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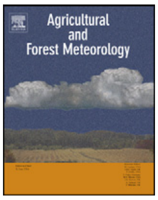

Forest fire activity in Sweden: Climatic controls and geographical patterns in 20th century

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ABSTRACT

We used Swedish county-scale forest fire statistics to quantify modern fire activity, identify its main temporal and geographical patterns, and evaluate statistical performance of six fire-related weather indices as proxy of fire activity in Sweden over 1942–1975 and 1996–2008, the periods with available county-scale fire statistics. The analyzed indices were monthly precipitation, SPI, MDC, PDSI, calibrated PDSI, and DI, a Drought Index calculated as a ratio between actual and equilibrium evapotranspiration. The modern fire cycle (FC) in the northern part of Sweden varies between 2×10^3 and 3×10^4 years, whereas in southern Sweden the FC is somewhat shorter (10^3–2×10^4 years). No temporal trend in average FC was evident at the country scale between the two periods. Significant and negative values of a Mantel test, obtained on county data for both periods ($r = -0.494$, $p = 0.001$ for 1942–1975 and $r = -0.281$ and $p = 0.015$ for 1996–2008) indicated the presence of a geographical pattern in annual forest fire activity. Over 1942–1975, PCA revealed that the central and northern counties formed one group with synchronized fire activity, and the southern and south–western counties formed another group. This pattern became less evident during the more recent period (1996–2008). Over 1996–2008, the analysis showed little synchronicity in annual fire activity across different parts of the country. The geographical position of a county had a clear effect on seasonal pattern of forest fires. In southern Sweden, the peak in the number of fires and the burnt area was in April–May, during a relatively short dry period immediately following the snowmelt. In northern Sweden, fires in the second half of fire season dominated the total annual area burnt. Analyzed indices differed considerably in their predictive power in respect to counties' records of annual area burnt. Calibrated PDSI was a superior proxy of fire activity for the southern region ($R^2 = 60.8\%$ in regression against total annual area burnt for respective provinces), and DI_{late} (Drought Index for the first half of the growing season) was superior for the northern counties ($R^2 = 73.3\%$). Predictive power of the indices was much higher for the recent period (1996–2002), with R^2 values staying within 81.2 and 97.8%. Even if modern levels of forest fire activity in Sweden are very low from historical perspective, there is a strong spatiotemporal association between fire activity and climatic variability at regional scales, which provides a basis for modeling of the future fire hazard.

1. Introduction

Forest fires have historically been a major disturbance factor in boreal landscapes, affecting forest dynamics (Zackrisson, 1977; Sannikov and Goldammer, 1996; Johnstone and Chapin, 2006), biodiversity (Granström, 2001; Schimmel and Granström, 1995), and contributing large amount of aerosols and greenhouse gases into the atmosphere (Amiro et al., 2001; Mouillot and Field, 2005; Bond-Lamberty et al., 2007). Forest fires provide complex economic impacts in affected regions (Bergeron et al., 2001; Yadav and Kaushik, 2007), and understanding of their environmental controls is therefore crucial for developing sustainable forest management polices (Johnson and Wowchuk, 1993). At finer spatial scales, landscape properties and human influences on both fuels and ignition frequency become increasingly more important, obscuring the role of climate (Wotton et al., 2003; Wallenius et al., 2004; Drobyshev et al., 2010).

Despite considerable fire suppression efforts (Cumming, 2005), many parts of the Northern Hemisphere boreal and hemi-boreal

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zone still experience patterns of fire activity primarily driven by climate variability (Bridge et al., 2005; Drobyshev and Niklasson, 2004). Examples of such regions are boreal Canada (Stocks et al., 2002) and the European as well as Asian parts of boreal Russia (Conard and Ivanova, 1997; Gromtsev, 2002). For instance, in the eastern part of European Russia, the annual burnt forested area can reach up to 5% of the total forest area (Drobyshev and Niklasson, 2004). In Scandinavia, forest fires have been increasingly controlled since the second half of the 19th century with the percentage of area burnt rarely exceeding 0.001% of the total forest area (SVO 2010). Particularly dry summers, as in 1992, 2002, and 2008 were nevertheless associated with higher frequency of forest fires (Räddningsverket 2010 database).

Climatic change resulting from increased greenhouse gas emissions may bring important changes in the intensity of regional fire activity. Although recent studies have demonstrated a general increase in precipitation over Scandinavia in the past decades (Hanssen-Bauer et al., 2005), projections of summer precipitation indicate drier summers in the future (Rummukainen et al., 2004), which can make fuels and weather conditions more conductive to large fire episodes. It is therefore of immediate practical interest to establish a link between weather conditions and regional fire activity.

In this paper we approach this task by analyzing the spatial and temporal patterns in modern forest fire activity in Sweden and their association with fire-related climatic and bioclimatic proxies. Specifically, we analyze county fire records, available for two periods, 1942–75 and 1996–2008. Our main goals were to

(1) Identify main geographical patterns of forest fires, and
(2) Evaluate applicability of different climate indices as proxies for sub-regional fire activity in Sweden.

Prior to analyses we make the following four assumptions. First, we assumed that aggregating data at county level (Swedish *län*) should increase the climatic and decrease the non-climatic (landscape- and human-related) signals in analyzed time series. County level fire statistics represented therefore a reasonable compromise between our interest in identifying large climate related patterns and the possibility to analyze sub-regional differences in fire activity. Secondly, due to the focus of the current study on climate-fire link, we did not consider the effects of fuel conditions or human activities (both promoting fires through providing additional ignition sources and suppressing fires). Although the effects of fuel accumulation has been proven to be of major importance in increasing fire risk in the boreal forests of North America (Amiro et al., 2004; Hyytiainen and Haight, 2010), little is known about this factor in Sweden (Granström, 2009), where its importance may be much more limited. Thirdly, in this study we did not consider the role of ignition sources and variation in effective ignition frequency. Although lightning ignitions likely varies across both climatic and vegetation gradients (Granström, 1993; Enoksson et al., 1995), we assumed that, in general, the variation in ignition density (both natural and human-related) is largely overridden by the direct effect of weather on fuel conditions. Finally, we considered the quality of the fire statistics and weather data being homogeneous across the study area and over the analyzed periods. Although this might not be the case, especially for the earlier analyzed period, no sound data and methodology was a priori available to adjust for such effects. In fact, this study may provide means of correcting for human biases by establishing a weather proxy for fire activity.

