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Human activity and demographics drive the fire regime in a highly developed European boreal region

J. Sjöström [a,*], A. Granström [b]

[a] Department of Fire and Safety, RISE Research Institutes of Sweden, Box 857, 501 15, Borås, Sweden
[b] Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden

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ABSTRACT

Organization of successful wildfire prevention and suppression require detailed information on ignition causes, size distributions and relations to weather. From a large and highly detailed dataset of Swedish wildfire incidents (n = 124 000) we assess temporal, geographical and human-related patterns over a 25-year-period (1996–2020). We find strong positive correlations between population density and wildfire occurrence, primarily caused by a wide spectrum of human activities. However, fires >10 ha mostly occurred in sparsely populated regions and were more often ignited by lightning or heavy machinery. Further, large fires had a history of long response times and insufficient mop-up, in turn intimately linked to low population density. We detect no trend over the 25-year-period in either fire weather, number of ignitions or burned area, but a dramatic decline in wildfire caused by children's play as well as by springtime burning of dead grass, a traditional fire use in rural areas. Our results indicate that irrespective of climate change, societal changes such as rural depopulation and cultural shifts are imminently important for the future fire regime in this intensely managed part of the boreal, and may warrant more attention worldwide.

1. Introduction

Weather is one obvious factor controlling fire activity and has been the main focus of recent discussions of future fire regimes, pointing to the effect of climate change [1–3]. However, human factors such as fuel management, fire prevention, detection and suppression capability are also critical [4–7]. Notably, anthropogenic ignitions dominate heavily over lightning ignitions in most regions [8,9]. At regional levels, fire occurrence therefore tends to correlate positively with anthropogenic parameters such as population- [10–12] and road density [13–15]. Fire consequences, e.g. the potential to destroy houses, also vary with ignition causes, which in turn vary with the abovementioned anthropogenic parameters [16]. Correct attribution to particular human activities is an obvious first step towards improved fire prevention, but there are only few in-depth analyses of anthropogenic ignitions [5,14,17,18].

Many factors directly affect fire suppression success. For example, in central Alberta, Arienti et al. [19] found response time (time between detection and onset of suppression) to be highly important, in addition to fire danger rating. Further, fire size distributions within an ecoregion typically follow a nature-bound power-law statistic [20]. Thus, in any particular setting of fuel, climate and fire suppression, the probability of large fire occurrence can be predicted based on smaller datasets of area-frequency distributions [21].

In the circumboreal coniferous forest belt, the combination of suitable fuel structure and periodic summer drought promote high-intensity and large-scale wildfires [3,22,23]. Most parts of the boreal have seen an increase in burned area during the last decades [24–26], implicating climate change. Sweden and the rest of Fennoscandia differ from this pattern in having a much lower proportion of area burned in recent decades [27]. Fennoscandia was one of the earliest boreal regions exploited for industrial forestry. The early adaptation to industrial forestry also led to active fire suppression and a sharp drop in burned area already in the late 1800s and early 1900s [29,30], down from previous levels that were on par with other parts of the boreal. Today the annual burned area is only about 1% of that in the mid-1800s, in stark contrast to the increasing fire activity in Mediterranean Europe [31], Siberia or the North American boreal [25]. More than 95% of the Swedish forest is managed for wood production, currently supplying 9% of the world's sawn wood export [28]. This requires effective fire protection, also to secure the building stock in rural areas that is vulnerable to wildfire [32].

Despite the overall low fire frequency, Sweden has recently

* Corresponding author.
E-mail address: johan.sjostrom@ri.se (J. Sjöström).

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experienced a number of high-intensity wildfires. For example, in 2014 a fire in central Sweden burned ~13 000 ha, 2/3 of it in crown fire during a single afternoon [33], and in 2018 a number of simultaneous fires completely overwhelmed the suppression resources and burned approximately 25 000 ha [34]. These incidents revealed a dearth of wildfire suppression resources in extreme fire-weather situations. Further, there are concerns that the fire climate will shift in the near future, leading to longer fire seasons and more severe fire-weather scenarios. Already dry parts of Sweden are projected to become even drier, resulting in increasing fire danger compared to today [35], as in several other parts of the boreal [36,37].

Sweden extends 1500 km in N–S direction and 300 km in E-W, with substantial variation in both temperature and precipitation [38]. This should lead to large differences with respect to wildfire within the country but to date there are few analyses of this. Granström [39] used incident reports from 1942 to 1975 to reveal sharp gradients in lightning ignition density, with the south-eastern part exceeding the south-western by a factor 3 and the northern half by a factor 5. This was attributed primarily to variation in summer humidity. Drobyshev et al. [40] suggested there is a northern and a southern fire region, based on analysis of monthly averages of weather data and county-level wildfire data for the periods 1942–1975 and 1996–2002. They found little yearly synchronicity in burned area between the north and the south, and suggested this was due to different weather patterns controlling fire in the respective region. Pinto et al. [15] showed that road density, population density and fire breaks (mainly open water) at a scale of 300 ha all had a positive association with fire occurrence but a negative association with fire size.

From the perspective of both climatic and societal changes in Fennoscandia, a thorough analysis of the present wildfire situation is called for. Such analysis must include the seasonality and fire-weather coupling of wildfires, as well as long-term trends in anthropogenic ignitions.

Here we investigate trends and patterns of wildfires within Sweden between 1996 and 2020, by exploiting an unusually detailed dataset of 124 000 wildfire incidents. We divide the country into 12 regions, to broadly account for variations in climate and population density. The trends in ignition causes, spatial distributions, seasonality and size distributions of wildfires and their covariation with population density are thereafter assessed. Each wildfire was matched with the daily indices of the Canadian Forest Fire Weather Index System CFFDRS [41,42] at a scale of 11 km for a sub-period of 22 years, to elucidate the weather-dependence of fires of different ignition causes.

2. Methods

2.1. Fire incidents

Swedish municipalities are required by law to provide wildfire protection, and this is done through the municipal multi-purpose rescue service that manages fire stations, strategically positioned in population nodes. Every incident that leads to a dispatch is registered in a database maintained by the Swedish Civil Contingencies Agency (Sw. MSB) since 1996. The incident commander files a report with information on time, place, resources spent, assessment of burned area, as well as free text segment describing the development of the incident [43]. The format of these incident reports has varied somewhat over the years and details of how we merged these are given in the supplementary material.

Between 1996 and 2020, the database contains 124 189 wildfire incidents that led to a dispatch. From these we extracted the time stamps of the alarm call as well as the arrival at the scene (only registered between 1998 and 2018). We also extracted the free text segment as well as coordinates for the incident, the cause of ignition and area burned, as reported by the incident commander that led the operation.

