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Scandinavian Forest Fire Activity Correlates with Proxies of the Baffin Bay Ice Cover

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Abstract: Understanding factors driving fire activity helps reveal the degree and geographical variability in the resilience of boreal vegetation to large scale climate forces. We studied the association between sea ice cover in the Baffin Bay and the Labrador Sea and observational records of forest fires in two Nordic countries (Norway and Sweden) over 1913–2017. We found a positive correlation between ice proxies and regional fire activity records suggesting that the Arctic climate and the associated changes in North Atlantic circulation exercise an important control on the levels of fire activity in Scandinavia. Changes in the sea cover are likely correlated with the dynamic of the North Atlantic Current. These dynamics may favor the development of the drought conditions in Scandinavia through promoting persistent high-pressure systems over the Scandinavian boreal zone during the spring and summer. These periods are, in turn, associated with an increased water deficit in forest fuels, leading to a regionally increased fire hazard. The Arctic climate will likely be an important future control of the boreal fire activity in the Nordic region.

Keywords: forest fires; disturbance regimes; climate-fire interactions; trends in drought conditions

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1. Introduction

Fire is the primary driving factor of the ecosystem dynamics in the boreal forest, directly affecting global carbon balance, atmospheric concentrations of trace gases including carbon dioxide [1], and regional surface energy budgets [2]. Regional fire regimes reflect large-scale atmospheric circulation processes [3–6]. Climatically induced changes in fire regimes impact the functioning of the boreal ecosystem by affecting regeneration and growth conditions for dominant tree species, forest composition, and successional pathways [7]. As a result, these interactions influence different ecosystem services such as carbon storage [8,9], biodiversity preservation [10,11], forest economic value [12] and the economies of local communities. In particular, a link between carbon emissions from boreal fires and climate warming has been an issue of particular concern [13,14].

Forest fire activity in the boreal zone has exhibited a large variability at multiple temporal scales [15]. Paleochronological studies have indicated changes in charcoal accumulation rates over the Holocene in response to solar radiation forcing [8] and large-scale changes in atmospheric circulation patterns [16–18]. Dendrochronological reconstructions based on the dating of fire scars and analyses of modern observational records have both revealed the role of the seasonal dynamics of climate systems in predisposing the regional vegetation to large fires through creating large water deficits in forest fuels [19,20]. The long-term trends in boreal fire activity remain a subject of discussion. In boreal Europe, studies have shown a large annual and decadal variability in burned areas, but no clear long-term trend during the 20th and early 21st centuries [21,22]. In Sweden, the areas burned during 2014 and 2018 were approximately three times higher the average level of fire activity since the 1990s [22]. Whether these years mark the start of a new era with more widespread fires in Scandinavia is unclear as the lack of observational records and their quality make relevant analyses difficult. However, recent studies reported no clear long-term trends in fire activity in boreal Eurasia [23–25]. North American studies documented both increasing [26–29] and decreasing trends [30] that exhibited a considerable geographical variability [29].

In an attempt to tackle the complexity of the fire regime drivers at the regional and sub-continental scales, studies have looked into the correlations between fire activity metrics and the main features of atmospheric and ocean circulation across large areas, often geographically remote from the regions in question. For example, Pacific decadal oscillation (PDO) and El Niño southern oscillation (ENSO) have been shown to control the occurrence of periods with large wildfires in boreal Canada and Alaska [27,31,32]. In southern South America, periods with increased fire activity have been linked to La Niña events leading to reduced winter and spring precipitation [4]. In Scandinavia, a recent study has demonstrated a connection between SST (sea surface temperatures) dynamics in the Northwest Atlantic and regional boreal forest fire activity [15]. The identification of such teleconnections helps provide a mechanistic interpretation of the fire activity drivers and serves as a test for the models predicting future states of the boreal forest. Analysis of teleconnections can, therefore, be viewed as a "statistical shortcut" to parameterize mechanistic relationships outside the domain of complex physical models.

A number of recent studies have shown the importance of the Arctic climate for the dynamics of the tundra and boreal biomes [33,34]. These studies pointed to the interactions between the drying Arctic air and the more humid air originating from the tropical regions that reaches the boreal zone through northward (towards boreal North America) or northeast transfer (boreal zone of Northern Europe). Arctic circulation and ocean dynamics in that region has been proposed to affect probability of high-pressure systems in the troposphere over the boreal forest, ultimately affecting regional fire activity.

