Myndigheten för samhällsskydd och beredskap

FORSKNING/STUDIE

Droughts and wildfires in Sweden

past variation and future projection

Faktaruta

Torka och skogsbränder i Sverige: Tidigare variation och framtida projektion

2015-2017

Göteborgs Universitet

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Projektet har gett inblick i den historiska variationen av brandfrekvens och brunnen yta i samband med skogsbrand. Sambanden mellan torrperioder, brandfrekvens och brunnen areal har också studerat samt framtida förändringar i torra perioder och brandrisk.

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Foto: Leif Sandahl, MSB

Publikationsnummer MSB1112 – June 2017
ISBN 978-91-7383-757-6

MSB har beställt och finansierat genomförandet av denna forskningsrapport. Författaren är ensam ansvarig för rapportens innehåll.

Foreword

This report provides a summary of a two-year (2015.5-2017.4) research project funded by the Swedish Civil Contingencies Agency (Myndigheten för samhällsskydd och beredskap: MSB). Wildfires in Sweden are not common or widespread, but the wildfires can be severe. The wildfires in Sweden are largely influenced by human activities, but changes in the climate, i.e. the drought condition, can also affect the fire activities and the fire size (burnt area of a fire). The idea of this project is to support municipalities and county administrative boards in the ongoing climate adaptation work, in relation to the changes in the drought condition and fire activities. Historical changes in the fire frequency and burnt area, and the role played by the drought condition on the changes, are investigated. Future projection of the drought condition and related fire activities is also explored in this project. I hope that the results of this project can provide useful methods and new knowledge in supporting of climate change adaptation.

The report has been developed based on the work conducted at the University of Gothenburg during the past two years. Deliang Chen from the University of Gothenburg and Veiko Lehsten from the Lund University have participated in the project's reference group and have contributed to the development of the project. Mikael Malmqvist from MSB has prepared the project the daily fire records for entire Sweden during the period 1998-2014. The project has received help and support from Åsa Fritzon, Bodil Lundberg and Björn Kerlin from MSB. Ulrika Postgård from MSB has provided much advice for implementation and reporting. I would like to thank all of you.

Finally, I would like to express my special thanks to Deliang Chen who has provided many good suggestions on the project work.

Tinghai Ou
Project leader
Gothenburg, May 2017

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Summary

The fire risk is expected to increase with the increase in the temperature. The overall objective of the project is to improve our understanding of the past changes in droughts and wildfires and to develop a set of future scenarios for droughts and wildfires in Sweden. Wildfires in Sweden are strongly affected by climate and weather condition, and human activities. A large part of the fires is ignited by human activities, and only about 7% of the fires are ignited by lightning. Changes in the human activities have impacts on the fire activities, weekend activities in the non-summer season which have led to more fires in the weekend compare to that during the working days. However, the weekly cycle cannot be found in the summer season. Human activities also influence the fire size. There have been more fires with fire size less than 0.1ha since the 1960s.

Both drought condition on a daily scale, associated with fire weather, and on seasonal to annual scale has effects on the fire frequency. Severe drought year is generally associated with a large annual burnt area. In a historical aspect, there are few years with severe drought condition in Sweden during the past few decades, but the mean condition is not that severe compare to the severe period around the 1970s over the past 80 years.

Drought condition in northern of Sweden is projected to be less severe with low fire risk of a large annual burnt area, but there could be few years with severe drought condition with high fire risk. The drought condition in the southern Sweden could be severe with more severe drought years, especially in the end of 21 century.

Finally, short-term drought, with a dry condition in the upper layer of the forest, is enough for a fire to be ignited and possibly spread with proper weather condition. There could be large area burnt even if the projected long-term drought is not severe. A monitoring system as well as an assessing system, which could provide a potential fire size, is needed for rescue agency. The information can help to decide how much and what kind of efforts is needed to control the fires.

1. Introduction

1.1 Background

Wildfire is a result of interactions between climate/weather, fuels, and people. Fire regime from some regions in Sweden is strongly affected by human activities[1,2]. Climate and weather condition also play an important role in the spatial-temporal variation of fire activities in Sweden[3]. High (Low) fire activity is generally associated with warmer and drier (wetter and cooler) conditions on inter-decadal scale. Warmer and drier climate may also lead to intensive and extensive wildfires[4], which is powerfully demonstrated by the recent recorded wildfire in Sweden for the past 40 years. On inter-seasonal scale, drought is also associated with wildfire, for example, there is a dry period following the snowmelt season in southern Sweden during April to May, which is associated with the peak of the number of fires[5]. Spatial distribution of nature fires, which are ignited by lightning, is strongly affected by the summer precipitation pattern in southern Sweden[6]. As climate change continues, the risk of fires in Sweden are expected to increase by the end of this century with the increasing of temperature[7], and there is a high risk of more frequent large fires due to the projected drier summer in the future[8] , especially in the southern Sweden[9].