2.2. Regional delineation

Sweden lies mostly within the boreal or hemiboreal regions, except for the north-western Scandes mountain chain which has large areas of tree-less tundra, and the southernmost tip of the Scandinavian Peninsula that extends into the temperate region [44].

Since the conditions for wildfires varies greatly within the country with regard to both fire danger and population density, we divided the country into twelve regions, each with relatively homogeneous climate and population density (Fig. 1, Table 1). Our regional boundaries coincide with municipal boundaries since suppression organization and reporting of incidents are a municipal responsibility. The largely tree-less high mountains are excluded from much of the analysis, due to overall low number of incidents here.

2.3. Analysis

After quality checking the fire incident material (see suppl. material) all incidents were categorised into either *Forest fire* (≥50% of the burned area consisted of "*forested areas including clear-felled land*") or *Grassland fire* (>50% of the area comprised of *non-tree-covered land*).

Forest fires were sorted into five size classes for analysis of ignition causes etc: <0.5 ha, 0.5–10 ha, 10–100 ha, 100–1000 ha and ≥1000 ha.

The annual variation in numbers and burned area as well as the seasonal distributions (two-week periods) were calculated for all size classes, ignition causes and regions individually.

We analysed fire size distributions by calculating the complementary cumulative distribution function, which describes the probability that an ignited fire will grow above a certain area, A

$$P(\text{Area} > A) = (N - i) / N,$$

where i is the number of the incident in the size-sorted set of N incidents $\{x_i\}$. This was done for grassland fires and forest fires separately. The result was thereafter fitted with a power-law function $P(\text{Area} > A) = CA^{-\alpha}$ between 2 and 100 ha. The same analysis was also done separately per region, but only for forest fires and excluding the mountainous region and the islands (Fig. 1), due to the small number of incidents there.

The distributions of ignition causes were derived for all different fire categories (all grassland fires and forest fires of different size classes). Ignition cause was mostly given in the original incident reports as one of a set of 17 separate causes. When the somewhat diffuse causes *Other sparks* and *Other known cause* were given for a forest fire larger than 0.5 ha ($n = 2512$), we read the "free text" sections of the report to further elucidate the actual cause. Further, all incidents stated to be larger than 20 ha ($n = 266$) were also read manually to confirm coordinates, identify obvious errors in categorization of the incidents and, if possible, verify the ignition cause.

Each fire between 1999 and 2019 (excluding 2007) was coupled to the daily FWI-index and its subindices [41] from data supplied by the meteorological institute of Sweden (SMHI) on an 11 km grid throughout the country. Additionally, to obtain a yearly average index of fire weather, we first calculated daily FWI index at 63 locations (Fig. 1a) distributed throughout the country. For each location and year, the seasonal severity ratio (SSR) was then calculated according to van Wagner [45].

$$SSR = 0.0272 \times \left(\sum_{i=1}^{N} FWI(i)^{1.77} \right) \Big/ N$$

where N is the number of days during the season (for simplicity covering the period June through August). With this data we define a nationwide yearly SSR as well as a characteristic SSR for each region averaged over the whole period. For the five years not covered by the gridded nationwide weather data (1996–1998, 2007 and 2020), we used a

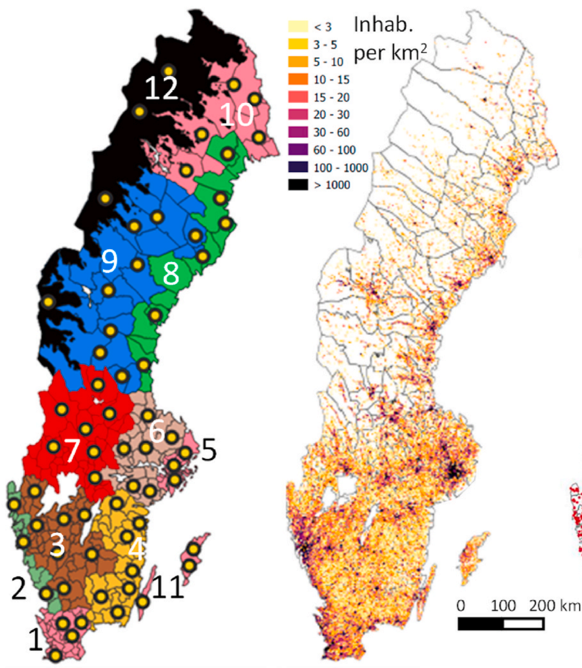

Fig. 1. (a) Geography of delineated regions. The numbers refer to regions in Table 1. Circles represent the locations used to calculate SSR from gridded weather data. (b) Population density, (c) Occurrence (1996–2020) of forest fires ≥1 ha and (d) ≥ 100 ha, see Fig. S1.

Table 1
Information on forested area, population density, wildfires and average seasonal severity rating for each of our delineated regions. Land cover and population data are from Statistics Sweden. The number for each region refers to the numbers in Fig. 1a.

Region	Forest/total land area[a]	Pop. density (km^{-2})	Annual number of forest fires per 10^4 km^2 forest/mire area[b]	Annual burned forest land (ppm)	Average Seasonal severity rating (SSR)[c]
1 Skåne	39%	121	73	68	1.9
2 West Coast	55%	131	250	155	1.3
3 West Götaland	63%	37	59	64	1.4
4 East Götaland	72%	34	68	85	2.1
5 Stockholm	57%	360	507	267	3.1[d]
6 East Svealand	66%	48	87	375	2.2
7 West Svealand	84%	16	37	73	1.1
8 North Coast	96%	17	25	77	1.7
9 North Interior	98%	4.1	12	142	1.2
10 Far North	91%	2.0	7.6	21	1.1
11 Baltic Islands	38%	19	109	112	2.4
12 High mountains	34%[e]	0.3	1.1	9	0.3

[a] Includes forests and mires.
[b] Incidents on forest land. Incidents with burned area <100 m^2 excluded.
[c] SSR is a summed index of the fire weather over a fire season [45], with high values indicating many high-danger days. Here we calculated an average for the period 1999–2019, using ≥3 locations per region with reanalysed data supplied by the meteorological service of Sweden (SMHI).
[d] The exceptionally high SSR in Stockholm region likely stem from more efficient shielding of Atlantic low pressures by the western Swedish and Norwegian landmasses, compared to regions further south or west [46].
[e] This number excludes mires.

number of weather stations (suppl. material Fig. S6) to define the nationwide SSR.

