, anthropogenic fires. Despite the low overall fire danger and small size of fires, the number of wildfire fatalities normalized by population size in Sweden is almost 40 % of that reported for southern Europe. Grass litter fuels close to buildings constitute a much higher fire hazard to the built environment than forest vegetation fuels, but only in spring when grass litter is highly flammable. It comprises the main fuel type by which flames ignite buildings in Sweden, but the presence of flammable garden vegetation also provides pathways for the ignition of buildings within the WUI. Ignitions that put people and buildings at risk in this region occur in rural settings and are nearly exclusively associated with intentional (non-arson) burning, and thus possible to avoid, through the promotion of safe burning practices.

CRediT authorship contribution statement

Frida Vermina Plathner: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Johan Sjöström:** Writing – review & editing, Funding acquisition, Conceptualization. **Anders Granström:** Writing – review & editing, Funding acquisition, Conceptualization.

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.

Acknowledgements

This work was funded by Formas under grant agreement number 2021–02396. The authors wish to thank Francine Amon for help with language editing and Hasan Sokoti for finding missing coordinates to grassfire incidents in 1997. There are no conflicts of interest.

Appendix

Table 5
Percentage distribution of all categories under each categorical variable. Signs of + and – indicate whether the proportion is significantly higher or lower than the sample average, at an alpha level of 0.05. A * marks where the proportion is significant when using a Bonferroni correction to alpha, i.e. $\alpha = 0.05/9$

Variable/ Category	Grass burning (%)	Debris burning (%)	Unknown (%)	Neglect (%)	Mechanical failure (%)	Other (%)	Deliberate (%)	Other yard maintenance (%)	Natural (%)
	N = 937	N = 931	N = 618	N = 411	N = 152	N = 76	N = 68	N = 55	N = 20
WUI									
Intermix (forest)	21	17	33	30	18	16	53	15	15
Non-WUI (forest)	70	73	49	51	66	68	26	44	85
Intermix (grass)	4	5	6	9	5	9	12	18	0
Interface (forest)	4	4	7	7	4	5	6	9	0
Interface (grass)	1	1	4	2	7	1	3	7	0
Dense	0	0	1	2	0	0	0	7	0
Vegetation									
Open	39	37	46	47	37	39	49	60	25
Arable	31	33	15	19	37	24	16	24	25
Urban	2	2	7	5	7	8	13	9	5
Coniferous	9	12	14	11	9	16	10	2	35
Deciduous/ mixed	14	13	13	9	8	8	9	5	10
Water	4	3	5	8	3	5	3	0	0
Building Type									
Outbuilding	24	25	18	19	20	24	31	31	20
Main	76	75	82	81	80	76	69	69	80
Outcome									
No ignition	78	87	81	85	86	83	84	93	70
Ignition	22	13	19	15	14	17	16	7	30
Civil Action									
Yes	45	38	21	33	25	17	25	55	10
Unknown/no	55	62	79	67	75	83	75	45	90

N = number of incidents.

Table 6
Characteristics (means ± standard deviations) for the quantitative variables. Variables are marked with + or -, depending on whether they're significantly larger or smaller than the overall mean, at a significance level of 0.05.

	Grass burning	Debris burning	Unknown	Neglect	Mechanical failure	Other	Deliberate	Other yard maintenance	Natural
	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std
Location									
Latitude*	6667962 ± 296531	6631783 ± 273697	6546375 ± 233304	6598225 ± 290877	6608860 ± 294604	6650133 ± 306450	6532572 ± 237562	6582107 ± 376664	6624688 ± 275478
Longitude*	517977 ± 141322	527504 ± 132735	517504 ± 134658	522982 ± 136474	525850 ± 125637	561447 ± 150986	510840 ± 131381	502117 ± 162244	493260 ± 108179
Demography									
Time to arrival (min)	16.0 ± 7.4	15.8 ± 7.9	14.9 ± 8.7	14.5 ± 8.7	16.2 ± 10.4	18.0 ± 10.3	11.7 ± 6.9	13.0 ± 7.1	19.5 ± 11.8
Population density (pers./km^2)	431 ± 1333	330 ± 970	521 ± 1301	427 ± 1100	389 ± 1377	339 ± 931	378 ± 825	610 ± 1396	293 ± 1062
Fire area (ha)	1.2 ± 4.4	0.7 ± 2.7	1.1 ± 5.4	1.9 ± 27	87.8 ± 1039	8.9 ± 63	1.3 ± 9.7	0.2 ± 0.8	479 ± 1334
No of buildings at risk	1.4 ± 0.9	1.4 ± 1.0	1.5 ± 1.9	1.4 ± 1.1	2.5 ± 10.6	1.7 ± 1.2	1.1 ± 0.3	1.2 ± 0.4	3.8 ± 9.2
Weather									
Temperature (°C)	9 ± 5	10 ± 5	14 ± 7	12 ± 6	15 ± 7	14 ± 7	11 ± 7	13 ± 6	22 ± 4
Relative humidity (%)	47 ± 12	49 ± 14	50 ± 15	52 ± 17	49 ± 14	49 ± 15	59 ± 20	50 ± 13	55 ± 20
24-h precipitation (mm)	0.3 ± 1.1	0.5 ± 1.7	0.7 ± 3.6	0.5 ± 1.6	0.9 ± 3.8	0.3 ± 0.8	1.0 ± 3	0.7 ± 1.8	3.6 ± 5.9

(*continued on next page*)

Table 6 (*continued*)

	Grass burning	Debris burning	Unknown	Neglect	Mechanical failure	Other	Deliberate	Other yard maintenance	Natural
	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std	Mean ± std
Wind speed (m/s)	2.6 ± 1.3	3.0 ± 1.6	3.2 ± 1.6	3.4 ± 1.7	3.3 ± 1.7	3.6 ± 1.9	2.9 ± 1.4	3.3 ± 1.6	2.0 ± 1.2
Wind gust (m/s)	7.6 ± 2.8	8.4 ± 3.3	8.5 ± 3.3	8.9 ± 3.3	9.1 ± 3.7	9.7 ± 4.3	7.6 ± 3.4	8.8 ± 3.1	6.8 ± 2.4
Global irradiance (W/m^2)	474 ± 204	477 ± 194	447 ± 232	409 ± 235	500 ± 229	478 ± 210	258 ± 269	448 ± 199	375 ± 241
Day of the year	111 ± 29	119 ± 39	140 ± 48	135 ± 56	154 ± 48	136 ± 39	155 ± 73	144 ± 49	195 ± 28

[*] Latitudes and longitudes are given in the planar coordinate system Sweref99 TM. Time to arrival is in minutes and population density in pers/km^2.

Data availability

Non-personal data will be available upon request.

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