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[1] Granstrom, A., 2001: Fire management for biodiversity in the European boreal forest. Scand J Forest Res, 62-69.
[2] Niklasson, M., and A. Granström, 2000: Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology, 81, 1484-1499.
[3] Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman, 2009: Implications of changing climate for global wildland fire. Int J Wildland Fire, 18, 483-507.
[4] Olsson, F., and Coauthors, 2010: A continuous record of fire covering the last 10,500 calendar years from southern - Sweden The role of climate and human activities. Palaeogeogr Palaeocl, 291, 128-141.
[5] Drobyshev, I., M. Niklasson, and H. W. Linderholm, 2012: Forest fire activity in Sweden: Climatic controls and geographical patterns in 20th century. Agr Forest Meteorol, 154, 174-186.
[6] Granstrom, A., 1993: Spatial and Temporal Variation in Lightning Ignitions in Sweden. J Veg Sci, 4, 737-744.
[7] Sjökvist, E., J. A. Mårtensson, J. Sahlberg, J. Andréasson, and K. Hallberg, 2013: Future periods of high risk of forest fires - Analyses of climate scenarios (Framtida perioder med hög risk för skogsbrand - Analyser av klimatscenarier). MSB report, MSB535, 66 PP.
[8] Rummukainen, M., S. Bergstrom, G. Persson, J. Rodhe, and M. Tjernstrom, 2004: The Swedish Regional Climate Modelling Programme, SWECLIM: A review. Ambio, 33, 176-182.
[9] Yang, W., M. Gardelin, J. Olsson, and T. Bosshard, 2015: Multi-variable bias correction: application of forest fire risk in present and future climate in Sweden. Nat Hazard Earth Sys, 15, 2037-2057.

In general, wildfires are not common or widespread in Sweden. Based on interviews and a survey of literature, Leandersson and Lillienberg (2011)[10] pointed out that the preparedness for future fire risk in Sweden today is insufficient to handle larger wildland fires. For example, the severe wildfire in Västmanland, Sweden, which broke out on the afternoon of 31 July 2014, affected over 15,000 hectares; over one thousand people were forced to evacuate from their homes and one man was confirmed to be killed by the fire[11]. A better understanding of the past changes in fires and droughts and their linkages, as well as early information about the droughts and fires in the future, would benefit the government policy maker, rescue agency and local resident.

This postdoctoral project, Droughts and wildfires in Sweden: past variation and future projection, started in May 2015, and has last for two years. The overall aim of this project is to improve our understanding of the past changes in droughts and wildfires and to develop a set of future scenarios for droughts and fires in Sweden. Statistics of historic fire records in Sweden will be presented in Chapter 2. Chapter 3 will show the historical link between drought and wildfire and their future projection.

1.2 Purpose and objective

This project aims to study the variations of wildfires and droughts in Sweden since 1944. The possible relationship between the two will be identified using historic data, which would increase our understanding of the statistics of the past fires and droughts, as well as the role played by the drought in determining the fire statistics. This knowledge will then be used to explore the future droughts projected by global climate models used by IPCC Fifth Assessment Report (AR5) as well as the fire risk, which provides useful information to national agencies and local governments in Sweden in their planning relating to droughts and fires.

The primary objective of the project is to improve our understanding of the past changes in droughts and fires and to develop a set of future scenarios for droughts and fires in Sweden. This includes: selecting one drought index which is best suited for fire related drought study in Sweden; analyzing the historic variation of droughts and fires; understanding the relationship between the droughts and fires; obtaining the information of the future change in the regional climate from global climate models; projecting future change in droughts and fires. Based on this set of information and associated methods and datasets, we will provide support to government policy maker in developing relevant protection and adaptation strategies.

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[10] Leandersson, A., and D. Lillienberg, 2011: Nationell beredskap mot skogsbränder vid eventuellt förändrat klimat, Lunds tekniska högskola and Lunds universitet, Report 5371.

[11] Source from http://en.wikipedia.org/wiki/2014_V%C3%A4stmanland_wildfire#cite_note-OneKilled-3

2. Historical variation of forest fires in Sweden

2.1 Historical records of forest fires

Annual frequency and burnt area of forest fire during the period 1944-1979 are extracted from the Statistical Yearbook of Swedish Forest Agency[12]. Annual fire frequency and burnt area of each county, with causes, are available during the period 1944-1969. Fire frequency with burnt area less than 0.1 hectare (ha) is also available during 1944-1975. From 1998 to 2014, daily fire record has been archived by the Swedish Civil Contingencies Agency[13]. Even if there are wildfires other than forest fires recorded in the daily fire records during the period 1998-2014, however, there are only forest fire records available during the period 1944-1979. Only forest fires are examined in this project in order to compare the statistics of fires for the two different periods.

2.2 Statistics of historical forest fires

2.2.1 Statistics of whole Sweden

The cause of a fire is very difficult to detect. The causes of a large part of the historical fire records cannot be detected, for example, 41% and 34% of the causes of the fires are unknown for the period 1998-2014 and 1957-1969 respectively (Fig. 1). Among all the recorded fires, nature fire (ignited by lightning) is only about 7% for both periods 1998-2014 and 1957-1969. During the two periods, the cause categories of the fires are similar, which can be compared.

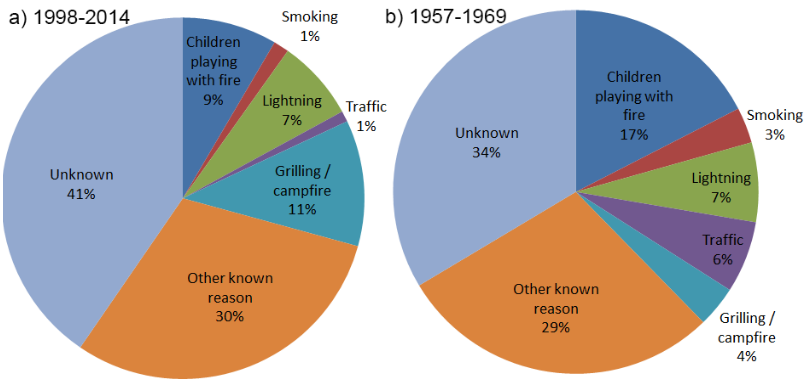

Figure 1. Causes of the fires for the period a) 1998-2014 and b) 1957-1969

The frequency (burnt area) of total fires is highly correlated with the frequency (burnt area) of fires ignited by lightning. The correlation coefficient between

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[12] Skogsstyrelsen: Skogsstatistisk årsbok (http://www.skogsstyrelsen.se/Myndigheten/Statistik/Skogsstatistisk-Arsbok/Skogsstatistiska-arsbocker/)

[13] Myndigheten för samhällsskydd och beredskap, MSB (https://www.msb.se/)

the frequency of the total and the lightning ignited fires is 0.77 during the period 1944-2014. During the same time period, the correlation coefficient is 0.71 between burnt area of total and lightning ignited fires (see Fig. 2). The fire frequency is also highly correlated to the burnt area. The correlation coefficient is 0.60 for all the fires and 0.82 for lightning ignited fires during the period 1944-2014 (missing data has been excluded).