In this paper, we test the hypothesis of the teleconnection between the Baffin Bay/Labrador Sea ice cover and Scandinavian fire activity (Figure 1A). The Labrador Sea, together with Baffin Bay, is a critical area of deep-water formation in the North Atlantic [35,36] and its conditions have been shown to relate to a number of large-scale atmospheric and ocean circulation patterns, such as NAO and AMOC [37,38]. In turn, conditions in the Northern Atlantic have been earlier hypothesized to affect regional fire activity in northern Scandinavia by influencing the position of westerly tracks and the strength of NAC [15]. As westerly tracks define, to a considerable degree, temperatures and precipitation dynamics over Scandinavia [39], it is logical to assume that they also affect the climatological fire hazard in the region. A weakening of ocean circulation in this part of the Atlantic and stronger regional winter cooling have been shown to result in increased fire activity in the following fire season [15]. The current analysis is an extension of our previous study that established a link between the dynamics of the Northern Atlantic and fire activity in northern Sweden over multiple temporal scales. Here we focus exclusively on the modern fire record, which has been improved to include a much longer continuous chronology of annually burned areas, stretching from 1913 to 2017. The modern fire record, which covered only northern Sweden in the initial study, now includes both northern Sweden and Norway, which makes it a more regional proxy of fire activity. In this study, we tested a hypothesis about a relationship between conditions in the Baffin Bay and Labrador Sea, expressed as dynamics of proxies for sea ice cover, and annually burned areas in northern Sweden and Norway. We test this assumption at annual scale and discuss the possible effects of this relationship under the future climate.