3. Results

3.1. Number and size variations and their relation to SSR

The number of wildfire incidents ($n = 124\ 189$) was divided nearly equally between grassland fires and forest fires, averaging almost 5000 incidents annually (standard deviation: σ = 33% of the mean), burning on average ~400 ha of grassland and ~3200 ha of forest land. The annual number of forest fires and grassland fires was highly correlated ($r^2 = 70\%$) while the number of forest fires >0.5 ha exhibited larger annual variation (Fig. 2a). With regard to area burned the annual variation was very large (σ = 182% of the mean). Forest fires >0.5 ha constituted only 10% of all forest fires but accounted for >83% of total burned area during the 25-year-period (Fig. 2b). Annual numbers correlated positively ($R^2 = 0.76$) with annual area burned.

The annual area burned correlated positively ($R^2 = 0.60$) with the Seasonal Severity Rating (SSR), averaged over the whole country. Specifically, the seasons of 1997, 2006, 2008 and 2018 all had both high SSR and a large number of forest fires >0.5 ha (Fig. 2c and d), and large burned area (Fig. 2b). There was no overall trend over the 25-year-period (1996–2020) in the number of fires, area burned or SSR (Fig. 2a and b).

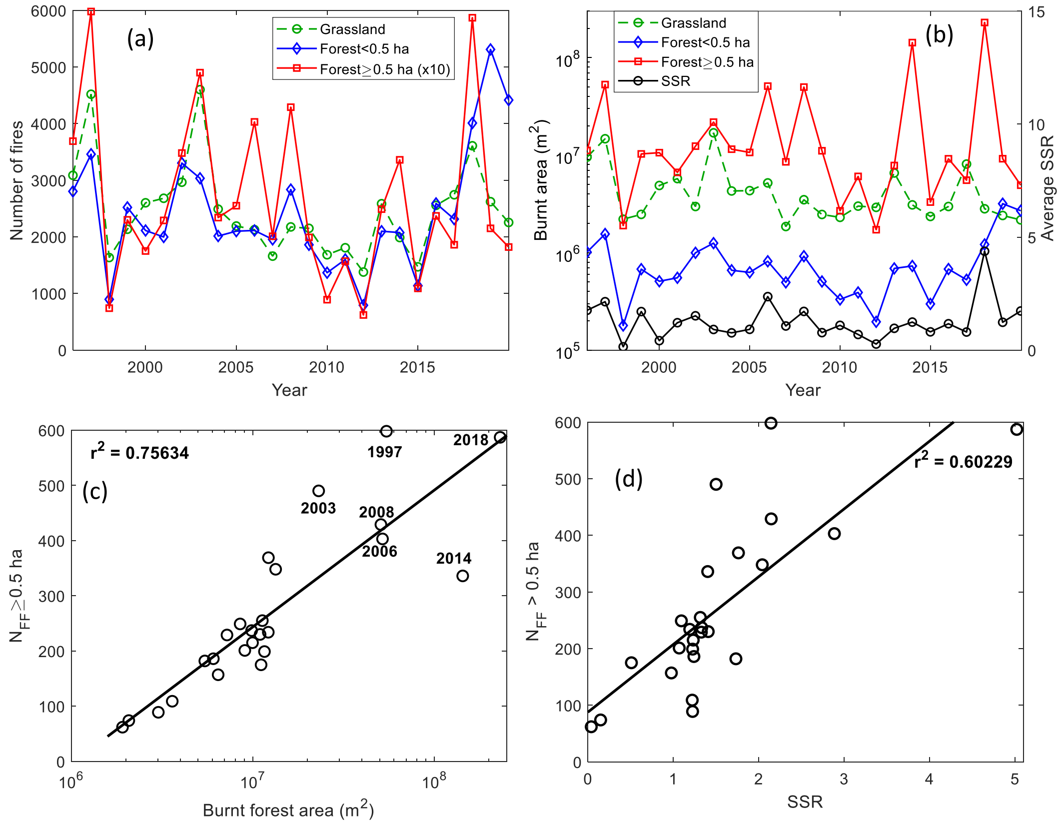

Fig. 2. (a) Number of fires over the years for grassland fires and forest fires below and over 0.5 ha. (b) Burned area (note log scale) over the years for the same categories. (c) N_{FF}>0.5 ha (annual number of forest fires exceeding 0.5 ha) vs annual burned forest area. (d) N_{FF}>0.5 ha vs corresponding national average seasonal severity rating (SSR).

3.2. Seasonality

In all regions there was a more or less marked seasonal separation between grassland fires and forest fires (Fig. 3a, S2). In most regions, grassland fires peaked 9–10 weeks before forest fires. Also, there was a clear north-south gradient for both fire-categories. In some southern regions there was also a tendency towards a bi-modal distribution of fires, with peaks both in spring and July.

As a measure of the length of the fire season we defined the period encompassing 75% of all forest fires >0.5 ha. This period started 41 days earlier and ended 21 days earlier in West Götaland compared to the Interior north (Fig. 3a).

Different size categories of forest fires varied in their seasonal distribution. Aggregated for all of Sweden, the frequency of the smallest forest fires increased until early May, stayed relatively constant until late July and declined gradually throughout late summer and early autumn. For fires of progressively larger size class, the peak frequency of occurrence became increasingly concentrated to July (Fig. 3b).

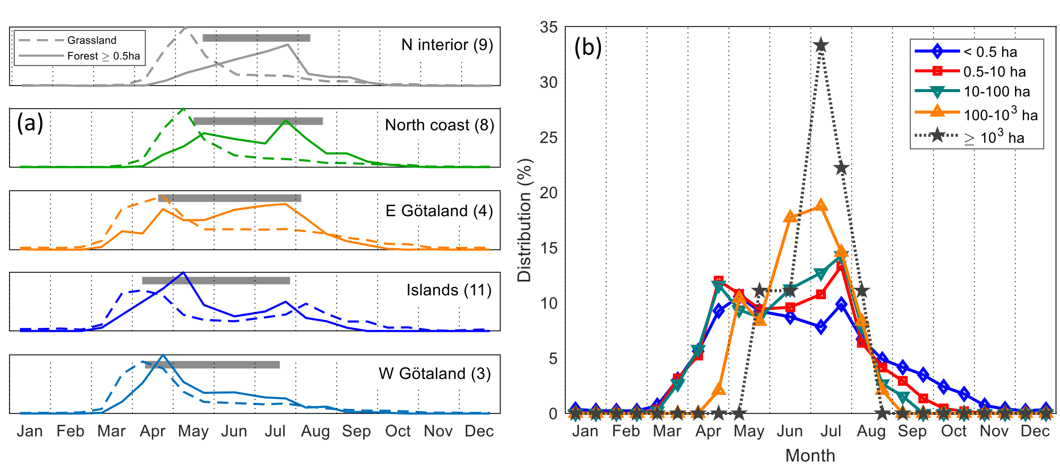

Fig. 3. (a) Seasonal distribution of grassland- and forest fires ≥0.5 ha in 5 selected regions. Numbers refer to the region number in Table 1 and Fig. 1. The grey bar indicates the central period for 75% of the forest fires ≥0.5 ha. See suppl. material (Fig. S2) for all regions. (b) Seasonal distribution for fires of different size classes.