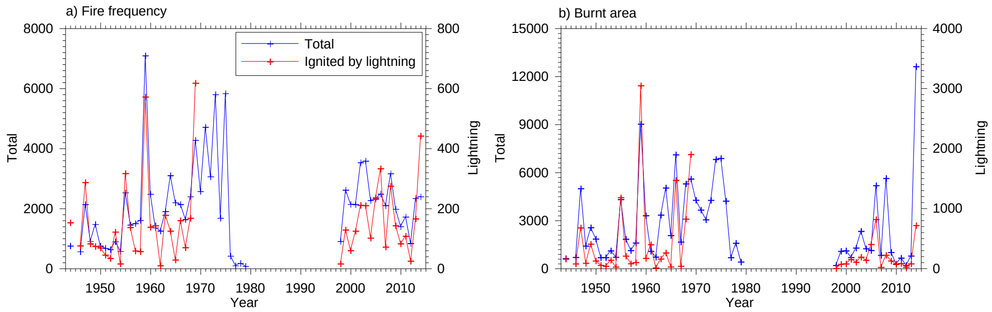

Figure 2. Annual variation the frequency and burnt area of forest fires for whole Sweden during the period 1944-2014

2.2.2 Statistics for three regions of Sweden

There is a distinct geographical pattern in the fire frequency of the forest fires as shown in Figure 3. Most of the fires have been ignited over the southern part of Sweden. A large part of the nature fires, ignited by lightning, locate over the Southeast of Sweden similar to the results in the earlier period 1953-1975, which is affected by the spatial pattern of available water (the difference between precipitation and evapotranspiration)[14]. In the present work, fire statistics of the traditional three regions of Sweden, Norrland, Svealand, and Götaland, are used to assess the regional characteristic of the fires in Sweden. Norrland is the northernmost region that consists of five counties. Svealand is the historical core region of Sweden that consists of seven counties. Götaland is the southernmost region that consists of nine counties.

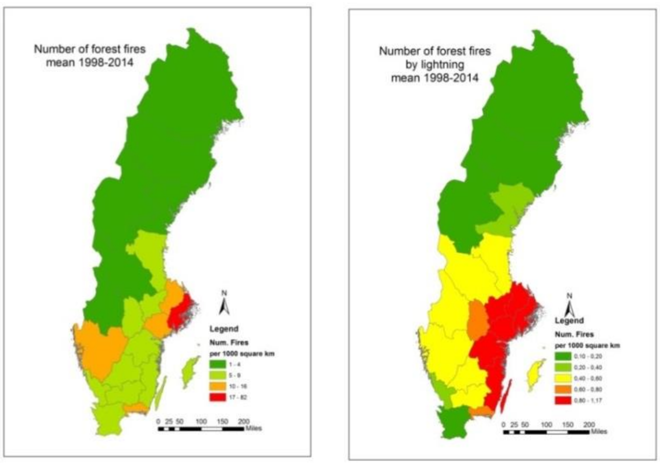

Figure 3. Spatial distribution of fire frequency for 21 counties of Sweden during 1998-2014 for all fires (lightning ignited excluded) (left) and the fires ignited by lightning only (right)

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[14] Granstrom, A., 1993: Spatial and Temporal Variation in Lightning Ignitions in Sweden. J Veg Sci, 4, 737-744.

Generally, there is similar interannual and interdecadal variation in the annual fire frequency of the three regions (Fig. 4). There is an increasing trend during the early period and it reached the peak in the early 1970s. After that, there is sudden decreasing in the fire frequency in the later 1970s. For the present condition, the fire frequency has decreased since the later 1990s for all the three regions. Associated with the changes in the fire frequency, the annual burnt area also illustrated a coherent variation for the three regions, with larger area burnt in the 1970s and less in the recent periods.

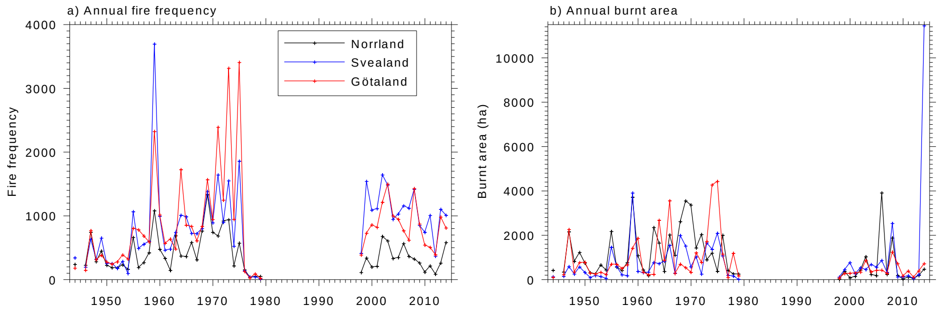

Figure 4. Historical variation of annual fire frequency and burnt area for three regions of Sweden during 1944-2014

In Norrland region, forest fire during the recent period, after 1998, is not very active. The annual burnt area, generally, follows the change in the fire frequency. However, the largest annual burnt area is in 2006, with 3905.38 ha area burnt, during which period the fire is not very active. In Svealand region, the fires frequency in the years around 2000 is close to the situation during the main active period 1970s. After that, there is a decreasing trend in the fire activities during the recent period. A recorded biggest fires over the past 70 years occurred in the year 2014, which has a big impact on the local environment and society. In the Götaland region, there is a significant increasing in the fire frequency during the period from 1944 to the earlier period of the 1970s. The fire frequency during the 1970s almost doubled compared to the previous period. The present condition of fire frequency is similar to the 1960s, but with less area burnt each year.