2. Study region

The total land area of Sweden is 41.3 × 10^6 ha, of which about 23 × 10^6 ha are forested (Skogsstyrelsen, 2010). Only 3% of the total forested area is considered as being in a natural state, i.e. not affected by human activities (Skogsstyrelsen, 2010). Sweden stretches over six bioclimatic domains, including the alpine zone, northern boreal forests, mid- and south boreal forests, boreonemoral and nemoral forests (Ahti et al., 1968). The main tree species in the boreal zone are Norway spruce (*Picea abies* (L.) H. Karst), Scots pine (*Pinus sylvestris* L.), with birches (*Betula pubescens* Ehrh. and *B. pendula* Roth) representing the deciduous vegetation. Hardwoods, primarily pedunculate and sessile oaks (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.) and European beech (*Fagus sylvatica* L.), become important components in the natural and semi-natural forests below ca. 59°N lat. (Nilsson, 1996). The proportion of forested area varies among provinces with values ranging between 35.5% (county of Skåne) and 77.9% (county of Västernorrland). Fires have been historically one of the major disturbance factors across different forest types in Sweden (Niklasson et al., 2002, 2010; Niklasson and Granström, 2000), where typical fire-return intervals at stand level ranged from 20 to 100 years before the fire suppression era (Niklasson et al., unpublished).

3. Methods and data sources

3.1. Climatic data

We used climatic data produced within the frame of the ALARM project (Mitchell and Jones, 2005). The data sets of monthly total sum of precipitation, average monthly temperature, average maximum monthly temperature, and average monthly cloud cover, were resolved on a 0.16670° grid (approx. 16 km × 16 km). The soil water holding capacity was set to 50 mm. This value was lower than in previous studies (150 mm in Sykes et al., 1996, and 100 mm in Drobyshev et al., 2011). Preliminary model runs revealed that lowering the value for water holding capacity generally resulted in higher R^2 values, probably due to better representation of the water balance of the upper soil layers. The spatial frame used in the calculations was limited by a rectangular area with the SW corner at 53.08°N 4.75°E, and the NE corner at 71.08°N 28.08°E, corresponding to the following points in ALARM notation: 95–115 (SW corner of the frame) and 235–223 (NE corner). Since ALARM data set ends in 2000, we used CRU TS 3.0 data for the analysis over 1996–2002 (Mitchell and Jones, 2005). The data is available globally at 0.5° resolution and at monthly temporal scale. Although original data set extends over 2006, cloudiness data, required to calculate Drought Index (see below), was available only till 2002.

3.2. Fire data

In Sweden instrumental data on single big fire years is available since the late 1800s (Högbom, 1934). In this study, an official forest-fire data set, produced by the Swedish Forestry Board www.svo.se (Skogsstyrelsen, 1945) was used to obtain county-specific data for 1942–1975 and country-wide data for 1975–1996. Data for the 1996–2008 period was obtained from the Swedish Civil Contingencies Agency (Myndigheten för samhällskydd och beredskap, www.msb.se). For both periods we only selected fires reported on forested land. No thresholds on fire sizes were given in either data set, although fires below 0.1 ha in size were absent in the forest statistic data for the 1942–1952 period.

3.3. Indexes

To relate climate variability with fire record we used monthly precipitation data and five indices of fire-weather: Palmer Drought Severity Index (PDSI) (Palmer, 1965), calibrated PDSI (Wells et al., 2004), Drought Index (DI) (Prentice et al., 1993), monthly drought code (MDC) (Girardin and Wotton, 2009), Standardized Precipitation Index (SPI) (McKee et al., 1993). Indexes had different input data requirements, temporal frames, and resolution (Table A in Appendix A). All calculations were done using various monthly data as input. Below we provide a short summary of the calculation principles for each of the indices.

PDSI is a water balance index combining precipitation, evapotranspiration, and water loss due to runoff (Palmer, 1965). Recently, a new version of PDSI was developed to allow comparison of drought intensities at locations with different long-term means of precipitation and temperature. The new version of the index, termed self-calibrating PDSI (Wells et al., 2004), is calculated by fitting a gamma function to the distribution of original PDSI values from each point. This essentially makes PDSI values calculated at different geographical locations comparable with each other.

The SPI is an index based on the probability of recording a given amount of precipitation at a specific point and can represent precipitation dynamics over user-selected time frames (McKee et al., 1993). A gamma function is used to standardize the probabilities and the value of zero indicates the median amount of precipitation. In practical terms, this value defines the point for which half of the recorded values are smaller or higher than that point (see http://www.wrcc.dri.edu/spi/spi.html).

DI was calculated as a ratio of actual to equilibrium evapotranspiration (AET/EET) over the period with average daily temperature above a defined threshold. The evaporative demand (EET) was understood as a function of net radiation and temperature, which approximated actual evapotranspiration when water supply is not limited. To calculate DI we re-programmed a version of the STASH model, which was originally developed to study the effect of climate changes on species distributions using factors considered to be physiologically important for the individual plant species (Sykes et al., 1996). Similar to PDSI (Briffa et al., 1994), the DI is calculated in a cumulative fashion, integrating the interplay of water supply and demand at seasonal, annual, and intra-annual scales. However, unlike these indices, DI takes into account radiation regime of a site over the whole year, which, together with temperature data, may allow for more biologically meaningful estimation of actual evapotranspiration demand, or, in the context of the current study, water balance of the forest fuels. Additional details of model design and calculation algorithms are available in Prentice et al. (1992, 1992) and Drobyshev et al. (2011).

In the following analyses we used indices, which were based on some mechanistic models, reflecting the amount of humidity in the upper soil horizons. Simple statistical indices, lacking such model in their computation, were therefore excluded from the analyses (e.g. the Angstrom index - Langholz and Schmidtmayer, 1993, and the Nesterov index - Nesterov, 1949). We also excluded Keetch–Byram Drought Index, since it was mainly designed for operational monitoring of fire risk (Keetch and Byram, 1968) and thus less appropriate for analysis of long-term (monthly scale and above) water deficit (Chan et al., 2004).

3.4. Statistical analyses

The presence of spatial patterns in the counties' fire histories was evaluated using the Mantel test (Mantel, 1987) run on a pair of matrixes: a matrix of distances between geographical centers of each county and a matrix of pair-wise correlations between annual burnt forest area in each province. The test was run on two periods: 1942–1975 and 1996–2008. The number of test permutations was 1000 in each case.

To assess the spatial extent of fire activity, we used the fire cycle statistic (FC, also termed *fire rotation*) defined as the period (in years) required to burn an area equal to the study area (Van Wagner, 1978). We calculated the FC as:

$$FC = \frac{T \times Area_{study}}{Area_{burned}},$$

where T is the length of the time period with available data in years; $Area_{study}$ and $Area_{burned}$ are the total forested area within a county and the forested area burnt in that county over the considered time period (in ha), respectively. Temporal changes in the FC were tested by the Wilcoxon match pairs text, a non-parametric alternative for *t*-test for dependent samples (Wilcoxon, 1945).