3.3. Size and spatial distributsions

There was a linear positive relation between the number of forest fires and population density per region (Fig. 4a). In contrast, the proportion of all forest fires that exceeded 0.5 ha decreased almost exponentially with population density (Fig. 4b). Thus, while fire occurrence (ignition density) was positively associated with population density at the national level (Fig. 1b and c), fires ≥100 ha occurred mainly in areas with low population density (Fig. 1d).

At the national level, the complementary cumulative distribution function, describing the portion of fires exceeding a certain area, followed a power-law dependence on area, $P(\text{Area} > A) \sim A^{-\alpha}$, over three orders of magnitude for forest fires and over two orders of magnitude for grassland fires (Fig. 5a). For both fire-categories, the linear range started at approximately 1 ha. The steeper the slope, the smaller the probability of fires growing large. Grassland fires had a steep slope, $\alpha = 1.40$, such that only 1‰ of the fires exceeded 17 ha. The slope exponent for forest fires (of which 1‰ exceeded 100 ha) was $\alpha = 0.92$, when fitted between 2 and 100 ha, but followed the same fit up to fire sizes of several thousand hectares (Fig. 5a).

Size distributions broken down per region yielded fitted slopes with α ranging from 0.8 to 1.2 (Fig. 5b). There was an approximately linear decrease in α with log population density.

3.4. Ignition causes

In the original incident reports each fire was assigned to one of 17 specific causes, if possible (Fig. 6). Forty-one percent of the forest fires were either not specified or reported as *Cause unknown*. For forest fires with a known cause, the top ignition causes were, in decreasing order: *Campfire, Arson* (deliberate illegal burning), *Lightning*, *Children's play*, *Other burning* (usually of garden debris or garbage) and *Burning of grass* (Fig. 6). *Lightning*, the only non-anthropogenic cause, was responsible for 7.6% of all incidents or 13% of those with a known cause. Grassland fires were instead most often ignited by *Burning of grass*, followed by *Arson*, *Children's play* and *Other burning*. *Campfire* and in particular *Lightning*, accounted for a much higher proportion of forest fires than of grassland fires.

For the forest fires, the distribution of causes shifted with fire size class (Fig. 6). For example, the relative contribution of *Arson* and *Campfire* decreased with increasing size class whereas the reverse was true for *Reignition*, *Lightning* and in particular *Other sparks* and *Other known causes*. The cause *Reignition* refers to an incident that has originally been controlled by the rescue service and handed over to the landowner for mop-up, only to rekindle later (usually one to several days later), leading to a new rescue service dispatch. *Other sparks* and *Other known causes* covered mainly refuse burning, powerline failure and machine activity (see suppl. material for a more detailed breakdown).

For forest fires, the seasonal distribution differed markedly with ignition cause. *Burning of grass*, *Children's play*, *Other burning,* and *Arson* all peaked in the early part of the season (solid lines in Fig. 7). *Other sparks* peaked in June whereas *Lightning* and *Reignition* had distinct peaks towards the latter part of July. *Campfire* had the widest distribution of all, extending into September.

For forest fires exceeding 0.5 ha, the average fire danger indices (on day of ignition) also varied with ignition cause (suppl. mat. Fig. S3). For example, fires caused by *Reignition* and *Other sparks* on average occurred at high FWI-values whereas *Burning of grass*, *Other burning*, *Lightning*, and *Children's play* occurred at relatively low average FWI-value. As for *Lightning*, average FFMC-value was markedly low but DMC high. *Reignition* was also associated with high DMC-levels whereas fires caused by deliberate *Burning of grass* had the lowest average DMC-levels.

For most of the ignition causes there was no trend over the 25-year-period in their relative contribution, with the exception of three. The proportion of all wildfires attributed to *Arson* increased, although less distinctly so for forest fires ≥0.5 ha (Fig. 8). Ignitions from *Burning of grass* instead decreased, from 15 to 20% during 1996–1998 to below 5% in the period after 2015, but with a large scatter between years. The most dramatic trend of all was for the category *Children's play*, which decreased steadily from around 12% in the late 1990s to below 2% in the last three years (Fig. 8).

With increasing regional population density, there was a clear decrease in the fraction of fires caused by *Reignition*, for all forest fires combined and in particular for forest fires >0.5 ha (Fig. 9). This relationship is fairly well described by an exponential decay function. The opposite trend, increasing fraction with increasing population density, was observed for *Children's play*, *Burning grass* and in particular for *Arson* (data not shown).

3.5. Time to arrival of the suppression crew

The distribution of Time from alarm To Arrival (TTA) of the suppression force at the closest accessible road varied, at the national level, with the different size classes (Fig. 10a). Median TTA increased from 14 min for the smallest fires (<0.5 ha) to over 32 min for the largest category (≥100 ha). Likewise, there were large regional differences with median TTA at 10 and 12 min in Stockholm and E. Götaland, respectively, but around 30 min for North Inland (Fig. 10b). For 14% of the forest fires in North inland the response time exceeded 1 h. Median TTA decreased monotonically with regional population density (suppl. material, Fig. S4).