A similar variation can be found for the nature fires, which ignited by lightning (figure not shown). Annual total number of fires is similar among the three regions. But a larger area has been burnt in the northern part compare to that in the southern part. The occurrence of nature fires is quite stable between the two periods.

There is a clear difference in the seasonal cycle of the fire frequency and burnt area in the three regions based on the fire records during the period 1998-2014 (Fig. 5). The major fire season for Norrland region is from April to September. There is longer fire season in both Svealand and Götaland regions, from March to October, compare to that of Norrland region. Most of the nature fires are in the summer season (June-July-August).

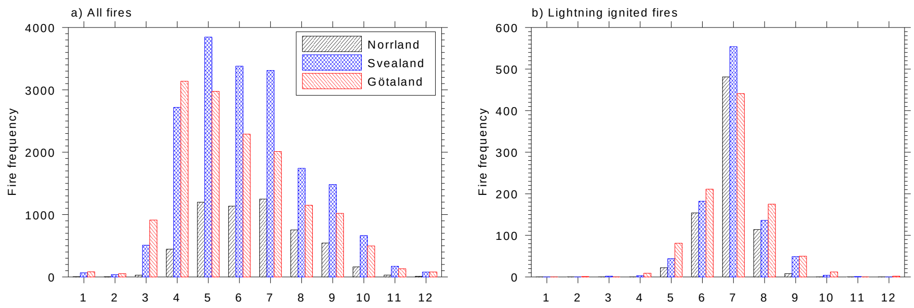

Figure 5. Seasonal variation of fire frequency for three regions of Sweden based on fires records during 1998-2014

For Norrland region, most of the area has been burnt between May and August (Fig. 6). The annual total burnt area is highly correlated with the area burnt in summer (June-July-August, in Table 1), which indicates that the importance in the summer burning to the total burnt area in this region. Similar results can be found for the Svealand region. The summer season will be a focus later for the two regions when we study the link between drought condition and fire burnt area. There is a long fire season for the Götaland region. Both spring and summer seasons are important when investigation the annual total burnt area of Götaland region. The burnt area from April to August can explain the most variation of the annual total burnt area in the Götaland region, which period will be a focus for later analysis.

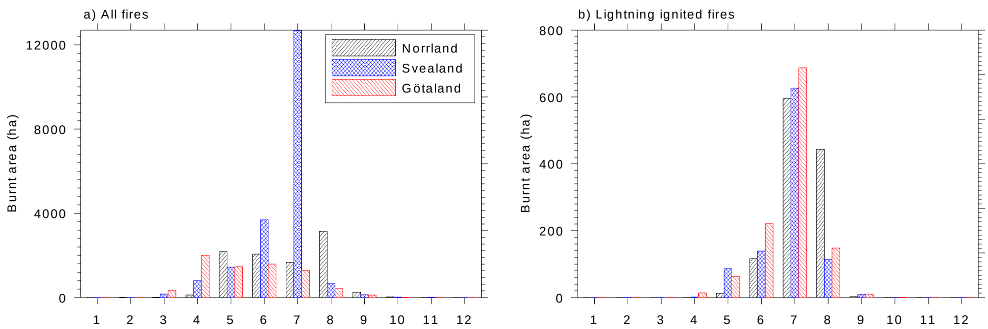

Figure 6. Same as Figure 5, but for burnt area

Table 1. Correlation coefficient between seasonal burnt area and annual total burnt area during 1998-2014 for three regions of Sweden

Name	All fires				Nature fires			
	MAM	JJA	MJJA	AMJJA	MAM	JJA	MJJA	AMJJA
Norrland	0.35	0.94	1.00	1.00	-0.12	1.00	1.00	1.00
Svealand	-0.04	1.00	1.00	1.00	0.01	0.98	1.00	1.00
Götaland	0.57	0.76	0.75	0.99	0.01	1.00	1.00	1.00

2.3 Human effects on forest fires

Changes in the human activities will affect the fire frequency in Sweden since most of the fires are ignited by human activities. On the interannual and interdecadal scale, there is a sharp increasing in the percentage of small fires, fires with burnt area less than 0.1 ha, in the 1950s for all the three regions (Fig.

7). The situation during the 1960s and early 1970s is similar to the present condition during which period the percentage of small fires is around 80% for Svealand and Götaland and 70% for the Norrland, which is almost doubled compared to the condition during the 1940s and early 1950s. This indicates that there is a strong effect of human actives on the burnt area of the fires under current condition.