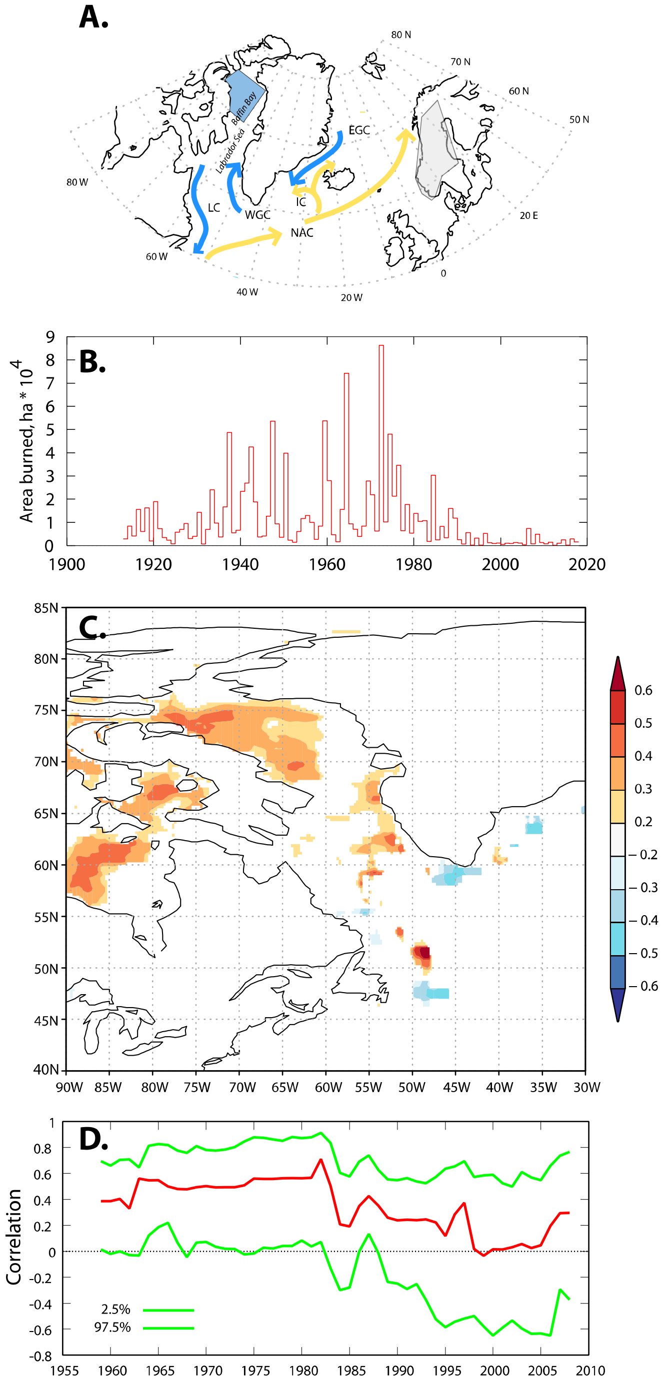

Figure 1. The study region, and the relationship between the Scandinavian fire record (detrended the total sum of burned areas in the northern Sweden and Norway) and estimates of sea ice cover from ERA5 reanalysis dataset over 1950–2017. (**A**) The study region with the marked sections of the Baffin Bay (blue color) and the Scandinavia (gray color), which were studied. NAC, North Atlantic Current; IC Irminger Current; EGC, East Greenland Current; WGC—West Greenland Current; LC, Labrador Current. (**B**) Cumulative chronology of burned areas for northern Sweden and Norway. (**C**) Field correlations over the Baffin–Labrador Sea area. Areas with significant correlation ($p < 0.10$) are colored. The value and direction of correlation are indicated by the color scale. (**D**) Running correlations (time frame for moving correlation analysis is 20 years) between the Scandinavian fire record and the area with the highest correlation values on A (70–75 N and 80–60 W). Green lines indicate bootstrap-derived 0.95 confidence intervals.

2. Methods

2.1. Fire Data

We used the sum of the annually burned areas over northern Sweden (the area above 61 N) and Norway during 1913–2017. The record from Sweden was a composite record as it combined data from the forestry statistics and the reconstructed values [22]. The Swedish data included a database produced by the Swedish Forestry Board [40] for the 1942–1975 and 1975–1996 periods. Swedish data for the 1996–2017 period was obtained from the Swedish Civil Contingencies Agency (www.msb.se). For all of the periods, we only selected fires reported on the forested land. In the Swedish dataset, fires below 0.1 ha in size were absent from the forest statistics data for the 1942–1952 period. In Sweden, the country-wide fire activity is dominated by the northern part of the country (north of 60 N) [21], which contains about 79% of the total forest area (SLU Skogsdata 2016, http://pub.epsilon.slu.se/13442/1/skogsdata2016.pdf, accessed on 12 November 2021). The fire activity in this region has also been shown to contain a strong climate signal [19]. We, therefore, considered areas burned in this part of the country for statistical analyses. The data from Norway featured a continuous observational record of the annually burned areas, produced by the Statistics Norway (http://www.ssb.no) and being available from 1913 (Figure 1B). We summed annual values of the burned areas for Norway and northern Sweden into a single chronology. The chronology was de-trended and first-degree derivatives were obtained to further enhance the high-frequency (annual) signal. The three largest fire years on the record were 1959 (53,627 ha burned), 1964 (74,213 ha), and 1972 (86,247 ha).

2.2. Climate and Sea Ice Data

We used the data on sea ice cover (SIC) available through ERA5 reanalysis [41]. Sea ice cover represents a fraction of a grid cell, covered by sea ice. The data are derived from direct observations and modelling carried out in the ECMWF integrated forecasting system (IFS). The data were resolved at 0.25 degrees and featured the monthly resolution. We de-trended the data to remove the long-term linear trend and first-degree derivatives were obtained to further enhance the high-frequency (annual) signal and to remove autocorrelation. Following the preliminary analyses of the SIC dynamics, we focused on the average sea ice conditions during January and February. To test the association of Scandinavian fire record with North Atlantic sea-surface temperatures (SST), we obtained SST from the UK Met Office Hadley Centre observations datasets [42].

2.3. Statistical Analyses

We ran Pearson correlation analyses between the fire record and SIC over the area broadly encompassing the Baffin Bay and the Labrador Sea. The preliminary analyses identified a high correlation between the fire record and the SIC over 70–75 N and 80–60 W. We correlated the ice data from that region with the fire record and evaluated the temporal stability of this relationship by analyzing correlations on a 20-year sliding frame over the whole period that was jointly covered by both chronologies. Similarly, the relationship between Atlantic SST and the fire record was evaluated through the Pearson correlation.