Principal component analysis PCA (Kruscal and Wish, 1978), based on the correlation matrix, was used to convert counties' fire records into a series of non-correlated principal components (PCs) for both time periods. Loadings of each province were mapped to visually identify sub-regions with synchronous fire activity. PCA was carried out separately for the two periods. In both cases we retained PCs with eigenvalue above the threshold value of 2.0, reflecting meaningful contribution of PC to the total data set variability.

Based on the PCA, the total amount of annually burnt areas was aggregated for groups of counties. These sub-regional chronologies of annually burnt area were regressed against precipitation data and the fire weather indices, calculated for each grid point. Following spatial resolution of original climate data sets, precipitation data and fire weather indices were gridded at 0.167° (ALARM data) and 0.5° (CRU data) for 1942–1975 and 1996–2002 periods, respectively. To account for possible/eventual non-linear relationship between fire chronology and weather data we used linear or exponential regression for each point and selected the one with the highest R^2.

Due to the nature of the used data sets, we could expect spatial autocorrelation effects in the results. First, there was a spatial autocorrelation in the climate data used to generate the fire weather indices. We, however, did not consider that as a problem in the current study. Climate itself is a phenomenon which is highly spatially autocorrelated. Although our computations were on single grid-cell level, our analyses and discussion were at the level of large sub-regions ($>10^2$ cells) - thus avoiding the effects of spatial autocorrelation among neighboring cells. Secondly, the spatial resolution of climate data was much higher ($\sim 10^2$ km^2) compared to the resolution of the sub-regional fire chronologies ($\sim 10^{4-5}$ km^2). This would make interaction between two data sets autocorrelated in space, since the same fire chronology would be used against multiple and partly autocorrelated climate grid points. In a sense, it was an inherent problem of the fire data set: to minimize random effects while estimating annually burnt areas, especially in a country with effective fire suppression policy, one has to capitalize over large areas, "moving" the scale of consideration away from the one of the climate data. Similarly to the first instance of autocorrelation mentioned above, scaling up the analysis and discussion towards larger geographical scale helped minimize its effects. Finally, we could expect autocorrelation between the two fire chronologies representing southern and northern Sweden. To check for this possibility we reported regression between two fire chronologies during both analyzed periods (1945–1975 and 1996–2008).

4. Results

Since the 19th century, forest-fire activity in Sweden has decreased (Fig. 1). Although a polynomial fit (annual

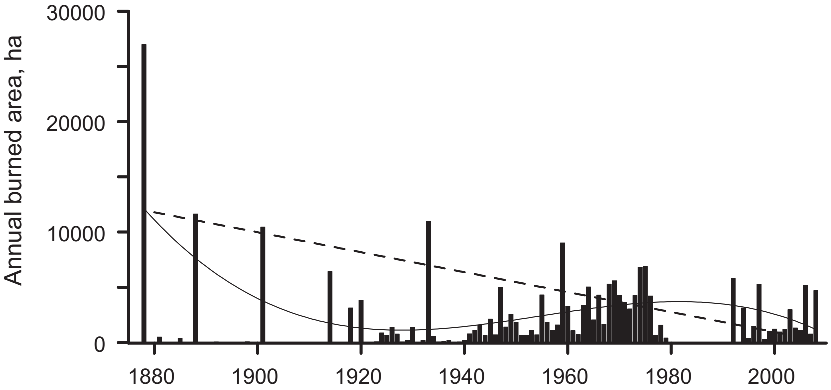


Fig. 1. Total annual forest area burnt in Sweden since 1879 (data compilation from (Hansen, 2003; Högbom, 1934; Skogsstyrelsen, 1945). Polynomial fit (degrees of freedom = 3) for all years (solid line) and linear fit for the maximum annually burnt area in each decade (dashed line) are shown.

area burnt = $2.52 \times 10^8 - 3.87 \times 10^5$ year + 1.98×10^2 year^2 + 3.37×10^{-2} year^3, $R^2 = 26.07\%$) suggested a moderate decline in fire activity, the contribution of large fire years has changed considerably over time. The amount of annually burnt area in large fire years at the end of the 19th century was almost one order of magnitude higher than in the following century (maximum annually burnt area = -9.03×10^{-1} year + 1.81×10^{-5}, $R^2 = 25.6\%$).

Data for 1996–2008 indicated that most of the fires occurred in spring in both southern and northern Sweden. However, the peak in burnt areas was observed over different periods: during spring period in southern Sweden, and in August in northern Sweden (Fig. 2).

Fire cycle (FC), averaged over the whole country, was 8.3×10^3 years for the 1942–1975 period, and 9.4×10^3 years for the 1996–2008 period (Fig. 3). The difference was not significant ($p = 0.768$). During both periods the lowest FC was observed in counties located in the southern Sweden: 1942–1975 in Stockholm (1.67×10^3 years) and 1996–2008 in Halland (1.75×10^3 years). By selecting the year with the maximum amount of burnt area within each period, we also calculated minimum country-wide FCs for the respective periods: 1.4×10^3 years (1942–1975) and 2.5×10^3 years (1996–2008). The difference between minimum FCs was significant ($p = 0.008$).

The Mantel test revealed a presence of significant spatial patterns during both periods. Pair-wise correlation with provincial fire records was negatively related to the distance between provinces, resulting in negative Mantel r for both periods: for the period 1942–1975 $r = -0.494$ ($z = 173.662$, $p = 0.001$); for the period 1996–2008 $r = -0.281$ ($z = 234.503$, $p = 0.015$). Regressing annual areas burnt in two groups of counties (below and above 60°N) against each other showed little correlation between them (Fig. 4).

We used fire statistics from the recent period (1996–2008) to assess synchronicity of large fire years across different counties. Four fire years with annually burnt forest area exceeding 2000 ha were selected: 1997, 2003, 2006, and 2008. Given equal contribution of each year in the total area burnt over the 14 years, a percentage of burnt area above ~ 7% (100%/14 years) would indicate increased fire activity. In most of the counties we did observed increased levels of fire activity, although these increases were marginal. In 1996, clearly increased levels of fire activity (>30%) were observed in Västerbotten, Jämtland, and Västernorrland (Fig. 5A) while a moderate (20–30%) increase was observed in Stockholm. The only year with sharp increase in fire activity in both south and north counties was 2003 (Fig. 5B). Two of the most recent big fire years, considering Sweden as a whole, were due to large areas burnt in one (2006, Norrbotten) or two counties (2008, Gävleborg and Östergötaland).