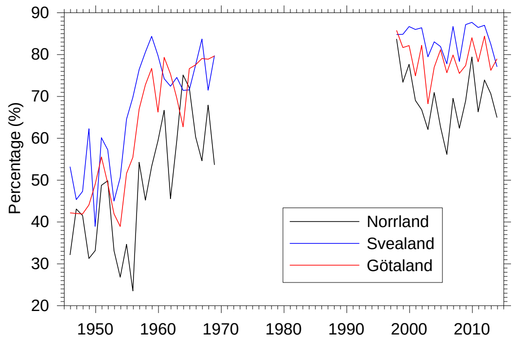

Figure 7. Percentage of the number of fires with fire size less than 0.1ha to the total number of fires for three regions of Sweden during 1946-2014

On the weekly scale, a clear increasing in the fire frequency during weekends can also be found in the fire records during 1998-2014 (Fig. 8). The weekly cycle of fires in Sweden has a clear seasonal variation. No weekend effects on the fire frequency can be found in the summer season (June-July-August), with a slightly higher frequency of fires in the working week than in the weekend. However, there are more fires in the weekend days compare to the working days in the non-summer season. The results are reasonable which indicate a change in the human activities between summer and non-summer season. During the non-summer season, people tends to stay outside in the weekend, for example, there are more fires ignited by landscaped with intent, children play with fire and burning of grass in the weekend. However, people use to take their vacation at home and children are also out of school during the summer season, during which period no weekend effects are found. One special case is fire ignited by grilling and campfire, in which there are weekend effects both in summer and non-summer season. The weekend effect is not found for the burnt area, which indicates that there are some other factors which control the fire size.

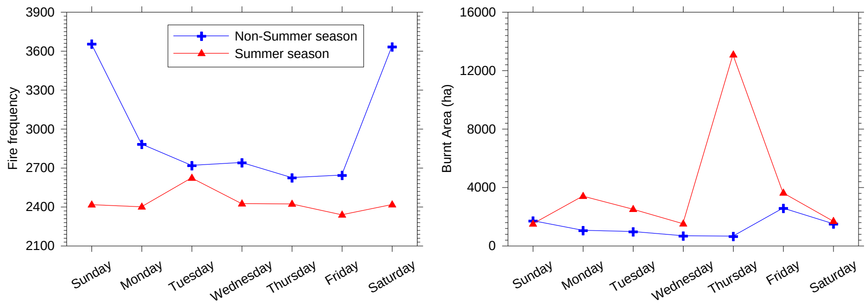

Figure 8. Weekly variation of fire frequency and burnt area for whole Sweden during 1998-2014

3. Droughts and forest fires in Sweden

3.1 Definition of droughts

Drought refers to a temporary decline in water availability, due mainly to changes in hydro-climatological variables such as precipitation and temperature[15], e.g. rainfall deficiency. Drought is a gradually developing event, so a precise determination of its onset and end is difficult. Dracup et al. (1980)[16] and Wilhite and Glantz (1985)[17] present different definitions of drought. According to its impact in a particular sector, drought can be classified as meteorological, hydrological, agricultural or socio-economic[18]. The most common type, meteorological drought, is defined as a natural water shortage resulting from a decrease in the amount of precipitation during a prolonged period, such as a season or a year[19].

3.2 Link between droughts and forest fires

3.2.1 Weather and fire

3.2.1.1 Fire Weather Index (FWI) system

Canadian Forest Fire Weather Index (FWI) System has been widely used in the world and in Sweden to examine the effects of fuel moisture and wind on fire behavior. The FWI system has six components[20]. The Fine Fuel Moisture Code (FFMC) is a numeric rating of the moisture content of litter and other cured fine fuels from 0 to 1.2 cm depth in the forest floor, which plays a significant role in ignition probability and spread. The Duff Moisture Code (DMC) is a numerical rating of the average moisture content of loosely compacted organic layers from 1.2 to 7 cm depth in the forest floor, which contributes to lightning receptivity and over all fire intensity. The Drought Code (DC) is a numerical rating of the average moisture content of deep, compact, organic layers below 7cm depth in the forest floor, which contributes to the depth of burn, intensity, and suppression difficulty. Three fire indices have been constructed based on

[15] Kundzewicz, Z. W., 2009: Adaptation to floods and droughts in the Baltic Sea basin under climate change. *Boreal Environ Res*, **14,** 193-203.
[16] Dracup, J. A., K. S. Lee, and E. G. Paulson, 1980: On the Definition of Droughts. *Water Resour Res*, **16,** 297-302.
[17] Wilhite, D., and M. Glantz, 1985: Understanding: the Drought Phenomenon: The Role of Definitions. *Water Int*, **10,** 111-120.
[18] Gathara, S., L. G. Gringof, E. Mersha, K. C. Sinha Ray, and P. Spasov, 2006: Impacts of desertification and drought and of other extreme meteorological events. CAgM Report No. 101, WMO/TD No. 1343, Geneva, Switzerland, 85 pp.
[19] Mishra, A. K., and V. P. Singh, 2010: A review of drought concepts. *J Hydrol*, **391,** 204-216.
[20] Canadian Wildland Fire Information System, http://cwfis.cfs.nrcan.gc.ca/

the three indices and wind speed, namely Initial Spread Index (ISI), Build-Up Index (BUI) and Fire Weather Index (FWI). The ISI is a numeric rating of the expected rate of fire spread. The BUI is a numeric rating of the total amount of fuel available for combustion. The FWI is a numeric rating of fire intensity.

3.2.1.2 Link between mean FWI and fire frequency

Gridded FWI from the Global Fire WEather Database (GFWED) (available from http://data.giss.nasa.gov/impacts/gfwed/)[21] is utilized. Monthly mean FWI and the temperature (T2m), relative humidity (RH), wind speed (WindSpd) at local time 12:00 and 24-hour rainfall (Precip) are averaged for each county. The correlation coefficient between the monthly time series of the selected indices and the fire frequency is calculated for each county during the period 1998-2014. Results are shown in Figure 9. The fire frequency is negatively correlated with Precip and RH, and is positively correlated with T2m. WindSpd is not important for the statistic of fire frequency. Among the three fuel moisture codes, DMC is higher correlated with the fire frequency compare to the other two. This indicates the importance of moisture content in the upper forest layer (above 7 cm) for fire ignition.