All forest fires were binned in 16 size categories between 10^{-2} and

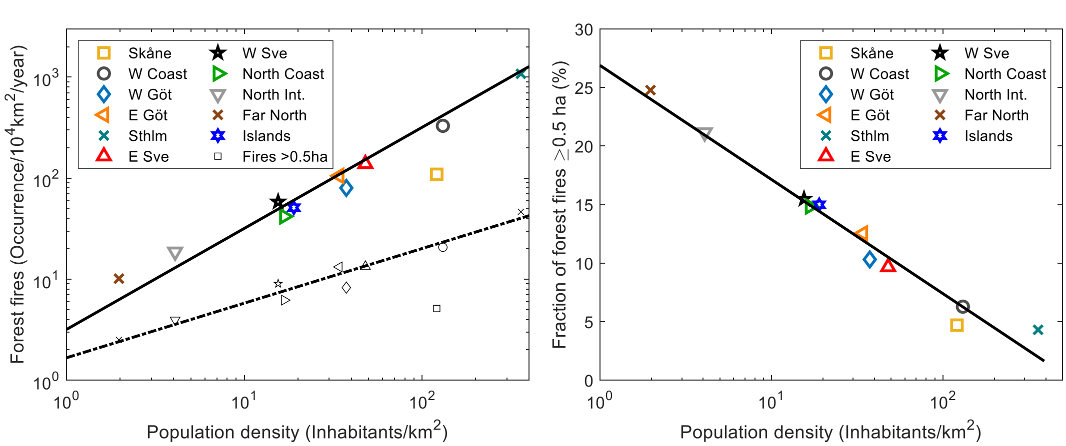

Fig. 4. (a) Annual occurrence of forest fires per unit land area in relation to population density for the regions. The solid line represents 0.318 fires per 10^3 inhabitants and year ($R^2 = 0.94$). Small symbols represent forest fires ≥0.5 ha. (b) Fraction of forest fires exceeding 0.5 ha in relation to population density. Solid line represents exponential decay $\sim \exp(-0.034\rho)$. The legend abbreviations refer to the regions in Table 1.

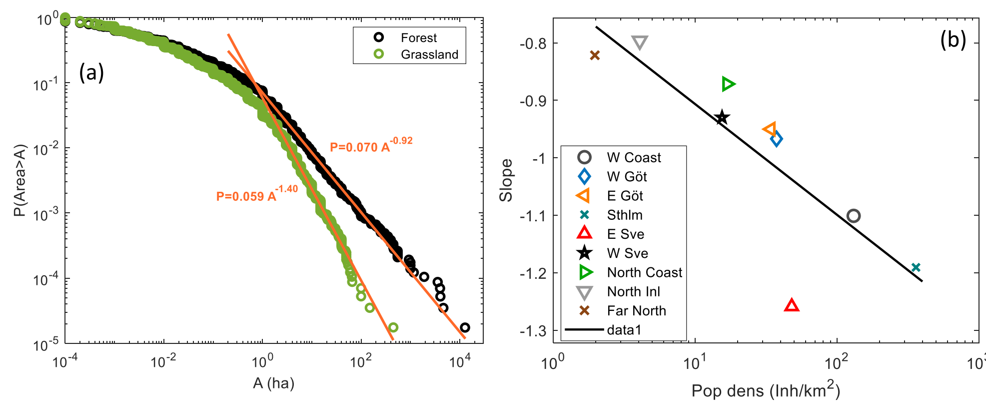

Fig. 5. (a) Complementary cumulative distribution function (portion of fires exceeding a certain area) against the final burned area (log-log scale) for grassland- and forest fires throughout the country. The lines are power-law fits to the data for fire sizes 2–100 ha. (b) The slope ($-\alpha$) of the Complementary cumulative distribution function for forest fires in each specific regions (Mountains, Islands and Skåne excluded) in relation to the corresponding population density.

1.3×10^4 ha and for each the median TTA was determined. The relation between median TTA and the logarithm of final area was linear up to 10 ha and TTA 30 min (Fig. 10c). Above 10 ha the relationship between final burned area and TTA was less clear but most large fires were associated with high TTA and for fires ≥300 ha ($n = 28$) the median TTA was 55 min.

TTA increased markedly over the period 1998–2018 (Fig. 10d). The increase was largest until the mid '00s, after which it stabilized. Using fitted polynomials, the increase in median TTA over the full period was 24%, 25% and 37% for grassland- small- and large forest fires, respectively.

4. Discussion

The dataset explored in this paper is large and unusually detailed, which makes it possible to elucidate the various factors controlling wildfire activity in term of numbers and area burned. Weather is obviously critical, but our analysis point to the overwhelming importance of the distribution of the human population, largely determining both the geography of ignitions and the spatial access to suppression resources.

4.1. Scaling of fire sizes

The power-law relation of forest fire size *vs* numbers held over more than three orders of magnitude in size, which is similar to other boreal regions [21], but contrasts with non-boreal Europe where scaling parameters hold over only 1–2 orders of magnitude [47,48]. The extrapolated trends for small (<0.2) and large (>2 ha) fires intersected at $A = 0.5$ ha, identifying the size above which the size – number relationship is scale-invariant, which suggests that fires attacked before growing to this size have a disproportionally low probability to grow further.

For the population of forest fires, the power-law scaling implies that the probability of exceeding a certain size decreases by 47% when that area doubles [49]. For grassland fires the corresponding decrease is 62%. Grassland fires are probably limited mainly by the size distribution of grass-dominated old-fields, i.e. the 'available' units of suitable fuel, whereas forest fires, in these continuously forested landscapes, are limited mainly by suppression, and to some extent weather-changes halting further expansion.

Geographical variations of the scaling coefficient have previously been shown, e.g. West to East in the USA [20,50] and North to South in Europe [47]. Explanations include variation in climate or vegetation [51,52], degree of fragmentation [53], or unknown effects of population density [20]. Here the scaling exponent decreased linearly with the logarithm of population density (Fig. 5b) but did not co-vary with the substantial regional differences in fire danger (SSR). Also, most of Sweden has relatively good accessibility through the dense forestry-road network [54] and coniferous forests dominate nearly all regions, so these factors should be relatively equal. We therefore believe that the main reason for scaling variation is fire station density, and strength of suppression forces, for which regional population density is a proxy.

4.2. Time to initial attack

It is clear that a common feature of large fires is a relatively long time to initial attack, which in turn is closely related to regional population density. On an area-basis, the resources available for fire suppression are highly linked to population density. Low population density gives long distances between fire stations and long average travel time to reach the fires (Fig. 10b and suppl. material, Fig. S4). It is also likely that time from actual ignition to detection and alarm is longer in sparsely populated areas, because >95% of the fires are first reported by the general public [55]. Another factor is that rural fire stations rely solely on staff that are on-call while employed elsewhere, which delays dispatch. All these factors inherently lead to long TTA and increased risk for large fire events.