Over 1942–1975, the three selected principal components (PCs) together explained 54.4% of variability in annually burnt forested area at the county level, with their contributions being 29.9, 14.6, and 9.8%, respectively. Since other components explained less than 9% of the total variability in the data set and their eigenvalues were below subjectively chosen threshold of 2.0, they were not included in subsequent analyses. The first two PCs revealed a well-defined south-north pattern, defining two groups of counties with dividing line at approximately 60°N. The third component represented a southern Swedish pattern in fire activity: it appeared to pick up a west-east gradient from generally summer humid western

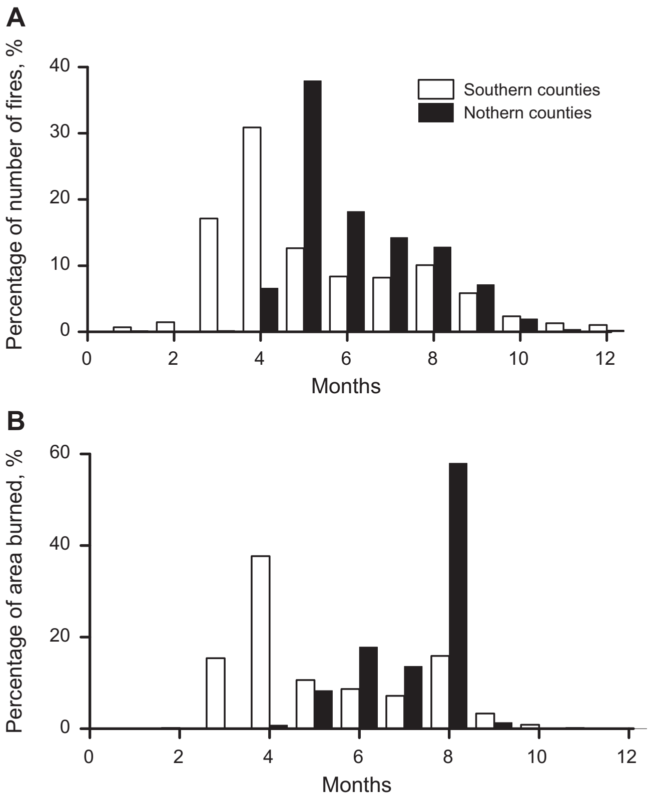


Fig. 2. Seasonal distribution of number of fires (A) and forest area burnt (B) in four most southern (white bars) and two most northern (black bars) counties in Sweden over 1996–2008. Southern counties included Skåne, Blekinge, Halland, and Kronoberg counties. Northern counties included Norrbotten and Västerbotten counties. Percentages are calculated as proportions in the total annual number of fires (A) or total area burnt (B).

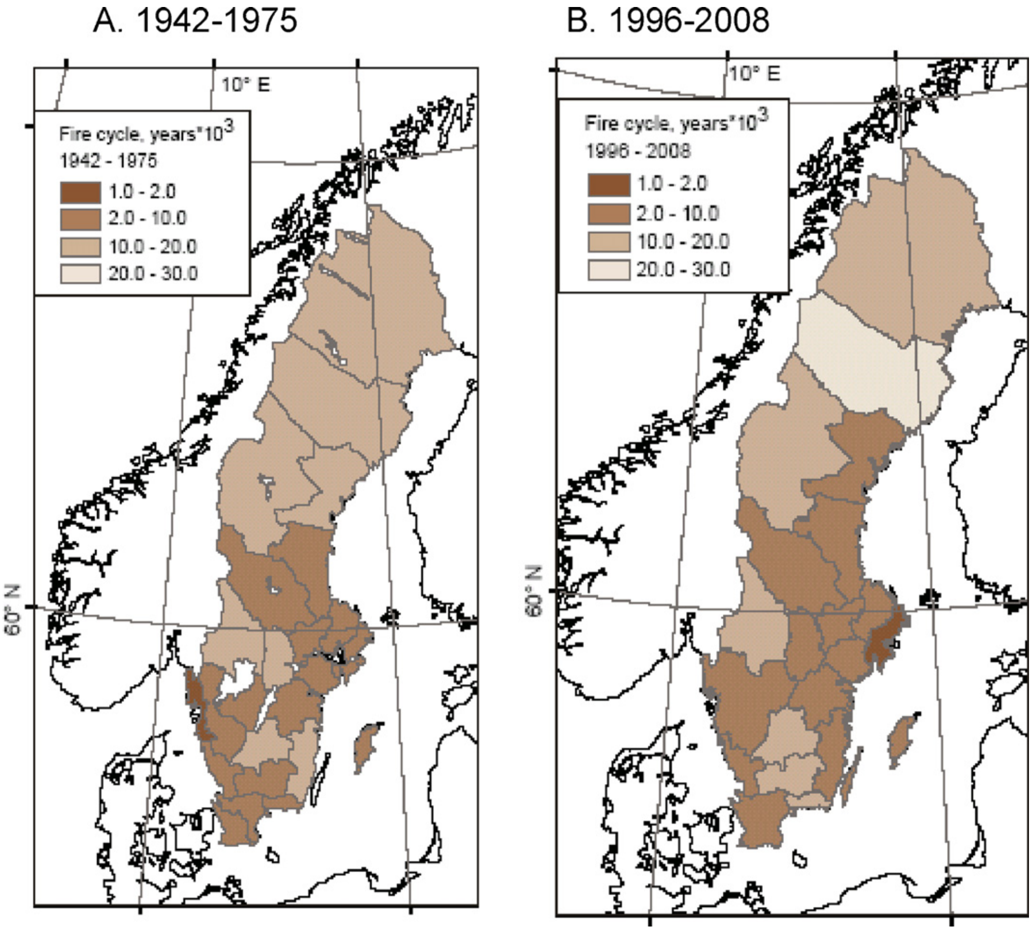


Fig. 3. Fire cycles (FC, thousand years) at the county level in Sweden for two periods: 1942–1975 (A) and 1996–2008 (B).

counties on the western coast to the counties with more continental climate in south-eastern Sweden.

Over 1996–2008, the first three PCs together explained 77.6% of the variance in the fire record, with each PCs contributing to 44.8, 20.3, and 16.3%, respectively. As in previous analysis, we limited the number of PCs to the first three components due to a large drop in PC's eigenvalues at transition between PC3 and PC4 (from 3.47 to 1.41) and keeping in mind relatively short fire record ($n_{\text{years}} = 13$), particularly, in respect to the number of counties ($n_{\text{counties}} = 21$). Similarly to the analysis of the 1942–1975 period, first three PCs generally represented south-north gradients, although some differences were evident. The overall pattern was much less pronounced as compared to the earlier period. Both group of southern and northern counties with high absolute PCA scores had more southerly position as compared to the earlier period.