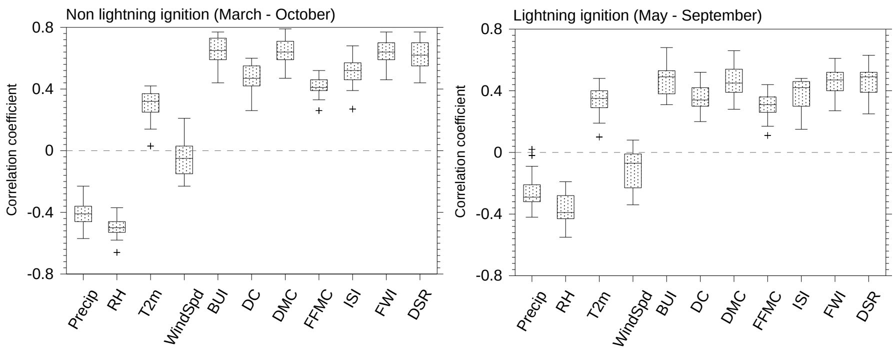

Figure 9. Correlation coefficient between the fire frequency and indices for the 21 counties

3.2.2 Long-term drought condition and forest fires burnt area

In the present work, three different drought indices are assessed against the fire statistics. They are the Self-calibrating Palmer Drought Severity Index (scPDSI)[22], the Standardised Precipitation Index (SPI)[23], and the Standardised Precipitation-Evapotranspiration Index (SPEI)[24] indices. Only the scPDSI index is calculated with fixed temporal scale (between 9 and 12 months) due to which the values of the index can be affected by the condition up to four years

[21] Field, R. D., and Coauthors, 2015: Development of a Global Fire Weather Database. Nat Hazard Earth Sys, 15, 1407-1423.

[22] Wells, N., Goddard, S. and Hayes, M. J., 2004: A Self-Calibrating Palmer Drought Severity Index, J. Climate 17, 2335-2351.

[23] Guttman, N. B., 1999: Accepting the Standardized Precipitation Index: A calculation algorithm. J. Amer. Water Resour. Assoc., 35(2), 311-322.

[24] Vicente-Serrano S.M., Santiago Beguería, Juan I. López-Moreno, (2010) A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI. Journal of Climate 23: 1696-1718.

in the past[25]. Both the SPI and SPEI indices can be calculated on different time since drought is a multi-scalar phenomenon. The SPI index is based on monthly precipitation only, while both precipitation and temperature (evapotranspiration) is considered in the SPEI index. The scPDSI index is calculated based on the 0.5 x 0.5 degree (longitude x latitude) resolution Climatic Research Unit (CRU)[26] data TS3.25[27] during the period 1901-2015. The SPI and SPEI indices are calculated based on the CRU TS3.24[28] which is similar to the version TS 3.25.

The link between the annual burnt area and the drought indices on different scales is examined for the 21 counties for two time periods (Fig. 10). Generally, the link between scPDSI and the annual burnt area is lower compared to that of SPI and SPEI indices with temporal scale smaller than 9 months, which indicates that the importance of short scale drought condition on the burnt area in Sweden. This is due to that the scPDSI has fixed temporal scale (between 9 and 12 months). The correlation coefficient between annual burnt area and SPEI is generally higher than that with SPI. For this case, SPEI index is one good candidate when monitoring the fire related drought condition on the monthly and seasonal scale for the Swedish counties.

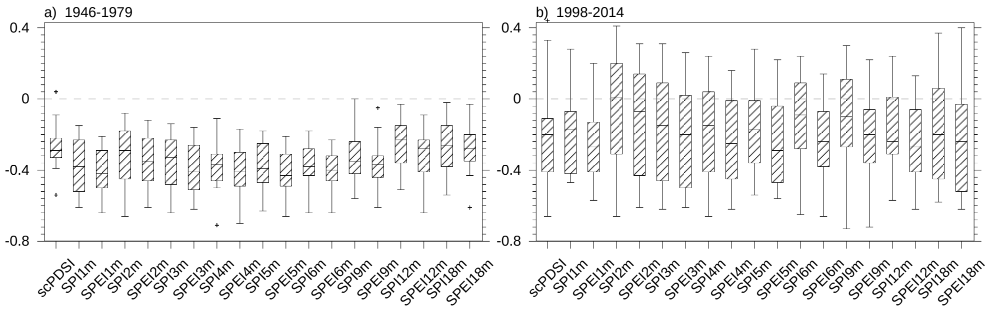

Figure 10. Box plots show the correlation coefficient between different drought indices for April-August and annual burnt area for 21 counties a) 1946-1979 and b) 1998-2014 (scPDSI, SPI1m and SPEI1m is calculated for the mean from April to August, value for the other multi-scale SPI and SPEI indices is retrieved on August, for example SPEI3m indicates the 3 month scale SPEI index on August which cover the drought condition from June to August)

As discussed before that the burnt area in June-July-August covers the most information of the interannual and interdecadal variation of annual burnt are for Norrland and Svealand. There is longer fire season for Götaland than the other two regions when looking at the burnt area, information from April to

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[25] Guttman, N.B., 1998: Comparing the Palmer drought index and the Standardized Precipitation Index. Journal of the American Water Resources Association 34, 113-121.

[26] http://www.cru.uea.ac.uk/

[27] van der Schrier G, Barichivich J, Briffa KR and Jones PD (2013) A scPDSI-based global data set of dry and wet spells for 1901-2009. J. Geophys. Res. Atmos. 118, 4025-4048

[28] Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H., 2014: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int. J. Climatol., 34: 623-642.

