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The performance of wildfire danger indices: A Swedish case study

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ABSTRACT

Wildfire danger indices, or fire danger rating systems, are widely used to inform decision-making related to wildfire risk management. Several studies have compared different indices' performance; however, results have shown that this varies in different parts of the world. Further, many of these indices have not yet been assessed for Swedish conditions. In this study, four different weather-based wildfire danger indices have been investigated by comparing their performance in predicting wildfire activity when applied to Swedish conditions. Daily index values were calculated for seven Swedish geographical regions during 2018, a year with high wildfire activity. The aim of the study has been to rank the ability of the methods to predict wildfire danger in Sweden which is why a single year with high fire frequency has been chosen as the "test year". The daily index values were compared to wildfire incident data, i.e.: *fire and rescue service personnel hours* spent on a fire, *total burned area*, and *number of daily fire ignitions*. Kendall's $\mathrm{Tau_b}$ correlation coefficient was calculated for each index and wildfire data in the seven regions. The indices were then ranked based on the strength of the correlation. It was found that three of the indices (those based on cumulative weather data) exhibited a significantly higher correlation with wildfire activity than the fourth index. Further, the Fire Weather Index, developed in Canada and currently used in Sweden, was identified as a good choice for Swedish conditions when compared to the three other indices.

1. Introduction

In Sweden, where forests cover 69 % of the total surface area, wildfires have been occurring naturally for hundreds of years (Niklasson and Granstrom, 2000; SCB Statistics Sweden, 2019). Sweden has a forested area of 280 000 km^2. This is the second largest forested area in Europe after Russia (SCB Statistics Sweden, 2019). This has resulted in the forest industry accounting for 9–12 % of employment and exports in Sweden (Industries, 2022). Fire is a natural part of many Swedish forests and some ecosystems and plants actually need fire to regenerate (Nilsson, 2005). When wildfires grow beyond control they can, however, lead to negative consequences, both economic and environmental as well as injury and loss of human lives (San-Miguel-Ayanz et al., 2017). Compared to other wildfire seasons in Sweden during the past decade, the wildfires across large parts of the country during the summer of 2018, were extreme both in terms of area burned and the resources needed in order to control the fires (Sjöström and Granström, 2020). These recent wildfires have sparked a debate on the preparedness and capability of Swedish authorities with respect to large wildfires (Björklund, 2018; Sjökvist, 2015).

One step in wildfire management activities is to identify when and where the wildfire danger is high. Indeed, being able to assess the wildfire danger adequately is a prerequisite for informed prevention and preparedness efforts. Wildfire danger indices can be used to assess the danger by predicting wildfire activity (de Groot et al., 2015). There are currently many different wildfire danger indices, also called fire danger rating systems, in use worldwide (Van Wagner, 1987; Groisman et al., 2007; Bradshaw et al., 1978). For the sake of clarity, the term 'wildfire danger index' will be used in this paper instead of the more common term 'fire danger index' to emphasise that we are studying wildfire danger and not fire danger in general. Wildfire danger indices calculate values for specific geographic areas, the values indicating the level of wildfire danger. Given that the numeric output of these indices is on different scales, it can be difficult to compare values between different indices, as well as understand what a specific value actually means in term of wildfire danger for a specific location. Some wildfire danger indices take into account fuel type, topography and weather into account, while other systems only include weather parameters (de Jong et al., 2016).

When the terms 'risk', 'hazard' and 'danger' are applied in fire research, there can be some confusion as to what is meant by the individual concepts and how they relate to each other. The wide range of

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inconsistent definitions within the literature has been highlighted by previous studies (Bachmann, 2001; Hardy, 2005). The lack of clear terminology has led to the terms 'fire danger' and 'fire hazard' being used interchangeably in some studies (Laneve et al., 2020), while others argue that these are different concepts (Bachmann, 2001). In some cases, 'fire hazard' is defined as being independent of weather (Hardy, 2005; United Nations, 1986), while weather is specifically included in other cases (Laneve et al., 2020). Further confusion is added when talking about 'risk', a term which is sometimes loosely used and defined in different ways by practitioners, academics and other stakeholders (Hansson, 2010). In Sweden, the 'fire danger' index values are used to assess what is typically termed 'fire risk' (Bachmann, 2001; Swedish Civil Contingencies, 2022).

In this study, 'risk' is defined as the combination of probability and consequence as defined by Kaplan and Garrick, (1981). In the context of wildland fire, 'wildland fire risk' is therefore the combination of the probability of a wildfire occurring in a specific place, under specific circumstances and the potential outcome that affects something or someone (Bachmann, 2001). The definition of 'hazard' according to Bachmann (Bachmann, 2001) has been used where 'hazard' is considered as 'as [a] process with undesirable outcomes', i.e. in this case the wildfire itself. The concept of 'fire danger' employed in this paper is that defined by the United Nations Food and Agricultural Organization (FAO) as a term which 'expresses an assessment of both fixed and variable factors of the environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact; often expressed as an index' (United Nations, 1986). Therefore, considering these terms in the literature, the concept investigated in this work is best defined as 'fire danger' or 'wildfire danger' and these terms will be used throughout.

Community planning and preparedness related to wildfire management strategies in Sweden rely partly on wildfire danger index values; for example, the extent in time and space of aerial wildfire monitoring is determined based in only part on wildfire danger index values (Swedish Civil Contingencies Agency and Skogsbrandbevakning med flyg – Myndigheten för samhällsskydd och beredskaps inriktning från 2020 [Wildfire surveillance by airplane – Guidelines for, , 2020), and local fire bans are based in part on wildfire danger index values (Swedish Civil Contingencies Agency, 2019). In the forest industry, the indices are also closely monitored. High wildland fire danger values may bring about temporary changes in activities by the forest industry, such as avoiding particularly dry areas or refraining from using machinery that may cause sparks as well as working during night time when temperatures are lower and relative humidity is higher (Skogforsk, Riskhantering avseende brand vid skogsarbete - Branschgemensamma riktlinjer [Fire risk management regarding forestry activities – Industry wide guidelines] S.S.F.R. Institute), Editor., 2021). When index values are high, SMHI (Swedish Meteorological and Hydrological Institute) issues warnings that are communicated to the public. Further, there is a platform available for Fire and Rescue Services (FRS) and other relevant authorities, which includes 'fire risk' index values for the coming 5 days as well as weather forecasts (Swedish Civil Contingencies, 2022).