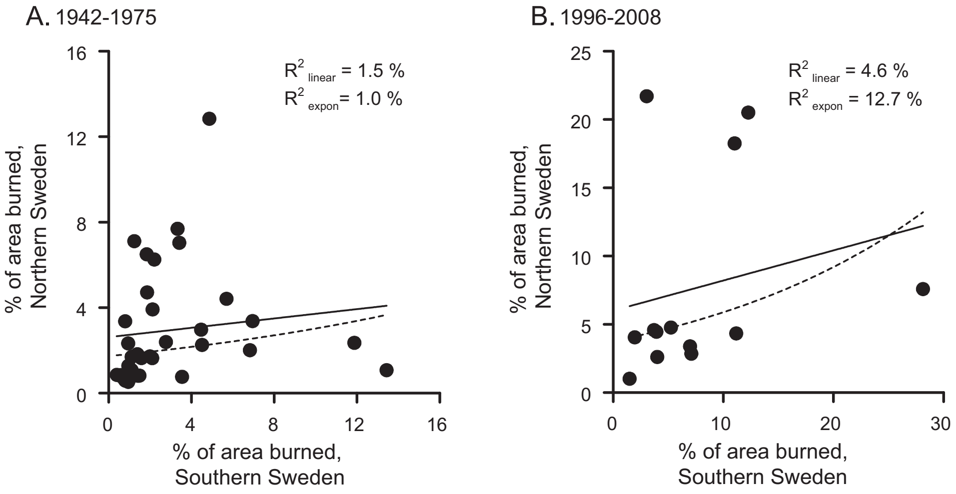


Fig. 4. Relationship between proportions of annual area burnt in south and north of Sweden during 1942–1975 (A) and 1996–2008 (B). Amount of variance (R^2) explained in linear (solid line) and exponential (dotted line) regressions is given for each period.

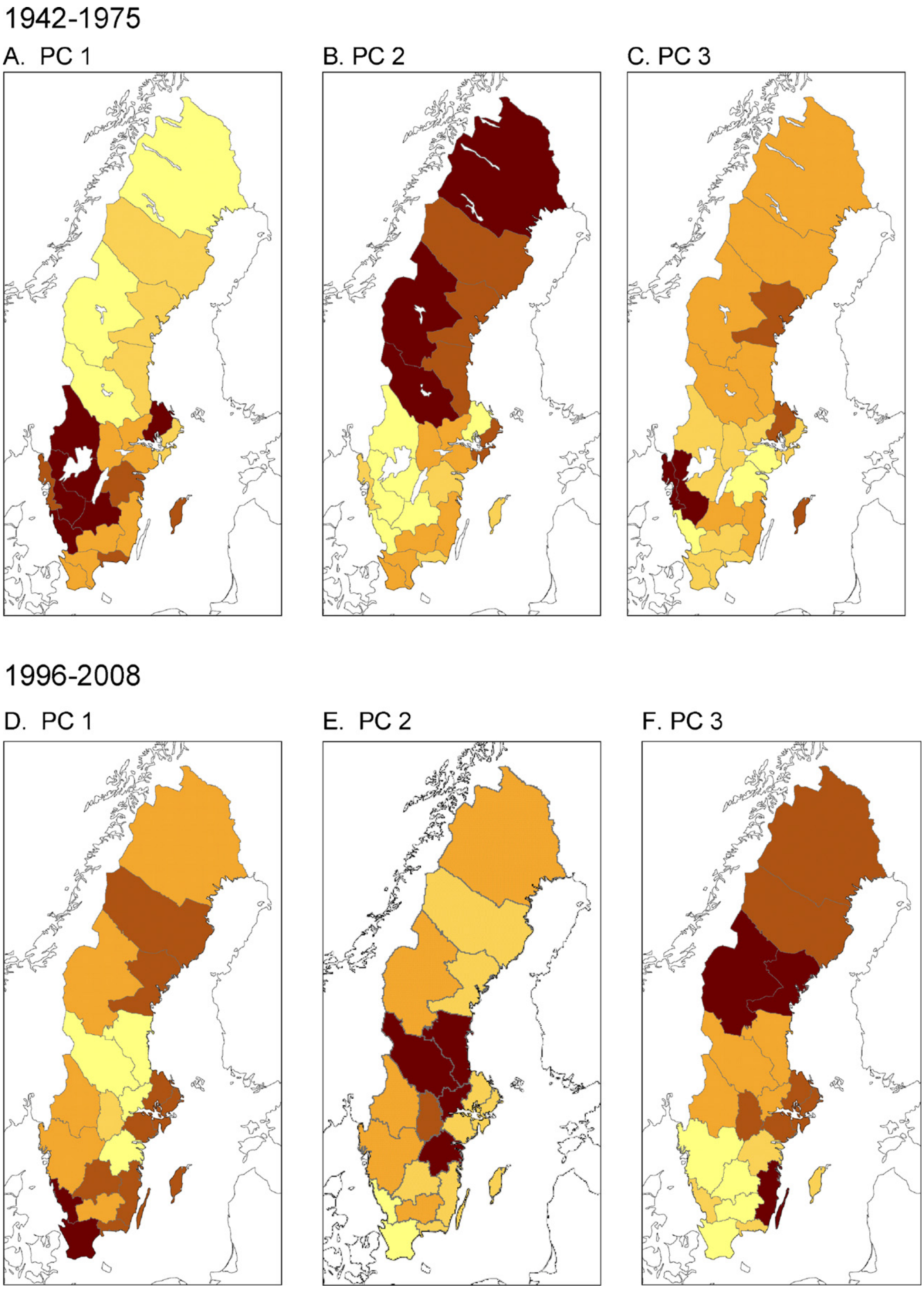


Fig. 5. Loading of three principal components of county-scale fire activity in Sweden for early (1942–1975, A, B, and C) and late (1996–2008, D, E, and F) periods.