We identify a long-term increase in TTA, particularly in the early part of the study period (Fig. 10d). This coincides in time with a general economic downturn for municipalities [56], exacerbated in rural areas by the ongoing depopulation [57]. Decommissioning of fire stations should immediately translate into higher TTA, but there are no reliable data on trends in station density over time, and other mechanisms might also have been involved. For example, throughout this period authorities have remarked on the problem of attracting part time fire fighters [58]. Also, the stabilization in TTA over the last few years could possibly reflect a higher priority for forest fire suppression after the catastrophic 2014 Västmanland fire [33].

4.3. Seasonal trends

The onset of the "effective" fire season (covering 75% of all fires) was approximately 6–8 weeks earlier in the south than in the north, reflecting the 1500 km N–S extent of the country. One major regulating factor in early season is the presence of a snow cover, which in the northernmost provinces typically lasts into late April, or even May [59], providing a buffer against early fires.

The seasonal separation of fires in grassland *vs* forest is fuel-related. Grass- and herb-dominated litter fuel, typical for abandoned fields and culturally modified areas close to habitation, is highly flammable in spring before green-up but later virtually fireproof, even in severe drought [59]. In contrast, the fuel bed under coniferous forest is dominated by moss and needle litter, and change little over the season,

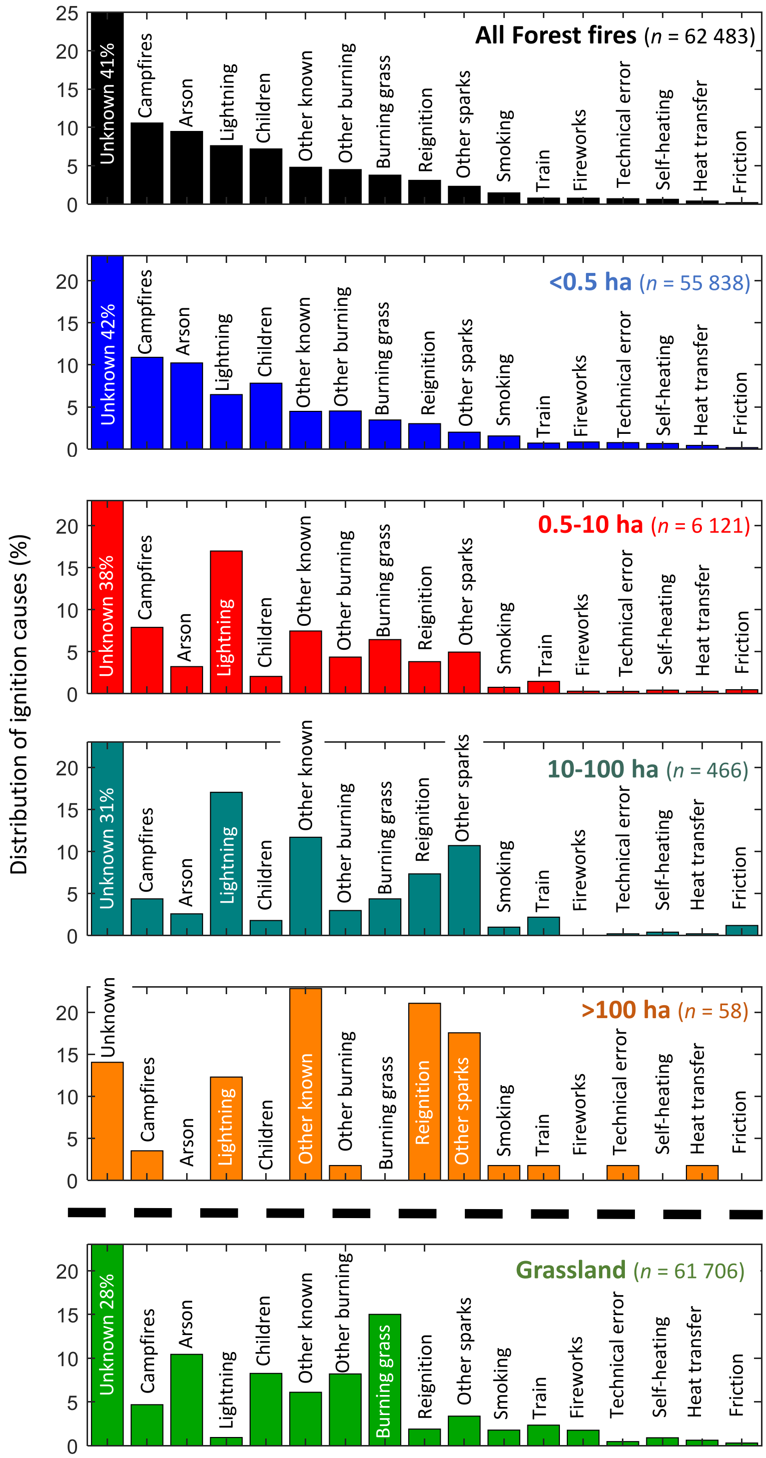

Fig. 6. Relative distribution of ignition causes for wildfires in Sweden (1996–2018). Panels represent (from top) all forest fires collectively, forest fires of progressively increasing size, and the lowermost panel represents all grassland fires.

although it requires substantially longer drying to become flammable [60]. Thus, if the spring season is sufficiently dry, both open grass-dominated areas and forests can be flammable simultaneously and ignitions in grassland can spread into forest and vice versa. This is the likely reason for the clear seasonal separation among certain anthropogenic ignition sources, also for Forest fires (Fig. 7). Some activities, e.g. children's play, will naturally happen in open areas close to habitation, whereas others, e.g. lighting of campfires, will more likely be in the forest proper, and thus have a less defined season.

4.4. Ignition causes

The form used by incident commanders for reporting contained 17 pre-defined ignition causes. For larger forest fires however, the plethora of ignition causes narrowed down considerably. Thus, 44% of all forest fires ≥100 ha with known ignition cause were due to either *Lightning*,

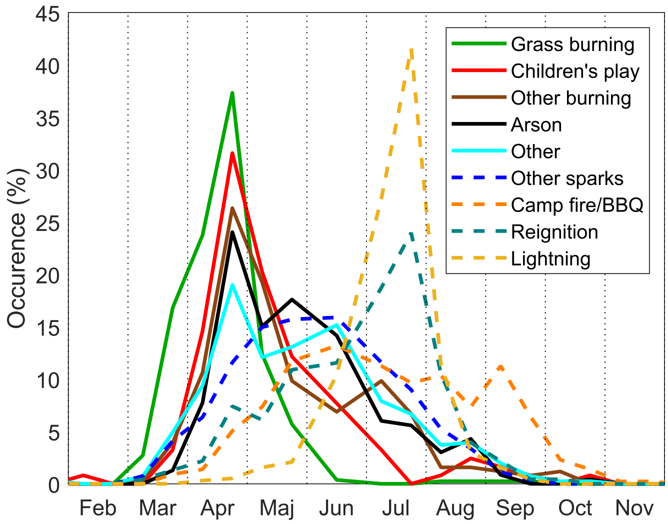

Fig. 7. Seasonal distribution of forest fires >0.5 ha for the most frequent ignition causes. Causes peaking in spring are rendered with solid lines and causes peaking later, with dashed lines.

forestry machines in operation or *Reignition*. Why so? First, these ignitions happen mainly in the forest terrain proper, in contrast to most other (anthropogenic) sources, which are near to roads and human habitation. Long travel distances from fire stations gives the fire time to grow, which lowers the chance of a successful initial attack [38].