The wildfire danger index currently used in Sweden is the Fire Weather Index (FWI), developed as part of the Canadian Forest Fire Danger Rating System (Van Wagner, 1987; Stocks et al., 1989). This index, developed principally from field experiments in local Canadian pine fuel types, illustrates the daily wildfire danger based on local meteorological input data (Van Wagner, 1987). Air temperature, precipitation, wind and relative humidity are the meteorological parameters required to calculate the FWI (Van Wagner and Pickett, 1985). Although the FWI was developed based on certain Canadian fuels, it is being used all over the world for varying conditions and fuels, including Sweden. The index has not been adapted to any particular Swedish fuels, although specific Swedish 'fire risk' thresholds were determined by Gardelin, (1997), which divide FWI values into six (6) different 'fire risk' classes (class 1 being a very small fire risk, class 6 being an extreme fire risk). More recently, a new set of thresholds have been proposed and implemented (Sjöström and Granström, 2020). Although fire risk classes have been determined for the Swedish application of the FWI, its adoption in the late 1990′s was based largely on the fact that it had been developed for boreal forests and not that it had been found to be particularly applicable to Swedish forests and land use. Therefore, there remains a need to study the effectiveness of the FWI in Sweden in comparison to other wildfire danger indices that have been developed for other conditions.

Several studies comparing indices have been conducted for different regions including Australia (Matthews, 2009), Austria (Arpaci et al., 2013), Finland (Tanskanen and Venäläinen, 2008), Sardinia in Italy (Sirca et al., 2018) and a selection of regions in France, Spain and Italy (Viegas et al., 2000). In these studies, the rankings of the most effective indices differed in the different geographical locations. These results suggest that the indices' performance may vary based on local characteristics such as vegetation, climate and demographic variables. Although some studies have been conducted specifically in Sweden, these have been focused on the FWI, not comparing it to other indices currently used around the world. Gardelin, (1997) compared the FWI to wildfire data (occurrence and burnt area) in Kalmar and Jönköping during 1989–1994 and found that the index performed well in illustrating the wildfire activity. Further, Sjöström and Granström, (2020) studied the relationship between the FWI and wildfire incidence and burned area. Despite this important work, there are several wildfire danger indices which have not yet been assessed for Swedish conditions and no study has previously presented how the FWI might perform in Sweden relative to other current alternatives. Indeed, the geographical sensitivity indicated by previous studies (Matthews, 2009; Arpaci et al., 2013; Tanskanen and Venäläinen, 2008; Sirca et al., 2018; Viegas et al., 2000) emphasizes the need for such a comparison specifically for Sweden.

The objective of this study is, therefore, to assess established wildfire danger indices by comparing their performance in predicting wildfire activity when applied to Swedish conditions. The comparison relies on the analysis of indices' performance in seven geographical regions in Sweden by ranking them in each region according to correlation coefficients between wildfire activity data and index values. The analysis also considers whether there is geographical variation in the indices' performance based on climatic region, as well as an analysis of which aspects of the wildfire data (for example burned area or number of ignitions) that the indices reflect the best. The selection of indices that have been compared was based on the findings of a literature review which was conducted with the specific aim of identifying existing wildfire danger indices that could potentially be used in Sweden (Pagnon Eriksson and Johansson, 2020). The study assessed 509 individual search results and suggested four prospective indices that should be compared: the Fire Weather Index (FWI), the Keetch-Byram Drought Index (KBDI), the Fosberg Fire Weather Index (FFWI) and the Nesterov Index.

Fig. 1 shows fire statistical data from The Swedish Civil Contingencies Agency (MSB). The data indicated that the number of wildfires each year in Sweden has fluctuated around 5000 ± 3000 fires per year, see Fig. 1a. The size of the fires has, however, varied considerably over time, with peaks occurring in recent years for 2014 and 2018, see Fig. 1b. Given the relatively low size of fires in Sweden most years, most detailed data is available for the 2018 fire season. Therefore, 2018 was selected as the focus for this case study to evaluate the performance of wildfire danger indices in Sweden. Given that the aim of the study is to rank the ability of a selection of fire danger indices to predict wildfire danger in Sweden, it was determined that use of a single year with high fire frequency would suffice as "test year".

2. Methods and data

The methodology can be broken into three main parts: the selection of the geographical areas in which the indices would be assessed; the

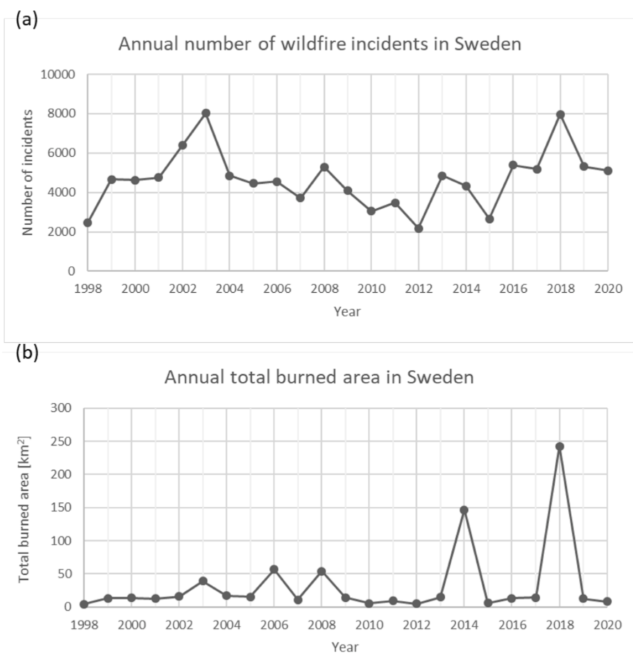

Fig. 1. Overview of wildfire statistics in Sweden during 1998–2020. (a) annual number of incidents, (b) annual burned area. Data from MSB's national online database (ida.msb.se). This data includes both forest fires and grass fires.

data collection of weather data to calculate daily index values in each region as well as wildfire data; and an analysis of the performance of indices using Kendall's Tau$_b$ correlation coefficient.

2.1. The studied wildfire danger indices

There are many different wildfire danger indices available worldwide (de Groot et al., 2015). A recent collation of 'wildfire risk indices' identified some eleven assessment methods or wildfire danger indices, of which the four used in this paper were identified as most promising for Sweden (Pagnon Eriksson and Johansson, 2020). Table 1 presents these four indices in terms of input data, index characteristics and source. The table focusses on the input data required and the characteristics of the various indices. References are provided in the table for each index, indicating full details of the calculation methods can be found.