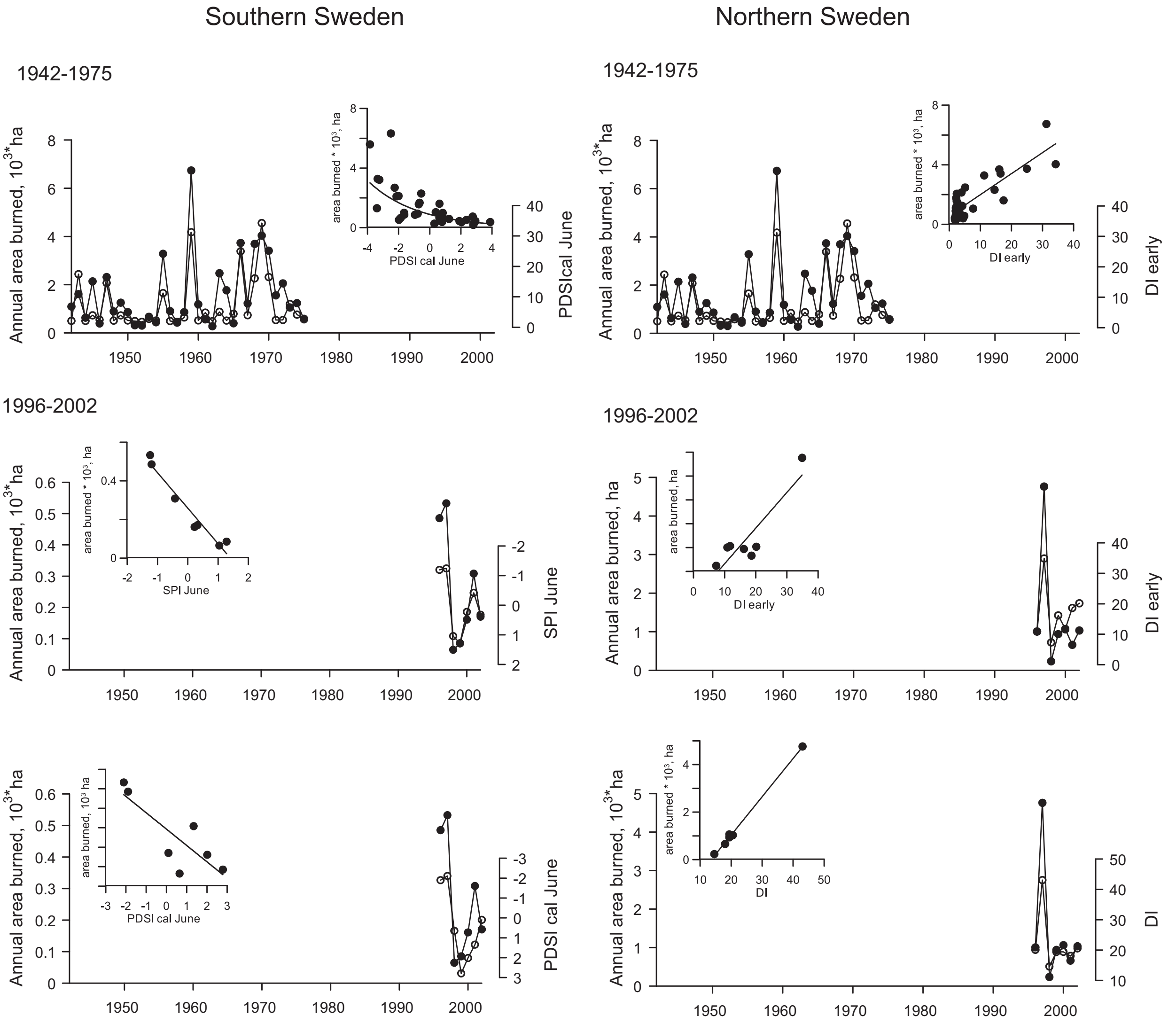


Fig. 6. Chronologies of sub-regional forest burnt areas and corresponding fire weather indices for two periods. Each sub-region is described by three graphs: with the best index for the earlier period, the same index for the later period, and the best index for the later period.

Over 1942–1975, both self-calibrated PDSI (scPDSI) and non-calibrated PDSI showed superior predictive power compared to other indices regarding total annual area burnt in southern Sweden (Table 1). Geographically, the highest R^2 values were observed along the Swedish east coast between 60° and 58°N (Fig. 6). June was the month with the highest R^2 for all monthly indices analyzed. For the northern part of the country, early season DI was clearly superior over other indices, with the amount of explained variance reaching over 70% (Table 1). Both early season DI and MDC, the two best predictors in this analysis, pointed to the northern part of Dalarna, centered around 62°N 14°E, as the area with highest R^2 (Fig. 6). Another high area R^2 was identified outside Sweden, at the western coast of Finland between 62° and 65°N. Highest R^2 values for other indices occurred somewhat later in the fire season, in June and July.

Over 1996–2002, the R^2 values in the regression analyses increased dramatically in both areas, showing little differences among studied indices. For southern Sweden, SPI for the period May–July and DI for the first part of the growing season were marginally better than other indices (Table 1). All indices pointed to the south-western part of Sweden and southern Norway below 62°N as the areas with highest R^2 (Fig. 7). Surprisingly, another area with high R^2 was located close to the northern coast of the

Table 1
Performance of different indices of fire related weather as proxy of regional fire statistics in Sweden for two periods (1942–1975 and 1996–2000). Data are average R^2 values (in %) for the 100 and 1000 km² areas, respectively, with the best fit between an index and fire statistics. For each index (except Drought Index, DI) the highest values of R^2 are indicated in brackets. DI, DI_E, and DI_L refer to the Drought Index, and Drought Index for the first and second half of the growing season, respectively. The highest values obtained for 1000 km² of each sub-region are marked with bold font. Spatial distributions of two best performing indices for each region and period are shown in Fig. 7. Precipitation refers to the total monthly precipitation. SPI frame was one month in each of the analyses.

Variables	south-western Sweden		Northern Sweden	
	1942–1975	1996–2002	1942–1975	1996–2002
Precip.	39.1–35.0 (6)	96.1–85.8 (6)	45.16–43.4 (6)	93.9–82.2 (8)
SPI	39.2–32.2 (6)	96.0–87.3 (6)	47.5–45.7 (6)	88.2–75.0 (7)
MDC	46.7–40.2 (6)	95.4–82.6 (7)	58.4–54.8 (7)	97.0–94.7 (8)
$PDSI_{non\text{-}calibr.}$	53.3–46.9 (6)	90.6–81.9 (7)	44.4–40.0 (7)	90.4–85.5 (7)
$PDSI_{calibrated}$	**60.8–48.9 (6)**	91.6–83.6 (7)	40.9–32.8 (7)	81.2–67.2 (7)
DI	44.9–40.4	93.8–82.7	54.6–49.9	97.8–94.3
DI_E	42.9–39.5	92.0–75.5	**73.3–63.1**	96.8–96.3
DI_L	31.0–23.8	97.4–86.5	43.0–38.1	96.4–89.6