To evaluate the relationship between SIC and the climatological proxy of fire hazard, we correlated the SIC with the standardized precipitation-evapotranspiration index (SPEI) calculated over Scandinavia. SPEI is a multi-scalar metric of evapotranspiration demand and is the difference between precipitation and reference evapotranspiration. The index can be calculated at multiple time scales, providing a nuanced measure of accumulated drought conditions [43]. SPEI values were generated on the ERA5 reanalysis dataset [41]. The relationship was evaluated for overlapping two-month periods covering spring and summer. For all analyses, bootstrapping of the original data (n = 1000) was used to evaluate the statistical significance of correlations at the level of the single-grid cell.

To test for the randomness of the observed correlation patterns, we calculated field significance as a fraction of the studied maps, i.e., a percentage of grid cells that exhibited a correlation above a 0.10 threshold. In other words, by relating the number of significant correlations (calculated on a grid cell level) to the total number of such correlations computed, we estimated the probability that a random process generated the observed pattern.

3. Results

Correlation analyses revealed strong and temporally consistent positive correlations between the fire record and winter (January through February) SIC for the Baffin Bay area, approximately limited by 70–75 N and 80–60 W. The correlation values spanned between 0.3 and 0.6 with the fraction of the map with a significant correlation being 31.4%, producing a highly significant pattern (field significance, p_{field} < 0.1%, Figure 1C). The positive correlation was broadly consistent over time although the second half of the study period (~1985–2017) revealed a decline in the correlation strength (Figure 1D). As our study period for the sea ice conditions included two winter months, the variability in the sea ice record was limited with the maximum value for the selected region being 0.994 and the minimum value 0.932.

North Atlantic SST correlated negatively with the Scandinavian fire record (Figure 2): correlations were more pronounced for the spring SST (proportion of the map with significant correlations 43.0%, p_{field} < 1%) than for the summer SST (36.7%, p_{field} < 1%). The spring SST around Iceland and the summer SST of the Norwegian and Northern Seas revealed a positive correlation with the fire record.

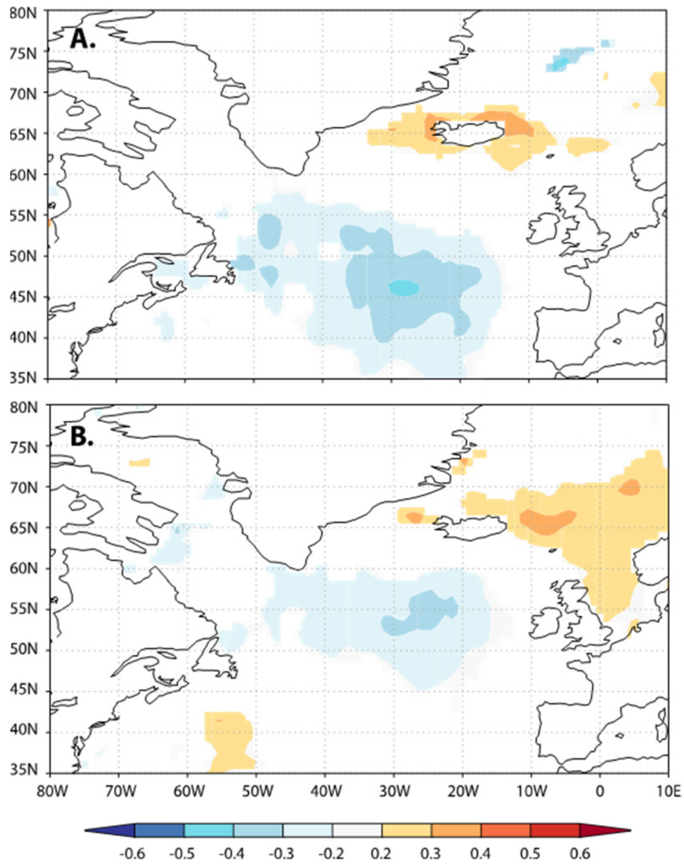

Figure 2. Field correlations between the Scandinavian fire record and sea surface temperatures (SST) in the Northern Atlantic for spring (March through May, **A**) and summer (June through August, **B**). The fire chronology was correlated with each grid-cell SST chronology over the given geographical extent. The areas with significant correlation (p < 0.10) are colored. The value and direction of correlation are shown by the color scale.