Table 1
The four selected wildfire risk indices and their respective characteristics, based on Pagnon Eriksson and Johansson (2020). T = temperature, RH = relative humidity, P = precipitation and U = wind speed. FWI (Fire Weather Index), KBDI (Keetch-Byram Drought Index), FFWI (Fosberg Fire Weather Index), ISI (Initial Spread Index), BUI (Build-Up Index).

Name	Input data	Characteristics	References
FWI	T, RH and U (all at noon), P (during the last 24 h), month and previous days' index values.	Cumulative index, different sub-components that characterise different fire aspects (ISI and BUI), shown to perform well in previous studies.	Van Wagner, (1987); de Groot, (1987)
KBDI	T (daily max), P (during the last 24 h), study area's mean annual P and previous days' index values.	Cumulative index, used as a sub-component in several other indices as it illustrates the effect of long-term drought, shown to perform well in previous studies.	Keetch et al., (1968)
FFWI	T (daily max), U (daily average) and RH (daily minimum).	Non-cumulative index, illustrates impacts of short-term weather on fire potential, shown to perform well in previous studies.	Goodrick, (2002)
Nesterov	T (daily max), dew point T or RH and P (during the last 24 h).	Cumulative index, shown to perform well in previous studies.	Groisman et al., (2007)

The FWI, KBDI and Nesterov index are all cumulative indices (Van Wagner, 1987; Groisman et al., 2007; Keetch et al., 1968). This means that these indices include details of index values from previous days. Therefore, these indices can include and illustrate the effect of long-term weather, such as the effect of several consecutive days without rain or with high temperatures. The FFWI, on the other hand, is not a cumulative index and does not contain information from previous index values (Goodrick, 2002). This makes the FFWI interesting to include in the comparison in order to see whether this has a significant impact on the performance of the index, compared to the other cumulative indices.

2.2. Wildfire data

In this study, wildfires are defined as either naturally occurring or human-caused (unplanned or uncontrolled) fires that burn vegetation. Therefore, wildfires in this study include both forest fires and grass fires. Although there are clear differences between forest fires and grass fires, it has been deemed relevant to group them together, to focus on the relative predictive potential of the fire danger indices independent of the type of wildfire. For this study, the Swedish Civil Contingencies Agency (MSB), which is the national fire safety regulatory authority in Sweden, provided access to wildfire data recorded during 2018 in all of Sweden. The details of the data are protected by Swedish law but access to the data may be granted upon request to MSB, the general contents of the data and how it was managed are described in this section.

Every time the FRS in Sweden respond to an incident, data from the incident is recorded in a report that is collected by MSB, the Incident Report. The data in the report includes information such as: date of the fire start and finish, coordinates, the time at which the FRS were alerted, the time at which the rescue operation ended, the total amount of hours that fire and rescue personnel worked on the operation, area burned, cause of fire and first ignited object. In such reports, the incident commander has the option to add information after the operation, such as a description of the fire extent or comments regarding the potential fire cause or FRS response, in a comment section (MSB, 2019).

Wildfires that occurred within the 60 km × 60 km area surrounding each of the seven weather stations, were selected from the MSB wildfire dataset. This resulted in a total of 578 wildfires within the seven study areas, see Table 2. The incident report data for each wildfire was obtained from MSB and each report was manually examined. Since burned area is estimated by the incident commander and manually entered into the report, this was compared with the description of the incident made by the Incident Commander in the comments field. In several cases, burned area was adjusted to match the description in the comments. Further, several data points were discarded based on information found in the comments field using the following criteria: the fire was planned and controlled (usually controlled burning of grass or a campfire), the fire did not spread to any vegetation (for example, the burning of paper on a school playground) or no fire could be found when the FRS arrived at the scene. Finally, there were some instances of wildfires that had been recorded twice – possibly because two different FRS organisations responded to the same fire, each submitting an incident report – meaning that one of the reports was removed as a duplicate. A total of 513 unique fire incidents were included in the final wildfire database.

In order to assess the calculated wildfire danger indices' performance, values for each index were compared to actual wildfire activity. Three parameters from the wildfire data were selected as representative measurements of wildfire activity. The three parameters are:

1) *FRS personnel hours* spent on a fire
2) *Total burned area*
3) *Number of wildfire ignitions* on a given day

Table 2
The seven studied regions (60 km × 60 km area) and total of wildfire incidents in each region during 2018.

	Vidsel	Delsbo	Älvdalen	Karlstad	Visby	Växjö	Malmö
Number of fires in 2018	15	34	28	100	25	91	220

Personnel hours was chosen as a measurement of wildfire activity as they provide an indication of the efforts and resources needed to respond to a particular wildfire. Recently Penney et al., (2020), conducted a study of which activities might be included in an FRS wildfire response, indicating correctly that *personnel hours* is a catch all term including all hours associated with the incident (e.g. travel to and from the event, active firefighting, observations and rest during and event). Nonetheless, this parameter gives a good indication of the relative significance of the event. When a high number of hours was required, this is expected to be reflected by a high wildfire danger index value. The same applies to *total burned area*. A large burned area is expected to be correlated with high wildfire danger. Although *personnel hours* and *burned area* both reflect similar aspects of wildfire danger, they were studied as two separate parameters as they can differ greatly in some cases. There could for instance be incidents when the burned area is high, but the personnel hours are low because FRS personnel arrived to the fire in its final phases; or where a fast spreading grassfire leads to a large area but does not require particularly large extinguishing efforts. Further, personnel hours are an important parameter to include as they are an indication of the strain that is put on local FRS. When the personnel hours are high this means that fewer resources are available for other types of incidents that the FRS personnel may need to respond to the same period of time (e.g. road accidents, building fires or health emergencies). This aspect is not captured by the burn area. The two first parameters are related to the impacts of fire and the difficulty of control while the third parameter is more linked to the ease of ignition. The *number of wildfire ignitions* on a given day was chosen as the third parameter as on days with high index values, wildfires are expected to ignite more often than on days with low index values. On days when more than one wildfire occurred within a region, personnel hours and total burned area were summed up to reflect the total contribution to wildfire danger from those two parameters for that particular day. For example, if two fires (A and B) start on the same day and burn 1 ha and 5 ha respectively, the total burned area of that day is 6 ha.

It should be noted that the probability of an ignition occurring is dependent on the ignitability of the vegetation (based on fuel moisture and weather), but also on the presence of an ignition source itself. The ignition source could for example be intentional or unintentional human ignition, sparks from train tracks or lightning. The randomness and unpredictability of the presence of an ignition source contributes to the uncertainty inherent to wildfire danger assessment.