Reignition had the highest mean DMC value of all ignition causes, highlighting that fires occurring after long drought, when the humus layer is dry, requires thorough mop-up. One worry for the future is the increasing proportion of absentee owners [61], living far-off their property, which cannot be called-up to perform this duty.

Interestingly, reignition is rarely mentioned in statistics from other boreal regions or from the USA. For example, it is not included as a cause category by the US Department of the Interior or the Forest Service [62]. This is probably not because the phenomenon is absent, but because the

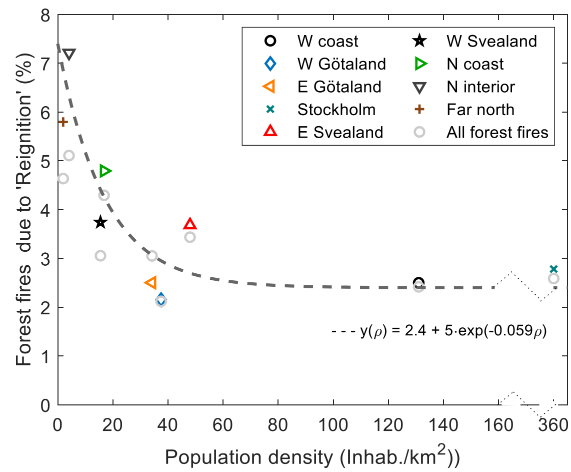

Fig. 9. Fraction of forest fires in each region caused by '*Reignition*', in relation to population density. Coloured symbols depict forest fires >0.5 ha and grey circles all forest fires.

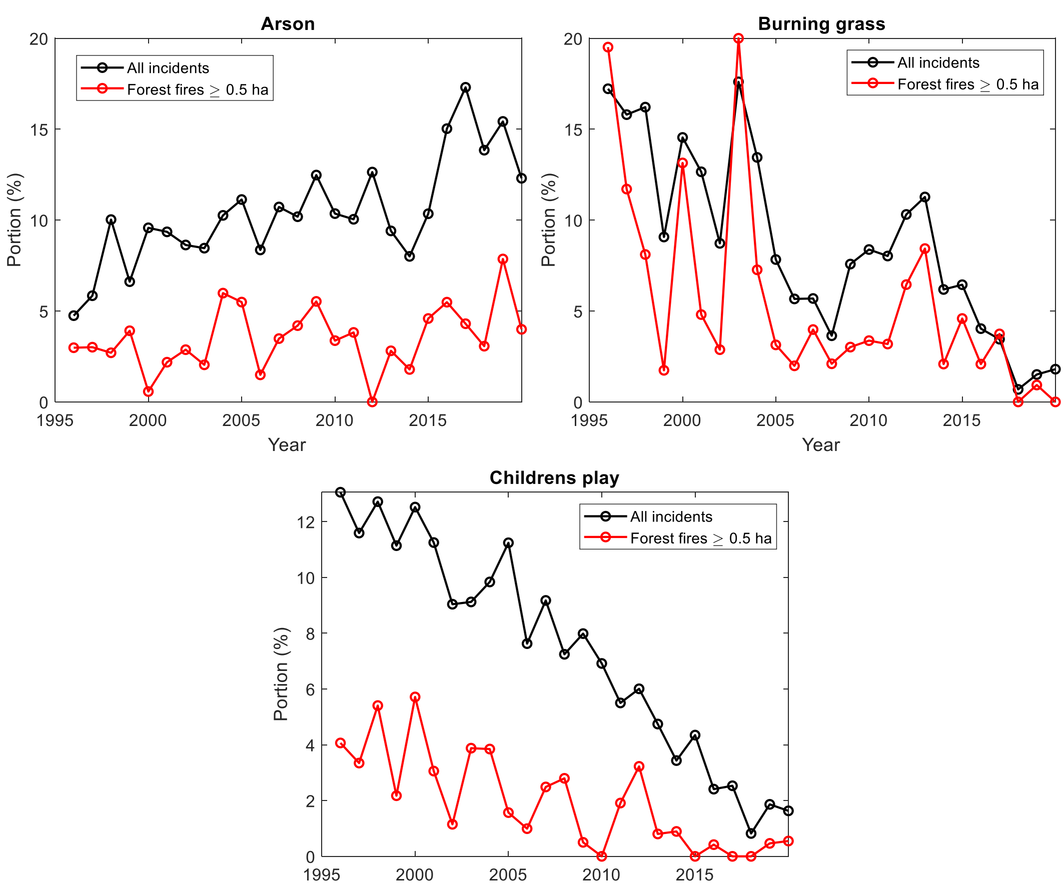

Fig. 8. The annual proportion all wildfires and of forest fires >0.5 ha contributed by the ignition causes '*Arson*', '*Burning of grass*' and '*Children's play*'.