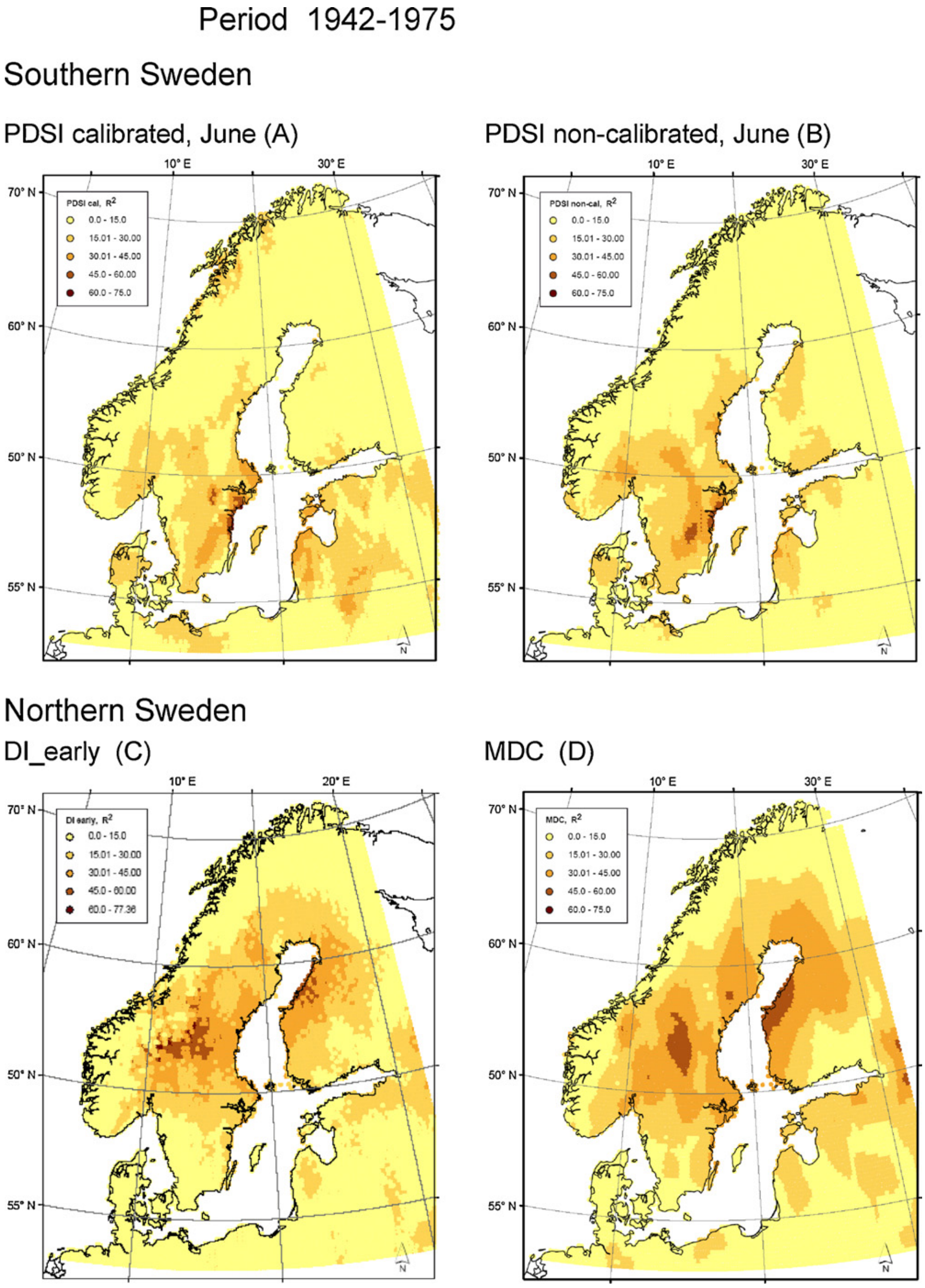


Fig. 7. Predictive power of fire weather indices in respect to county-scale fire activity in Sweden for two periods (1942–1975 and 1996–2002). Note differences in color scales between the periods.

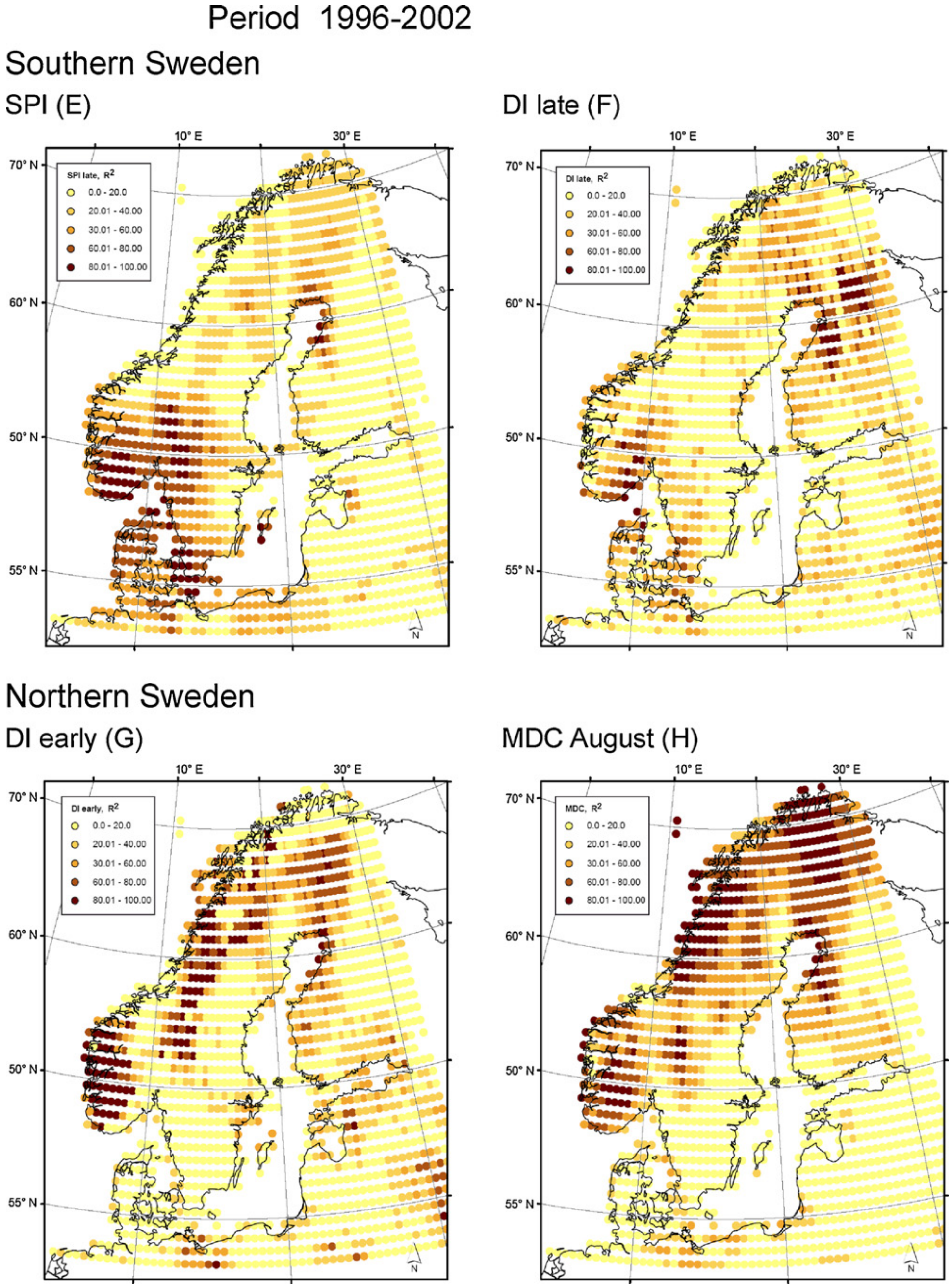
Gulf of Bothnia, at around 65°N (Fig. 7). For northern Sweden, early season DI and MDC in August were marginally better than the other indices. The area with high R^2 values stretched from southern Norway till northern Sweden, partly overlaying with such area in the analysis of the Southern Swedish fire record for the same period.