2.3. Geographical scope

The geographical scope of the study covers seven different regions in Sweden. These were selected based on two criteria related to weather and climate. Firstly, each region was selected due to its proximity to a weather station providing geographically relevant weather data. In this context proximate was interpreted as within an area of 60 km × 60 km with the weather station at its centre. The criteria for selecting a weather station was that it had to record measurements for all relevant weather parameters. The relevant parameters are those required to calculate the four wildfire danger indices, namely temperature, precipitation, relative humidity, and wind speed. All of the recorded measurements were collected by the Swedish Meteorological and Hydrological Institute (SMHI). Some weather stations in Sweden do not measure all the parameters or were not active during the specific period of 2018 included in this study.

The second criteria was that the stations should cover a variety of regions of Sweden in order to better represent the climate variation throughout the country. Beck et al. (2018) have produced an updated world map with Köppen-Geiger climate regions based on long-term observations (1980–2016) of precipitation and temperature. According to their study, Sweden contains three climatic regions: Dfb in the south (D = continental, f = without dry season, b = warm summer) Dfc in the north (D = continental, f = without dry season, c = cold summer) and ET in the far north (E = polar, T = tundra). The ET region in the northernmost parts of Sweden covers a limited area with very few wildfires (Sjöström and Granström, 2020). Therefore, the analysis was focused only on the Dfb and Dfc regions. Fig. 2 shows the geographical locations of the weather stations within the two climatic regions that were selected were: Vidsel, Delsbo, Älvdalen, Karlstad, Visby, Växjö and Malmö. The northern most weather stations, Älvdalen, Delsbo and Vidsel, are in the Dfc climatic region (i.e. cold, without dry season, cold summer). The remaining four weather stations, Visby, Karlstad, Malmö and Växjö, are in the Dfb climatic region (cold, without dry season, warm summer).

2.4. Weather data

Weather observation data was retrieved from SMHI's public database (Swedish Meteorological, 2022). Although weather stations were selected to ensure that data was as complete as possible, there were some gaps that required adjustment of the data. The reason for adjusting the data instead of leaving days with missing data 'empty' is that three of the indices (FWI, KBDI and Nesterov) are cumulative and require index data from the previous days. Depending on the gap, different data generation strategies were used. The FWI, for example, requires weather observations at noon and in some cases, data was missing at that exact time. When such data was missing, data from the nearest hour was selected to replace the missing data, e.g. on May 15, 2018 wind speed data was missing for noon in Malmö. This data could be estimated using the wind speed data for 9 am on the same day, as shown in Table 3 (if such data was available). When data was missing for an entire day, an average value was calculated using data from the days immediately before and immediately after the missing data. In a few cases when data was missing for several days, data from the nearest weather station was used rather than generating data from measurements before and after the gap. When data from a neighbouring station was used, the distance between the two stations never exceeded 50 km. The general weather within such a distance was compared for the two weather stations before and after the gap to confirm that there was agreement in weather measurements.

The stations of Visby and Delsbo are those for which data from the furthest stations was used to replace missing data. The station in Visby had no observations for wind speed during July 28 – August 9 and no observations for humidity during July 21 – August 9. Data was retrieved from the nearest weather station, which was in Fårösund, 45 km away. In Fårösund, during the months before the missing data, wind speed and relative humidity was similar between Visby and Fårösund. In Delsbo, wind speed was missing during September 20 – October 29 and data was retrieved from the nearest station, Kuggören, 50 km away. As Kuggören is close to the coast, it is typically windier than Delsbo. However, the data was only used for a limited time which, furthermore, occurs after the wildfire season. The effect of using the wind data from Kuggören was investigated by comparing the difference in correlations which are described in section 2.5. The correlations calculated when using the wind data from Kuggören were compared to correlations from using wind data from Kuggören minus the average wind difference between Kuggören and Delsbo. It was found that the differences in correlation

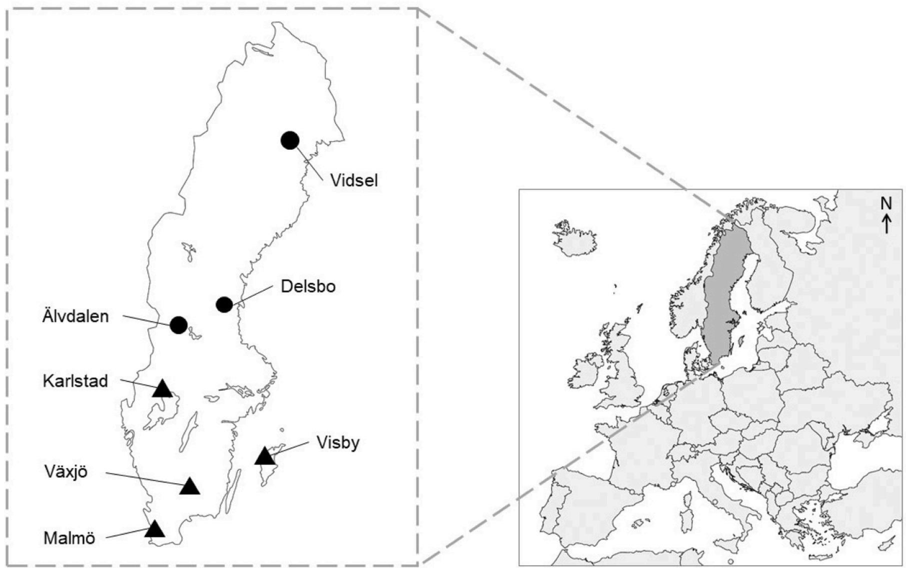

Fig. 2. Map of Sweden showing the placement of the seven selected study regions. Circles indicate regions that are in the Dfc climatic region (cold, without dry season, cold summer) and triangles indicate regions in the Dfb (cold, without dry season, warm summer). The map of Europe, on the right, was created using map chart.net.

Table 3
Weather observations for the Malmö region from May 12, 2018 to May 16, 2018. Data in the "at noon" columns is based on measurements at noon unless otherwise indicated. T = temperature, RH = relative humidity, P = precipitation and U = wind speed. FWI = Fire Weather Index, KBDI = Keetch-Byram Drought Index, FFWI = Fosberg Fire Weather Index.