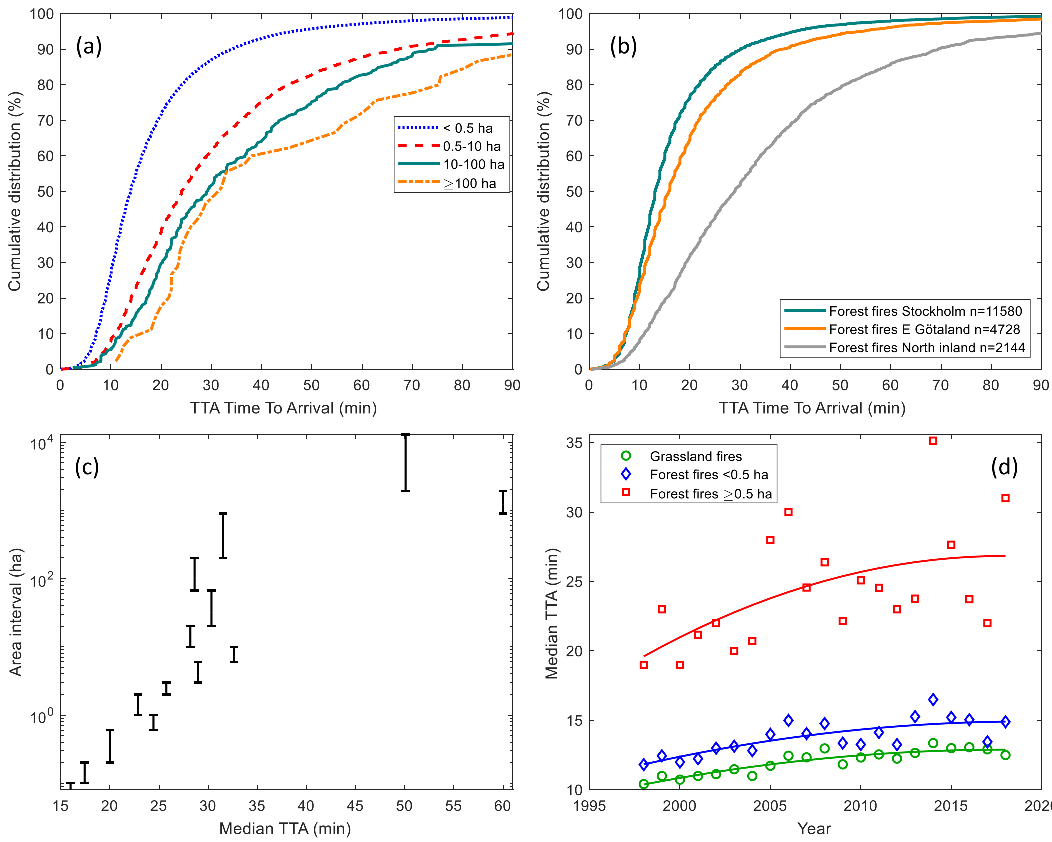

Fig. 10. (a): Cumulative distribution of TTA (Time To Arrival) for forest fires of different size classes. (b) The corresponding distributions for all forest fires in Stockholm, East Götaland and North inland. (c) Binned area intervals of forest fires (represented by the horizontal bars) against the median TTA in the binned group. (d) Median TTA during each year from 1998 to 2018, for grassland fires and forest fires (below and above 0.5 ha) with 2^{nd} order polynomial fits.

same organization handles both containment and mop-up; failures in the latter will not be labelled re-ignition.

4.5. *Long-term trends*

Although we found no clear trend for either lightning- or anthropogenic ignitions collectively over the 25-year-period, the relative contribution of certain ignition sources did change. *Arson*, or deliberate illegal ignitions, increased somewhat. This contrasts with the USA, where arson ignitions peaked during the 1970s and has declined ever since [62]. We see no obvious reason for this upward trend, but it should be noted that arson-fires are not always intended to cause wildfire as they often start when other objects, such as sheds, are ignited but then spread into vegetation fuels. Thus, the increase could potentially have been due to changes in fuel structure near to habitation over the period (Cf. Vermina Plathner et al. [32]), rather than an increase in arson *per se*.

The proportion of wildfires resulting from deliberate grass burning decreased markedly over the period (Fig. 8). We believe this reflects a general decline in traditional spring burning. Often the text description stated that a grassfire had been set by elderly people as part of traditional land management in spring, but then had escaped.

Wildfires caused by *Children's play* show the most substantial temporal trend over the 25-year-period, decreasing precipitously. A likely reason for this is the decline in unsupervised outdoor time among children, observed in Sweden as well as in other 'western' countries [63]. Several reports show a decrease in outdoor activities [64] combined with increasing time spent behind a computer or other screen [65]. Additionally, the decrease in smoking among adults [66] possibly limits children's access to matches and lighters.

Variation in weather is evidently important for the dramatic annual variation in area burned and if fire-climate changes in the future, this will be consequential. From the perspective of climate change, our 25-year observation period is relatively short, but we cannot find any trends in either number of fires or area burned, in contrast to the findings for other parts of the boreal such as Russia [24,26] or Canada [25]. Likewise, we cannot find any long-term trend in the length of the fire season, its start or end dates, for any of the studied regions (suppl. material, Fig. S5). It has been shown that years with high forest fire activity correlate with the occurrence of high-pressure cells over the region [67], which do not exhibit any significant trends [23]. Thus, even if future projections suggest a longer burn season [68] and more severe summer droughts in parts of the country [35], these have not yet manifested themselves.

Our findings suggest that in the present fire-climate, variation in human activity (for which population density is a proxy), is a critical factor for both fire occurrence and the likelihood of large, high-impact fires. Since the bulk of wildfires are caused by people, the future wildfire situation in Sweden will be highly sensitive to cultural changes that affect various anthropogenic ignition sources. But this also means that the potential for fire prevention measures should be large. At least some measures are straightforward albeit costly to implement, as in the case of ignitions caused by forestry machines [69]. For example, the cost of idling a single modern forestry machine is estimated at around 200 US $/h (D. Rönnblom, personal communication). Preventive measures directed at the general public in the form of information and restrictions may be cheap but their efficacy is less clear [5]. It should be noted that the use of open burning in the terrain is still allowed in Sweden except in case of very high fire danger, in contrast to neighboring Finland and Norway, which both have a blanket fire ban during summer.

In conclusion, we show that fire occurrence and burned area (whether antropogenic or lightning-ignited) in Sweden are strongly related to regional population density, which differ by a factor >100. A consequential trend, therefore, is the ongoing depopulation of rural areas in large parts of the country [57], and particularly in the already sparesly populated North. Lower population of course means fewer ignitions but the net effect of this for area burned will likely be overshaddowed by an increasing proportion of fires growing large. In the long run depopulation leads to lower density of fire stations and decreasing capacity to recruite personnel, which then must be somehow countered by more efficient wildfire suppression. Certain steps in this direction have already been taken in response to the difficult fire-season of 2018: Increased state-provided helicopter support [70], and a requirement for cooperation between municipalities, particularly at the level of command and control [71].

Our results indicate that societal changes such as rural depopulation and cultural shifts are imminently important for wildfire in this intensely managed part of the boreal, and that these factors may warrant more attention worldwide in discussions on future wildfire trends.

CRediT author statement

Johan Sjöström: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Visualization; Writing - original draft; Writing - review & editing. **Anders Granström**: Conceptualization; Formal analysis; Funding acquisition; Methodology; 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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.firesaf.2023.103743.

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