We averaged the SIC over the region where it showed the highest correlation with the fire record (70–75 N and 80–60 W) and regressed it against SPEI over the Scandinavian peninsular (Figure 3), using two-month averaged SPEI over spring and summer. SIC was negatively correlated with SPEI over a larger section of the northern Scandinavian peninsular during April–May (the proportion of the map with significant correlations was 41.99%, $p_{\text{field}} < 5\%$, Figure 3A). Over May–June, the areas with a significant negative correlation covered most of Scandinavia (63.45%, $p_{\text{field}} < 5\%$, Figure 3B). A broadly similar but weaker pattern was observed for June–July SPEI (39.57%, $p_{\text{field}} < 5\%$, Figure 3C) and no pattern was visible for the late summer SPEI (13.3%, $p_{\text{field}} > 20\%$, Figure 3D). SPEI over the Scandinavian peninsular revealed a strong and geographically widespread negative correlation with the fire record (Supplementary Materials, Figure S1).

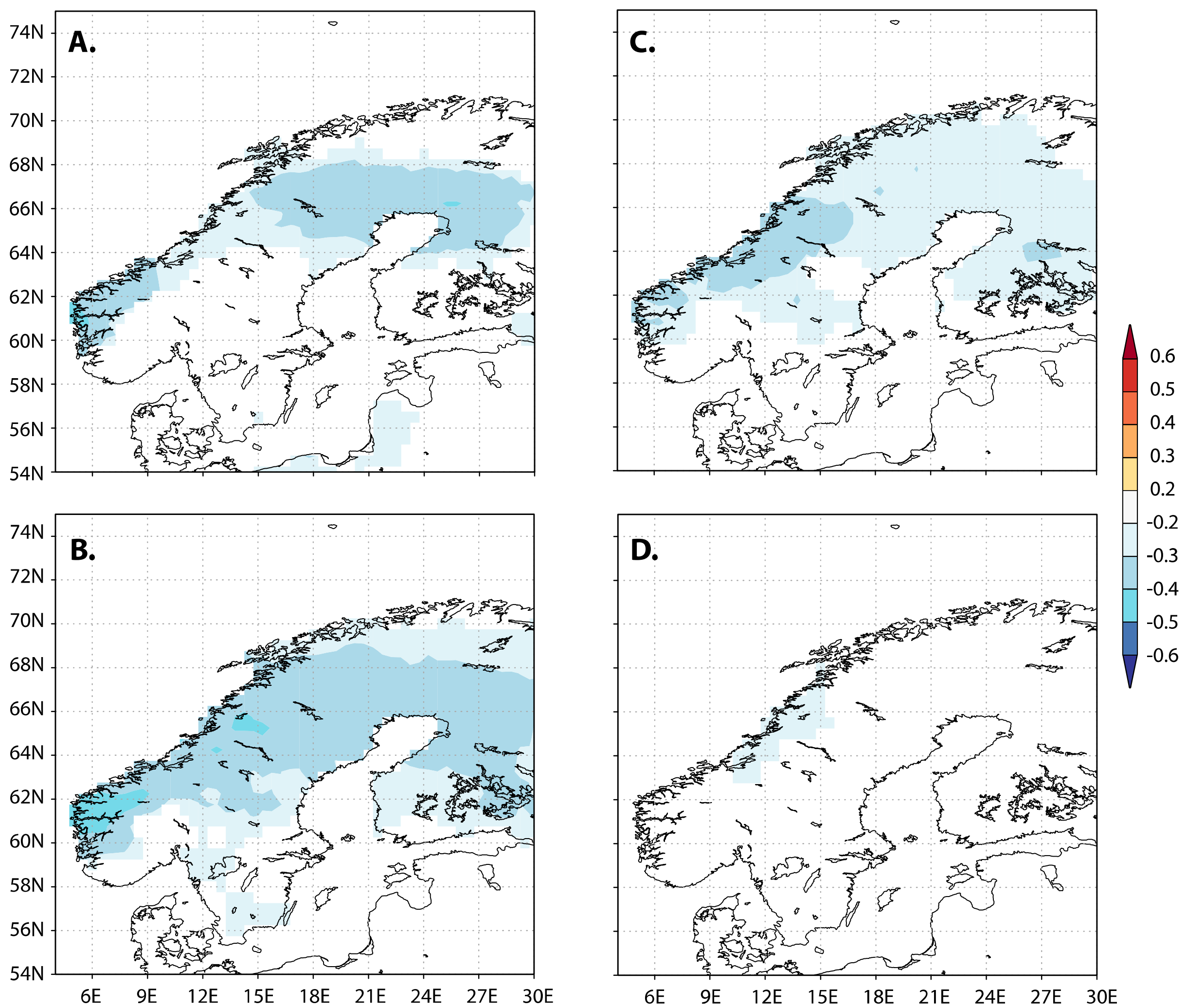

Figure 3. Field correlations between the sea ice content over 70–75 N and 80–60 W and 3-month SPEI index for April−May (**A**), May–June (**B**), June–July (**C**), and July–August (**D**). Areas with significant correlation ($p < 0.10$) are colored. The value and direction of correlation are shown by the color scale.

4. Discussion

The positive and temporally consistent correlation between the index of annually burned areas in Scandinavia and proxies for sea ice cover in the Baffin Bay indicated the presence of teleconnection affecting fire weather conditions in this part of Northern Europe. The Baffin Bay and the Labrador Sea is an area of the North Atlantic associated with deep water formation [44] that affects atmospheric and ocean circulation in the Northern Atlantic region. In a modeling study, the Labrador Sea conditions were shown to relate to North Atlantic and Arctic oscillation, with negative temperature anomalies and heavier ice conditions associated with negative NAO and AO states [38]. The authors have attributed the effect to changes in low-level baroclinicity affecting, in turn, baroclinic disturbances and synoptic storms.

We propose that higher ice cover of the Baffin Bay and ocean cooling, both positively associated with the modern Scandinavian fire activity, reflected the reduced strength of the North Atlantic Current and the Atlantic meridional overturning circulation (AMOC) and increased southward sea ice and fresh water exported from the Labrador Sea. In turn, reduced AMOC led to a weaker westerly