Input data for index:	FFWI, KBDI, Nesterov	FWI	FFWI	FWI	FFWI, Nesterov	FWI	FWI, KBDI, Nesterov	KBDI – annual mean
Date	***T*** **(°C) daily max**	***T*** **(°C) at noon**	***U*** **(m/s) daily avg**	***U*** **(m/s) at noon**	***RH*** **(%) daily min**	***RH*** **(%) at noon**	***P*** **(mm) last 24 h**	***P*** **(mm) 2014–2018**
12/05/2018	18.5	17.6	1.0	0.9	63	67	0	724.1
13/05/2018	24.6	24	3.0	6.4	29	29	0	
14/05/2018	27	26.1	2.0	3.9	31	38	0	
15/05/2018	23.5	23	0.6	2[a]	41	46[a]	0	
16/05/2018	26.9	26	2.1	3.8	28	32	0	

[a] Observations for these values were missing at noon and values from the closest available time, i.e. 9:00 AM, are given.

were so small that they did not have an impact on the analysis of the results. In other words, the final ranking of indices was the same for both wind data sets. Therefore, the use of wind data from Kuggören was determined to be acceptable for the period in question. Wind speed is only required to calculate the FWI and FFWI while relative humidity is required for the FWI, FFWI and Nesterov index.

The weather data for each station was used to calculate daily wildfire danger indices for 2018. Tanskanen and Venäläinen (2008) used data from weather stations, in a similar manner to this study; choosing to let the index be representative of an area of 140 km × 140 km with each weather station at its centre. In other previous studies, the area has been dependent on the grid resolution of the weather data, ranging from very large (approximately 277 km × 277 km (Venäläinen et al., 2014) to much smaller areas (approximately 4 km × 4 km (Pinto et al., 2018) and 2 km × 2 km (de Jong et al., 2016). In yet other studies, indices were calculated for different ecoregions of the study area where weather data from one or more weather station within the ecoregion was used to calculate an index which could represent the entire ecoregion (Arpaci et al., 2013; Sirca et al., 2018). In these studies, calculated indices represented areas of varying sizes.

For this study, it was determined that an index value could represent an area of 60 km × 60 km with the weather station at the centre of this area. This is a compromise between the very large and very small grids applied in previous studies. The choice of the grid size facilitated comparison between index values and wildfire activity within that area, i.e. a 60 km × 60 km-area was large enough to include data points for wildfires during 2018, yet small enough to ensure data availability for the weather while maintaining proximity to alternate weather stations to fill in missing data.

2.5. Statistical analysis

A common measure is needed to evaluate the four wildfire danger indices' performances with respect to data from past wildfires as well as to compare them to each other. There does not seem to be any consensus on which method is the best suited for such comparison (Arpaci et al., 2013; Sirca et al., 2018). Several different methods and tests, including percentile analysis, regression analysis and Spearman's rank correlation, have previously been used to study the accuracy of fire danger indices (de Jong et al., 2016; Tanskanen and Venäläinen, 2008; Sirca et al., 2018). Eastaugh, Arpaci and Vacik (2012) have shown that non-parametric methods tend to be better indicators of correlation than parametric methods. Therefore, in this study, Kendall's Tau_b correlation a non-parametric correlation measure has been chosen (Puka, L., Kendall's Tau, in International Encyclopedia of Statistical Science, M. Lovric, Editor, 2011). This method provides a measure of the strength of association and direction of the relationship between two variables (for instance FWI and total burned area, or KBDI and number of hours required to put out a wildfire). Variables must be either ordinal or continuous. The variables must also be paired observations in order to be ranked. An advantage of using Kendall's Tau_b is that it accounts for tied ranks. It was calculated using the following relationship (Puka, L., Kendall's Tau, in International Encyclopedia of Statistical Science, M. Lovric, Editor, 2011):

$$Tau_b = \frac{C - D}{\sqrt{(C + D + t_A)(C + D + t_B)}}$$

where C and D are the numbers of concordant and discordant pairs respectively. The number of tied pairs for variables A and B are denoted t_A and t_B.

Kendall's Tau_b ranges from -1 to 1. If the value is zero, there is no relationship between the variables. Values of -1 and 1 respectively indicate a perfect negative or positive correlation. The correlation coefficients were calculated using the statistics software SPSS. Input data is exemplified in Table 4.

To determine whether the correlation values are significantly different from each other, hypothesis testing was conducted using two-tailed Z-tests, at a significance level of $\alpha = 0.05$.

3. Results

3.1. Calculated wildfire danger indices

The calculated wildfire danger index values for each of the seven regions during 2018 are presented in Fig. 3. All indices but one, the FFWI, increase leading up to the summer and decrease after the summer. This relates well with the months during which wildfire activity is high compared to the rest of the year in Sweden, as shown in a study by Sjöström and Granström (2020). They could see that the frequency of grassfires culminates around April while the majority of forest fires occur in May, June and July. The first and last few months of the year have much lower values in Fig. 3. The FFWI varies noticeably more on a daily basis than the other indices and the increase in values during the summer months is not as clear as for the other indices.

The highest values for each index occurred in different regions. For the FWI, Vidsel saw the highest value while Malmö saw the highest values of the Nesterov index and KBDI, and the highest FFWI values occurred in Visby. Interestingly, the Nesterov index and KBDI indicated relatively low values in Vidsel, which is where the highest FWI was calculated among the seven regions for 2018.

3.2. Comparison of wildfire danger indices based on correlation coefficient

The results of the Kendall Tau_b correlation coefficients are shown in Table 5. The values indicate that for each region, the index with the relatively strongest correlation with the wildfire activity parameters varied depending on the region. All but two sets of pairs (FFWI in Delsbo and Vidsel) have a statistically significant and positive correlation between the wildfire danger indices and the fire parameters. This indicates, as expected, that a higher calculated wildfire danger represents a higher number of personnel hours required at an incident, a larger fire area and a higher number of daily fire ignitions. In Delsbo and Vidsel, the correlations between the FFWI and the fire parameters were not significant. Note that the index with the highest correlation for 'personnel hours' also had the highest correlation for 'total burned area' and 'number of fires per day'. For instance, in Malmö, the FWI had the highest correlation for 'personnel hours' (0.491) compared to the correlations for Nesterov, KBDI and FFWI (0.452, 0.389 and 0.165 respectively). FWI also had the highest correlation for the two other fire parameters. Further, although the parameter 'number of fires per day' has a higher correlation in comparison to the two other parameters in 20 of the 28 cases, the difference in correlation coefficients for one index within one region are often very small. This can partly be attributed to these three parameters being positively correlated with each other. Because there are differences in how the four indices are calculated, including some input data only being used for certain indices (e.g. wind), it is expected that certain indices will be more adept at capturing different aspects of the wildfire parameters. For instance, the inclusion of wind in the FWI could be expected to result in a higher correlation with burnt area in cases when wind-driven fire spread lead to large burned areas. However, this is shown in these result. There is no clear indication that a particular fire parameter is better correlated with a specific index across the seven regions. In each region, the highest correlation values are indicated in bold in the table.