August is required. Then the year with the annual burnt area available is selected and the linkage between the annual burnt area and mean SPEI index is illustrated in Figure 11. The annual burnt area for all fires and the lightning ignited only fires are assessed separately. There is an exponential linkage between annual burnt area and the mean SPEI index. The results are consistent between two periods, 1946-1979 and 1998-2014. The year tends to have a large burnt area when the mean SPEI index below some kind of threshold. The threshold can be determined with a given value of the burnt area based on the fitted exponential function. In this work, the year with the annual burnt area larger than 1000ha is regarded as a year with severe fires for the three regions. Then the threshold of the regional mean SPEI index linked with a large burnt area can be retrieved. The annual burnt area tends to be larger than 1000ha when the regional mean SPEI index during summer is less than -0.459 for Norrland. The annual burnt area tends to be larger than 1000ha when the mean SPEI index from April to August is less than -0.377. The threshold of 1000ha burnt area for Svealand is -0.817 for regional mean SPEI index during summer. But there are years with large burnt areas which is associated with mean SPEI index bigger than -0.817. The threshold could be too strong for the Svealand region. For this case, similar thresholds of regional mean summer mean SPEI (-0.459) as for the Norrland region is chosen for Svealand to illustrate the years with severe drought, which has potential with a large area to be burnt.

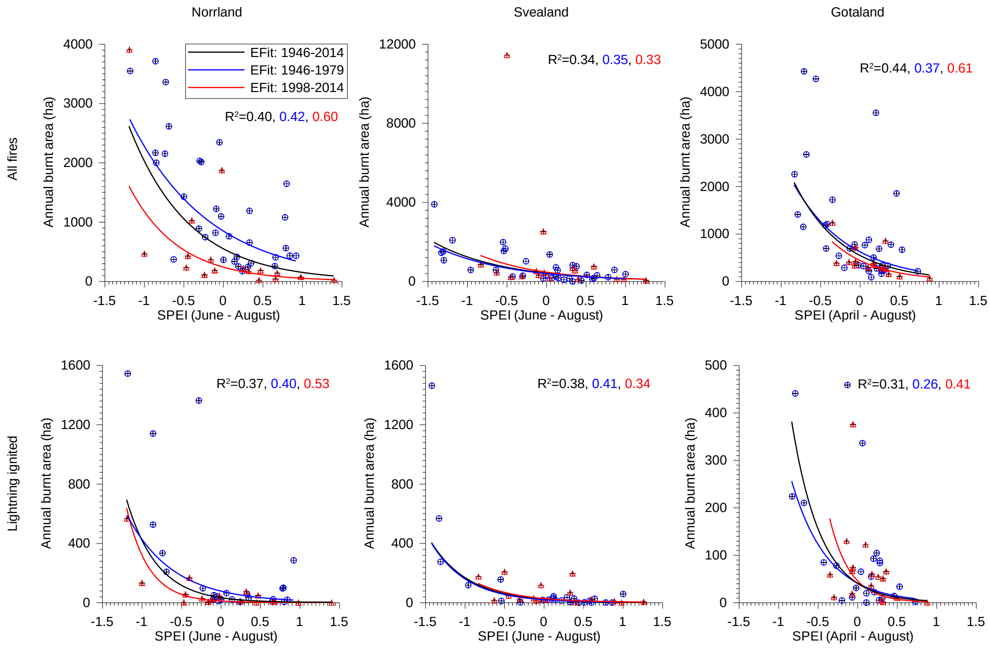

Figure 11. Link between seasonal mean SPEI indices and burnt area for all fires (upper) and lightning ignited fires (lower) of three regions of Sweden (June-August for Norrland and Svealand, and April-August for Götaland) (Fitted by Exponential function)

3.3 Projected change of drought in Sweden and forest fire risk

Based on the threshold of mean SPEI index, the year which tends to have large burnt area can be selected. This can also be done for the future change in the SPEI index to investigate the future change in the fire potential. For this purpose, 8 global climate model (GCMs) which participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5)[29] with both stabilization of radiative forcing (RCP4.5)[30] and comparatively high greenhouse gas emissions (RCP8.5)[31] available are selected. Information of the 8 GCMs can be found in Table 2. Historical simulation and future projections during 1951-2100 are downscaled to 44km horizontal resolution using the Rossby Centre regional atmospheric model (RCA4)[32]. The horizontal resolution is close to the 0.5 x 0.5 degree (longitude x latitude) resolution which used to calculate the observed drought indices. Mean SPEI index for from June to August (JJA) are calculated for Norrland and Svealand regions, while the mean SPEI index from April to August (AMJJA) is calculated for Götaland region.

Table 2. Information of global models used in the Regional Downscaling Experiments by Rossby Centre regional atmospheric model (RCA4)

Modeling Center	**Model**	**Atmosphere resolution (longitude × latitude in degrees)**
CCCma	CanESM2	2.8125 × 2.7906
CNRM-CERFACS	CNRM-CM5	1.4063 × 1.4008
CSIRO-QCCCE	CSIRO-Mk3-6-0	1.8750 × 1.8653
IPSL	IPSL-CM5A-MR	2.5000 × 1.2676
MIROC	MIROC5	1.4063 × 1.4008
MPI-M	MPI-ESM-LR	1.8750 × 1.8653
NCC	NorESM1-M	2.5000 × 1.8947
NOAA-GFDL	GFDL-ESM2M	2.5000 × 2.0225

The years with JJA SPEI are less than -0.459 are chosen, which indicate the severe drought year, for Norrland and Svealand regions. Number of severe drought years within a 31-year period is counted and the mean SPEI index of the selected years is also calculated. Similar work has been done for Götaland, but with AMJJA SPEI index less than -0.377. Results from both observation and model simulation are illustrated in Figure 12. We can see that the historical model simulation generally agrees with observation during the period 1951-2010 for the regions, during which period number of the server drought years decreased and the drought intensity of the selected years weakened for all the

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[29] Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. B Am Meteorol Soc, 93, 485-498.