transfer of warm and wet air masses towards Scandinavia and an increased presence of dryer Arctic air masses over that region. This interpretation is consistent with both a positive correlation between Scandinavian fire record on one side, and SIC and SSTs on the other (Figures 1 and 2). We also noted that the correlation strength declined since the late 1980s. This dynamics might be related to the general intensification of the AMOC since that time [45], leading to the stronger transfer of the heat and humidity towards Northern Europe that might limit impact of the Baffin Bay and Labrador Sea dynamics upon fire weather over the Scandinavian peninsular.

The temporal scale at which the Baffin Bay ice conditions affect forest fire hazard in Scandinavia is of particular interest. Although our study documented significant relationship at the annual scale, it is likely that it may extend towards above-annual scales. As the Labrador Sea hosts the currents that are directly involved in the production of deep water formation, they are intimately connected to the Atlantic meridional overturning circulation (AMOC) that amplifies climate-driven climate variability at the centurial timescales [37]. Indeed, models indicate that the atmospheric response to increased sea ice conditions in the Labrador Sea may exhibit negative feedback on long-term patterns of NAO-AO variations [38]. Specifically, the modelling suggests that the total Labrador Current volume transport correlates with the NAO with time lags of 0–3 years [46]. The origin of variability in the Baffin Bay and Labrador Sea ice conditions is outside the scope of the current study. However, we note a recent study proposing an important role of southern oscillation (as represented by SOI, southern oscillation index) in affecting sea-level pressure patterns over the Northwest Atlantic, possibly affecting Baffin Bay/Labrador Sea's ice conditions [47].

Colder North Atlantic SST has been linked to an increase in fire activity in northern Scandinavia [15] (Figure 2). A comparison between independent dendrochronological reconstructions of fire activity [19] and summer surface air temperatures [48] in that region has revealed an increased fire activity during colder periods since 1400 AD (Figure 5 in [15]). Similarly, analyses of regime shifts in the Holocene long dynamics of Scandinavian fire activity reconstructed from charcoal in lake sediments [49] and in the North Atlantic conditions [50–52] have revealed increases in fire activity during colder periods in the Atlantic and the Nordic region [15].