The indices were ranked based on the highest correlation for each region, 1 indicating the index with the strongest correlation with fire parameters and 4 indicating the index with the weakest correlation. Table 6 contains a summary of the ranking for the various indices and indicates that the FWI has the strongest correlation in four of the seven regions. In those regions where FWI does not rank first, it is always second, suggesting that it may be more effective than the other indices. The FFWI shows the weakest correlation in all regions.

In many regions, the numerical difference between correlation coefficients is very small. In Delsbo for example, the number of fires per day has a correlation of 0.214 with the FWI and 0.225 with the Nesterov index. In order to identify whether the differences in correlation coefficient are statistically significant, hypothesis testing was conducted for all comparisons. In Table 6, rankings based on correlation coefficients that are significantly different from the others are indicated with two asterisks (**). Hypothesis testing has showed that the order of ranking for FWI, Nesterov and KBDI is not statistically significant in most of the regions. It has, however, been established for all regions that FFWI ranks in fourth place. In Malmö, it has also been established that KBDI ranks third as its correlation coefficient is significantly different from the other indices. Looking at the northern region Dfc (cold, without dry season, cold summer), to which Vidsel, Delsbo and Älvsdalen belong, we can see that each region has a different index that ranks first in Table 6. In the other climatic region, Dfb (cold, without dry season, warm summer), three regions have the same ranking, with the FWI in first place, namely Karlstad, Växjö and Malmö. However, Visby, which also belongs to that climatic region, the ranking is different. There does not seem to be any clear differences in index ranking based on which climatic region the weather station is placed in.

Table 4
Example of input data in SPSS to calculate correlation coefficients between index and fire parameter. For instance FWI and Personnel hours, FWI and Burned area, FWI and number of fires. Data for the Malmö region, August 1, 2018 to August 5, 2018. FWI = Fire Weather Index.

Date	FWI	Personnel hours	Burned area (m^2)	Number of fires
01/08/2018	7.56	5.37	7	3
02/08/2018	21.25	8.51	400	2
03/08/2018	37.58	2.33	2	1
04/08/2018	32.99	35.28	700	1
05/08/2018	42.12	22.49	759	4

4. Discussion

The predictive performance of four wildfire danger indices was assessed by comparing the correlation coefficients of the calculated wildfire danger indices with actual wildfire data. The correlation was based on data from wildfires that occurred in seven Swedish regions during 2018. This year was chosen as a "test year" due to the relatively high fire frequency ensuring that most data was available for this year. Given that the aim of the study has been to rank the ability of the

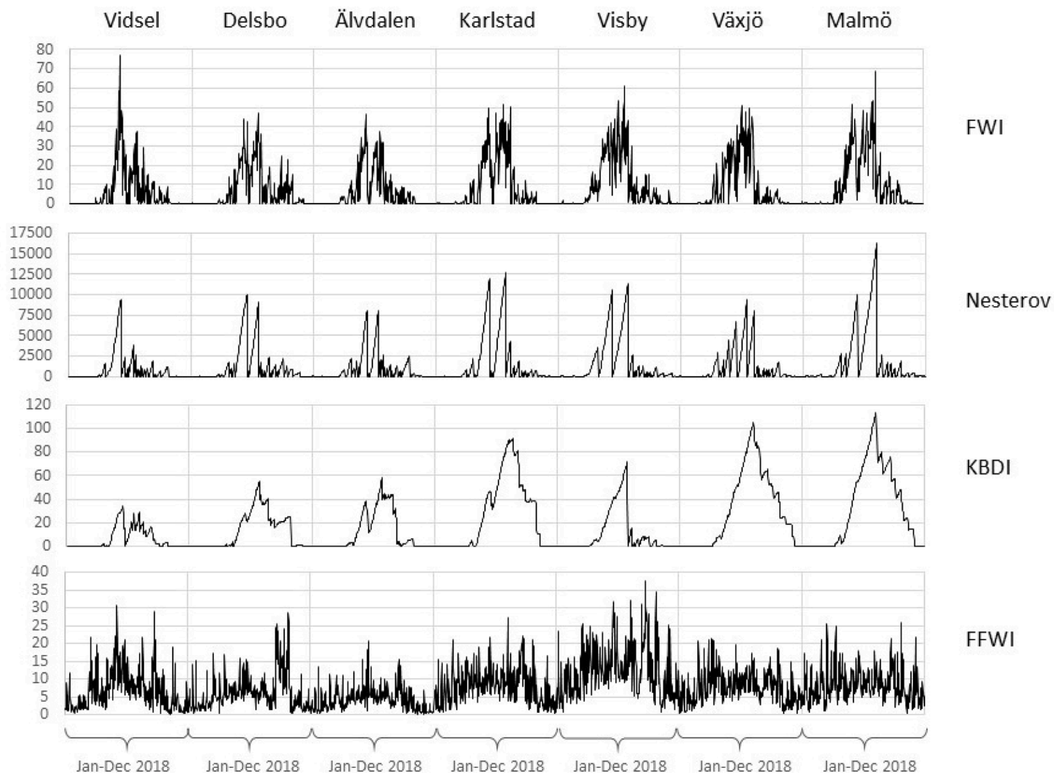

Fig. 3. Results of the four indices calculated based on weather data for 2018 in each of the seven studied regions. The calculations are presented for January-December for each of the studied regions. The regions are presented from North to South. FWI = Fire Weather Index, KBDI = Keetch-Byram Drought Index, FFWI = Fosberg Fire Weather Index.

Table 5
Kendall Tau_b correlation coefficient based on wildfire danger index and wildfire data from 2018. Hours, Area and Fires respectively represent the fire parameters 'Personnel hours', 'Total burned area' and 'Number of fires per day'. The index in bold is the one with the highest correlation values for each region. FWI = Fire Weather Index, KBDI = Keetch-Byram Drought Index, FFWI = Fosberg Fire Weather Index.