[30] Thomson, A. M., and Coauthors, 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change, 109, 77-94.

[31] Riahi, K., and Coauthors, 2011: RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Climatic Change, 109, 33-57.

[32] https://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552/climate-scenario-data-from-the-rossby-centre-1.34020

three regions. The number of server drought years will continue decreasing till the middle of 21 century for both RCP4.5 and RCP 8.5 projection. After that, the number increases a little but still less than the peak period in the 1970s. This agrees with the results of by Yang et al (2015)[33], in which the number of high fire risk days project to decrease in the northern part of Sweden. There is no clear trend in the drought intensity of the selected year. There may be some years with server drought condition at the end of 21 century under RCP4.5 projection, but there is large uncertainty between different models.

The number of server drought years in Svealand is projected to decrease under the RCP4.5 scenario. The results from RCP8.5 is different with that under RCP4.5, in which the number of severe drought years tends to increase until the end of 21 century compare to the condition around 2020. Changes in the intensity of selected years are similar between the two projections, with a decrease from 1951 till the 2020s and then increase until the end of 21 century.

For Götaland, there is a large uncertainty in the projected changes in the drought condition. The number of server drought years continuously decrease from 1951 to the end of 21 century under RCP4.5 projection, with no clear change in the intensity. But there is projected to be more server drought years under RCP8.5 projection in the end of 21 century, with strengthened drought intensity. This indicates that the fire risk might be high in the end of 21 century under RCP8.5 projection.

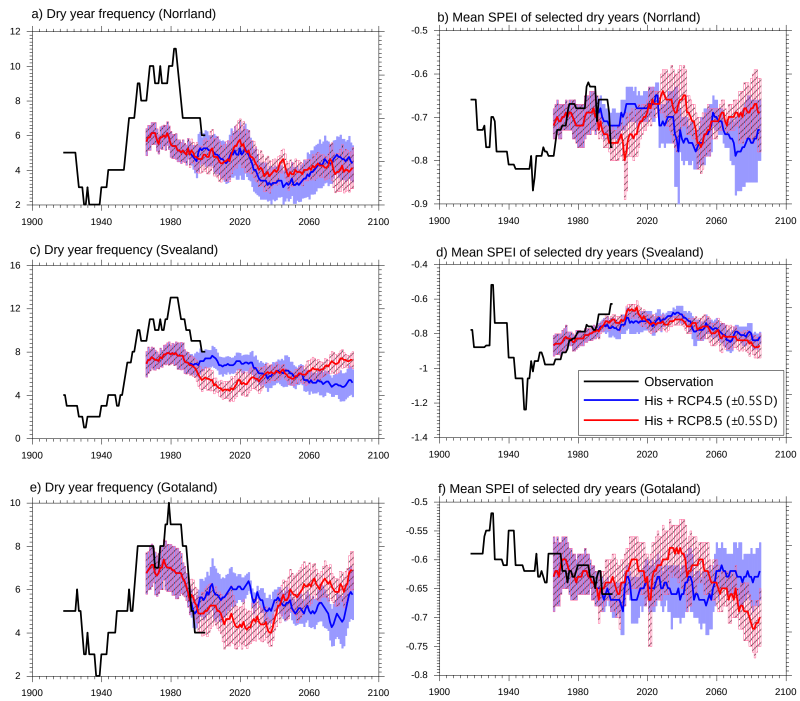

Figure 12: Historical variation and projected change of the drought year frequency for every 31 years and the mean SPEI of the selected drought years for three regions of Sweden based on RCP4.5 and RCP8.5 scenarios during 1951-2100 (uncertainty included), results from observation are also included

33 Yang, W., M. Gardelin, J. Olsson, and T. Bosshard, 2015: Multi-variable bias correction: application of forest fire risk in present and future climate in Sweden. Nat Hazard Earth Sys, 15, 2037-2057.

4. Conclusions

The project has provided detailed insight into the historical variation in the fire frequency and burnt area of forest fires in Sweden, as well as the link between drought condition and forest fires frequency and burnt area. Projected changes in the drought condition and fire risk have also been explored. The following conclusions summarize the main results of the project:

- There is longer fire season with higher fire frequency in the southern part of Sweden compare to that in the northern part.
- A large part of the fires in Sweden is ignited by human activities. Fire frequency in Sweden is strongly affected by human activities on both daily and seasonal to annual scale. Higher fire frequency is found during the weekend for the non-summer season, but no weekly cycle can be found in the summer season. On interannual to interdecadal scale, the percentage of small fires, fire size less than 0.1 ha, has increased since late 1950s which might be due to the impact of human activities.
- Both drought condition on the daily scale, associated with fire weather, and on seasonal to annual scale has effects on the fire frequency.
- SPEI index, in which both precipitation and temperature condition is considered, is one good candidate when monitoring the fire related drought condition on the monthly and seasonal scale for the Swedish counties.
- Severe drought years, indicated by strong negative SPEI index, are generally associated with a large burnt area.
- The drought condition for the past few decades in Sweden is not that severe compared to the severe period around the 1970s over the past 80 years.
- Drought condition in northern Sweden is projected to be less severe with low fire risk of a large annual burnt area. While the drought condition in the southern Sweden could be severe with more severe drought years, especially in the end of 21 century.

Myndigheten för samhällsskydd och beredskap
651 81 Karlstad Tel 0771-240 240 www.msb.se
Publ.nr MSB1112 - June 2017 ISBN 978-91-7383-757-6