The observed teleconnection between sea ice conditions in the Northern Atlantic and annually burned forest areas in Scandinavia suggested that the Arctic climate being the principal driver of sea ice and SST dynamics [53,54] may exercise an important control upon the frequency of fire prone episodes in that region. We speculate that the cooling of the Arctic regions, resulting in increased SIC and sea ice extent, and accompanied by a corresponding decrease in the North Atlantic SST, may affect the degree of the southward migration of the cold and dry Artic air masses. This dynamics likely affect the development of persistent high pressure systems over the Scandinavian boreal zone during summer months [19]. Warming of the summer SST in the proximity of the Scandinavian peninsular during more fire-prone years (Figure 2B) could be indicative of such high-pressure cells. These atmospheric conditions are associated with an increased water deficit in forest flues, leading to a regionally increased fire hazard. At the same time, a weak NAC resulted from the increased flow of cold and less saline Arctic water into the western North Atlantic, would lead to a southward shift of the western storm tracks redistributing precipitation away from Scandinavia and towards central and southern Europe.

In addition, a positive correlation has been reported between the amount of the Arctic ice and winter–spring extratropical storminess [55]. Given that the same pattern also holds in the summer, a less stable atmosphere and an increase in the number of lightings leading to fire ignitions may further enhance regional fire hazard. Consistent with this assumption, modelling studies have indicated an increased frequency of mid-latitude storms during the Little Ice Age (LIA) [56], which could be related to higher meridional flow [57]. The overall pattern of increased fire activity under a cooler climate [15] may not be unique for Scandinavia. A dendrochronological reconstruction of fire activity in western Quebec has revealed a higher fire frequency during LIA than during the following warmer period [58]. However, as climatological fire danger reflects a balance between precipitation and temperature controlling evaporation, it is the combination of trends in both factors that ultimately control fire activity.

Future of the Scandinavia Boreal Fire Activity

Our study does not support the results of GCM experiments predicting higher aridity and, therefore, higher fire hazard in Scandinavia under the future climate [59]. According to the patterns revealed in this study, warming of the Arctic and the decline in sea ice extent under solar or human-related forcing [60] should translate into higher precipitation in Scandinavia due to stronger NAC and the associated westerly air and moisture atmospheric transport. In particular, the northward propagation of the thermohaline anomalies predicted under the future climate [61] imply warmer Atlantic SSTs, a lower amount of Arctic ice, and a likely decline in regional fire activity of Nordic countries as a result of increased air humidity. Discrepancies between empirical and modelling results may point to a lack of adequate parameterization of regionally important features of ocean-atmospheric circulation, affecting forest fire regimes. Another interpretation may explain differences in predictions by changes in the sensitivity of fire regimes to temperature and precipitation dynamics. In particular, a future increase in fire season precipitation may be overridden by a larger increase in temperature, resulting in higher aridity and fire regimes being more temperature-driven. In line with this interpretation is the predicted warming of the Arctic [62] and boreal regions with increasingly de-glaciated Arctic and North Atlantic [63] functioning as a heat contributor to the atmosphere, especially during the autumn season [64]. However, analyses on multiple temporal scales over the Holocene have shown consistency in the empirically observed association between generally cooler periods and increased boreal fire activity under different climates [15], which does not appear to support the idea of the change in sensitivity of fire regimes to precipitation. In fact, the general decline in the extent of the Arctic ice has been suggested to translate into higher precipitation in the boreal regions [65]. This pattern has received further support from the analyses of water vapor isotope ratios in the Greenland ice core over the Holocene [66]. We conclude that the Arctic climate will likely be an important control of the future boreal fire activity in the Nordic region.

Supplementary Materials: The supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13010060/s1. Figure S1. Field correlation between detrended fire record over Northern Sweden and Norway and 3-month SPEI over May–July. The field significance is <0.1%.

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Abbreviations

AMOC	Atlantic meridional overturning circulation
ENSO	El Niño Southern Oscillation
ERA5	The 5th generation ECMWF Atmospheric Reanalysis of the Global Climate
GCM	global circulation model
LIA	Little Ice Age
NAC	North Atlantic Current
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
SIC	sea ice cover
SPEI	Standardized precipitation-evapotranspiration index

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