	Älvdalen				Malmö			
	FWI	Nesterov	KBDI	FFWI	**FWI**	Nesterov	KBDI	FFWI
Hours	**0.253****	0.228**	0.234**	0.152**	**0.491****	0.452**	0.389**	0.165**
Area	**0.253****	0.228**	0.236**	0.151**	**0.492****	0.455**	0.381**	0.154**
Fires	**0.252****	0.23**	0.233**	0.154**	**0.516****	0.469**	0.402**	0.173**
	Delsbo				**Växjö**			
	FWI	**Nesterov**	KBDI	FFWI	**FWI**	Nesterov	KBDI	FFWI
Hours	0.214**	**0.225****	0.203**	0.071	**0.340****	0.319**	0.294**	0.123**
Area	0.216**	**0.227****	0.205**	0.072	**0.336****	0.317**	0.287**	0.121**
Fires	0.217**	**0.228****	0.208**	0.074	**0.342****	0.322**	0.297**	0.119**
	Visby				**Vidsel**			
	FWI	Nesterov	**KBDI**	FFWI	FWI	Nesterov	**KBDI**	FFWI
Hours	0.221**	0.206**	**0.246****	0.109*	0.147**	0.101*	**0.191****	0.065
Area	0.221**	0.207**	**0.246****	0.108*	0.147**	0.101*	**0.191****	0.065
Fires	0.224**	0.206**	**0.249****	0.112**	0.146**	0.101*	**0.191****	0.064
	Karlstad							
	FWI	Nesterov	KBDI	FFWI				
Hours	**0.397****	0.358**	0.324**	0.222**				
Area	**0.399****	0.361**	0.316**	0.221**				
Fires	**0.401****	0.365**	0.337**	0.229**				

* Indicates when the correlation is statistically significant ($p < 0.05$) while ** Indicates when the correlation is statistically significant ($p < 0.01$). The p-values indicate the statistical significance of the correlation as obtained from SPSS.

methods to predict wildfire danger it was determined that use of a single year would suffice to obtain an indication of performance. The results of this study indicate that all four indices are positively correlated with the studied wildfire parameters (fire and rescue service personnel hours, burned area and number of ignitions). This means that increasing values in wildfire danger indices can be used to indicate a potential increase in

Table 6
Index ranking based on correlation coefficient for the seven studied regions. The regions are presented in order from North to South. FWI = Fire Weather Index, KBDI = Keetch-Byram Drought Index, FFWI = Fosberg Fire Weather Index.

Index/Region	Vidsel	Delsbo	Älvdalen	Karlstad	Visby	Växjö	Malmö
FWI	2	2	1	1*	2	1	1
Nesterov	3	1	3	2	3	2	2
KBDI	1	3	2	3*	1	3	3**
FFWI	4**	4**	4**	4**	4**	4**	4**

* Indicates significantly different correlation between two indices.
** Indicates when the ranking is statistically significant (p = 0.05).

wildfire activity.

The indices were ranked based on the strength of their correlation coefficient for each region. Hypothesis testing showed that the FFWI had a significantly lower correlation coefficient in all of the regions. A particularity of the FFWI is that it is a non-cumulative index (Goodrick, 2002). It is argued that because the index changes on a daily basis regardless of the weather conditions on previous days it is not able to reflect the increase in wildfire danger that occurs after several days of warm and/or dry weather, resulting in lower correlations than the other cumulative indices. The non-cumulative nature of the index resulting in it being less effective at predicting wildfire danger is supported by some previous studies. For example, the FFWI did not perform well compared to other indices in a study done in Austria (Arpaci et al., 2013). Another study, in which five indices were compared in southern Europe, also found that the only non-cumulative index in their study performed poorly in relation to the other cumulative indices (Viegas et al., 2000). However there is a case, in Sardinia, in which the FFWI did correlate well with wildfire risk (Sirca et al., 2018), indicating that it performs better in some weather regions than others.

Although the FFWI clearly ranks fourth, the difference between the FWI, KBDI and Nesterov index is more subtle. Each of the three indices rank first in at least one of the regions. Apart from in Karlstad and Malmö, where hypothesis testing showed that the FWI has a significantly higher correlation than the KBDI, it is not possible to determine a statistically significant 'winner' among these indices. However, we can notice that the FWI ranks first in the majority of the regions, and the FWI is in second place for all those cases where it is not first. Similarly, the FWI was one of the two highest ranking indices, along with the IFI (Integrated Fire Index) developed in Sardinia, in a study by Sirca et al. (2018). The FWI also performed well in a study in Finland (Tanskanen and Venäläinen, 2008); however, it could not be determined if it was better than the other studied indices.

The results in this study suggest that the FWI might overall be a slightly better index than the KBDI and Nesterov index for Swedish conditions, although the differences in ranking are not statistically significant in any case in comparison to the Nesterov index. The Nesterov index was actually the index that had the overall best performance in a study in the Mediterranean region (Viegas et al., 2000).

Because previous comparative studies have not used Kendall's Tau_b correlation coefficients in their analysis (Gardelin, 1997; Matthews, 2009; Arpaci et al., 2013; Tanskanen and Venäläinen, 2008; Sirca et al., 2018), the Tau_bvalues calculated in this study cannot be directly compared with this previous work. Nevertheless, it is important to discuss the numerical value of the calculated correlation coefficients. The Tau_b values range from 0.064 (FFWI and number of fire ignition in Vidsel) to 0.516 (FWI and number of fire ignitions in Malmö). Knowing that a Kendall Tau_b of 1.0 indicates a perfect positive correlation, it is interesting to reflect on the correlation values themselves.

One reason for the correlations not being higher is the inclusion of non-fire days in the dataset. Days with high wildfire danger indices but no fire ignition will have zero-values for the three wildfire parameters. Fig. 4 illustrates this concept for a range of FWI-values and personnel hours. In the figure, each circle represents one day in 2018. Only days which include a fire ignition will have personnel hours associated with the circle, although all days have a FWI. Since non-fire days are included in the data to take into account how well the indices perform for all days, this naturally results in lower correlation coefficients, i.e. some high FWI days have low predictive quality. Moreover, this explains why the correlation coefficients close to large cities, like Malmö and Karlstad, are higher than in rural areas, like Vidsel and Visby; as many fires start from human activity (intentional or unintentional), which means that certain areas will have more fire days (and fewer non-fire days) than others. When there are fewer non-fire days, as is the case in Malmö and Karlstad, the correlations for all four of the indices are higher. This is one reason for the focus on comparing the correlation between indices in the same area rather than between geographical areas. It should also be noted that public warnings regarding wildfire danger and fire bans might reduce the number of ignitions during high wildfire danger index days because people are more careful than if no fire bans or warnings were issued. This may result in fewer fires on high wildfire danger days which in turn contributes to lower correlations. However, this affects the four indices equally, therefore not changing the ranking of the indices.

Regarding weather data quality, it should be noted that the indices are based on meteorological records which were not always complete.

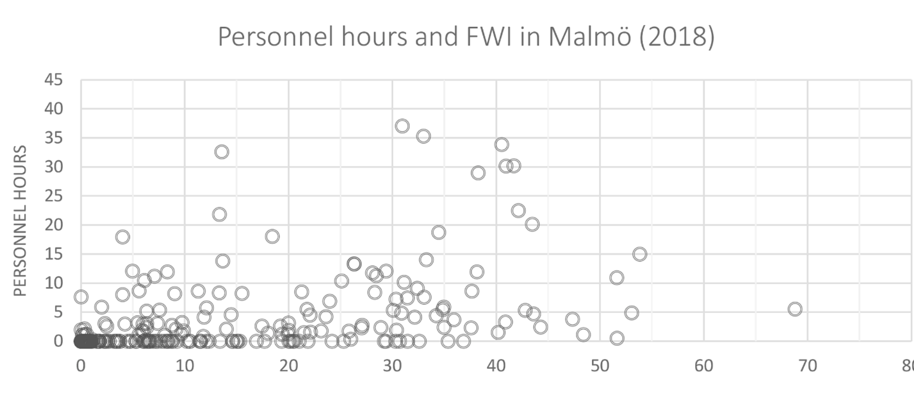

Fig. 4. Scatter plot of the number of FRS personnel hours spent on a wildfire incident in relation to the FWI. The data is for the Malmö region, during 2018. FRS = Fire and Rescue Service, FWI = Fire Weather Index.

Different methods for handling weather data gaps were used depending on the size of the gap. An assumption was also made that calculated indices represent an area of 60 km × 60 km, which does not consider local weather variations. However, because the same weather data and assumption of uniform weather in the 60 km × 60 km-area was applied for all four indices it is not expected to have a significant effect on the ranking of the indices. Further, the indices cannot be expected to achieve a perfect correlation because weather is far from being the only factor influencing the wildfire danger. Fuel types and structures are local factors that highly influence the wildfire danger. Ignition location can influence how quickly a fire is discovered and by extension, how quickly the FRS personnel can commence extinguishment (Sjöström and Granström, 2020). Topography and the resources of the local FRS can also impact how easily a fire can be extinguished.

As wildfire danger is an abstract concept, it is important to consider the internal validity of the three selected wildfire parameters. The indices are assessed based on how well they predict wildfire danger. In this study, FRS personnel hours, burned area and number of ignitions all represent components of wildfire danger. Wildfire danger could also have been represented by wildfire impact, measured in economic losses from damaged properties or timber, or wildfire rate of spread. However, the selection of representative wildfire parameters was limited by the available information for individual wildfire incidents. It is argued that the three chosen parameters satisfactorily cover a number of factors of fire danger as defined by the FAO (United Nations, 1986).

There is, however, an additional uncertainty associated with using personnel hours because it not only depends on how difficult the fire is to extinguish, but can also vary based on the landowner and whether a specific wildfire response methodology has been developed in the region which requires more or less fire service participation in post-fire clean-up. If a fire occurs on land where the landowner has the capability to conduct post-extinguishment or post-fire clean-up within the own organisation (something which is common for large forest owners), this can release the FRS personnel by allowing them to terminate their activities earlier than is otherwise possible. Moreover, data for total burned area from the fire incident data reports was not entirely reliable, which is why all 578 wildfire data points were manually checked with information in the comments field in the report, and adjustments made based on an expert evaluation of the burned area data. Finally, an uncertainty associated with using the wildfire data recorded by MSB is that it only includes fires to which the FRS have responded. This means that fires that have gone undetected and that have been extinguished without the help of the FRS are not included in the wildfire data.

One important aspect to consider when assessing these results is their generalisability. The calculated correlation coefficients and subsequent index rankings are valid for the seven regions specifically included in this study, for this particular year (2018). Regarding spatial generalisability, it can be argued that the regions included in this study provide a good geographical coverage of Sweden as they are distributed in different climatic zones, from the south to the north. It should be noted that the northernmost climatic region (ET, polar tundra) has not been covered. This is partly because the climatic region covers a small area compared to the two others and because few wildfires occur there. This means that the results are not representative for the ET region, which has its own topography and vegetation. Regarding the time scale, we cannot generalise the results over a long time in Sweden. Instead, the results reflect how well the indices performed during 2018. Given that this is a year with a relatively high number of fires and high fire risk, we can assume that at the very least the indices work well when they are most needed. It is possible that a dataset including more years could have resulted in different rankings for the indices included in this study; but it is unlikely that the differences would be significant given that three of the four indices give similar correlations.

5. Conclusions

This study has compared four different wildfire danger indices in seven geographical regions in Sweden for 2018, a highly active wildfire year. The geographical regions represented the two main climate regions in Sweden. All four indices exhibited a positive correlation between the calculated index value and the actual wildfire activity for all seven regions included in the study. Three of the indices are cumulative, meaning that the effect of weather over several days is included in the daily index value, while the fourth index is calculated with daily weather data, independently from previous days. The results indicate that the cumulative indices exhibited a significantly higher positive correlation to wildland fires and appear to be preferable for Swedish conditions. The Fire Weather Index (FWI), developed in Canada, is presently applied in Sweden for wildfire management activities. The work indicates that this index is a good choice amongst the studied indices for Swedish conditions.

It should be noted that weather is not the only parameter that influences the wildfire danger. Any weather-based wildfire danger index should therefore be considered together with other local factors such as fuel types and topography. The consequences and impacts of a wildfire will also depend on external aspects such as FRS access to the fire and the ability of citizens to evacuate. The wildfire danger should therefore also be considered in terms of community vulnerability to influence FRS decisions concerning resource needs and preparedness during the fire season. The correct level of readiness for one FRS in Sweden may not be the same as another simply based on the calculation of a wildfire danger index.

CRediT authorship contribution statement

Claude Pagnon Eriksson: Data curation, Writing - original draft, Formal analysis. **Nils Johansson:** Investigation, Writing - review & editing. **Margaret McNamee:** Conceptualization, Funding acquisition, 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.

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Part of the wildfire data used in the study is publicly available through ida.msb.se. Part of the wildfire data that is not publicly available can be made available upon request to the corresponding author, with the permission from MSB (Swedish Civil Contingencies Agency). Weather data observations used in the study are from SMHI (Swedish Meteorological and Hydrological Institute) and are publicly available for download through http://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=all.

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