5. Discussion

5.1. Forest fire activity in Sweden over 20th century

Forest fire activity in Sweden has changed dramatically over the course of the 19th and 20th centuries (Fig. 1). The major trend is a gradual decrease in the annually burnt area, which is particularly evident when the large-fire years are considered. An increasingly effective fire-suppression policy is the primary reason for this change (Granström and Niklasson, 2008). Development of a dense forest-road network, which helped to reduce the time gap between fire ignition and initial attack by fire fighters (Hansen, 2003), have apparently been one of the most crucial conditions for effective fire suppression (Cumming, 2005). The fact that the long-term decrease in annually burnt areas was more evident for the big fire years than for the year with "average" fire activity, indicated a more efficient control of fires which escaped initial attack, i.e. the first fire suppression attempt (Pettersson, 2007; Vidén and Sju, 2009).

In the context of century-long dynamics of burnt areas, forest fire activity in Sweden did not demonstrate a clear long-term trend over the 20th century. Similarly, no clear long-term trends in fire



Period 1996-2002

Southern Sweden

SPI (E)

DI late (F)

Northern Sweden

DI early (G)

MDC August (H)

Fig. 7. (*Continued*)

activity have been identified in several separate studies of boreal forest in Eurasia, where fire chronologies reveal large annual variability (Hayasaka, 2003; Drobyshev and Niklasson, 2004; Yefremov and Shvidenko, 2004). This pattern is quite different from the one observed in many boreal and mixed forests of North America, where the area burnt during single large-fire years has been increasing (Skinner et al., 1999; Fauria and Johnson, 2006). In some parts of the eastern North American boreal forest, however, fire activity has declined, the effect being attributed to increased humidity (Le Goff et al., 2007). Beside climatological explanations, patterns of fuel accumulation may, at least partly, may be important in this context. In Scandinavia, fuel accumulation under natural conditions occurs up to around 40 years after a fire (Schimmel and Granström, 1995), thereafter reaching a steady-state. Another potential contributor for higher fire hazard, encroachment of shade-tolerant species (Niklasson et al., 2002), is less apparent in Scandinavia than in North America, probably due to more intensive forest management with more frequent thinnings.

Modern forest fire activity in Sweden is one to two orders of magnitude lower than the levels estimated in dendrochronological reconstructions available for Scandinavia over 15–18th centuries Fig. 1 (Niklasson and Granström, 2000). Almost the same level of differences exists between modern forest fire activity in Sweden and in the eastern European boreal and mixed forests, where fire suppression is much less efficient and unfragmented natural forests are more abundant (Drobyshev and Niklasson, 2004). In the 20th century, the fire cycle in Sweden has remained relatively stable, and most of its variation was associated with geographical position of the counties. The typical fire cycle in northern Sweden varied from 10×10^3 to 20×10^3 years, while somewhat shorter cycles were common in the southern part of the country (10^3 to 10×10^3 years). Although this pattern showed an overall resemblance to the geographical pattern of natural fire ignitions (Granström, 1993), differences in growing season temperatures (Nilsson, 1996), and longer fire season in the south, were likely factors behind the shorter fire cycle in the southern counties.

Overall, we observed little synchronicity in forest-fire activity at the country scale. As a rule, large fire years in southern Sweden (1960, 1964, 1975–1977) were not noted in the north (1955, 1959, 1963, 1966, 1968–1970, 1972, 2006). Over both periods, less than 30% of the big fire years occurred in both sub-regions (years 1947, 1959, 1997, and 2003). In the earlier period (1942–1975), a geographical pattern revealed from the PC analysis indicated two groups of counties with similar fire regimes located approximately below and above 60°N (Fig. 5). This geographical threshold is in line with the results of a previous study of growing season DI in Scandinavia, which suggested that the detectable influence of westerly transfer of wet Atlantic air on soil water regime during the growing season may reach around 59°N (Drobyshev et al., 2011). This asynchronous behavior of forest fires between southern and northern counties was also visible in the 1996–2008 period, although the division between southern and northern counties was much less pronounced, possibly a result of a poorly conditioned PCA matrix operating with 21 variables (=counties) and only 13 records (=years). During that period, fire activity in three of the most recent large fire years in Sweden (1997, 2006, and 2008) was highly asynchronous at the country scale and dominated by single large fires within single counties (Fig. 8, Vidén and Sju, 2009).

A county's geographical position had a clear effect on seasonal pattern of forest fires (Fig. 2). In southern Sweden, the peak in the number of fires and the burnt area occurred already in April–May, probably during a relatively short dry period immediately following the snowmelt. These were likely grass fires spreading over ground classified as forest in the records. We hypothesize that such areas were, to a larger degree, abandoned and increasingly forested farmland. Since their timing preceded the onsets of both lightning strike season and lightning ignited forest fires (Enoksson, 2010), their origin was most likely human-related (e.g. grass burning). In northern Sweden, it was the fires in the second half of fire season (since August-according to 1996–2008 data, Fig. 2) which dominated the total annual area burnt. In this region, an increase in the area burnt in the second part of the fire season was probably related to declining water content of forest fuels accumulating over the summer. Although no fire severity data is available for forest fire in Sweden (MSB Fire Database 2010), we hypothesize that average fire severity, an important measure of fire-induced transformation of original habitat (Ryan, 2002; Schimmel and Granström, 1995), generally increased from south to north. The most fire-prone period in the south was likely associated with shorter drying period and, therefore, higher fuel water content in the south, as compared to the north.

5.2. *Relationship between forest fire activity and climate–comparison of fire weather indices*

Despite the fact that forest fire activity in Sweden is very low from the historical perspective, total amount of annually burnt area aggregated over large ($\sim 10^4$ km^2) areas revealed a clear association with climatic variability. Periods with strong water deficit (considered in this paper primarily as water deficit of upper soil layers) increased forest fire activity, which pointed to an important role of weather variability affecting fuel conditions, and subsequently, the fire hazard. Although in the current study we present results from two time periods, the following discussion will be primarily based on the analysis of the longer record (1942–1975).

For both 1942–1975 and 1996–2008, annual burnt area in southern and northern Sweden was largely independent from each other (Fig. 4), suggesting different climate systems being responsible for establishment of fire-prone weather. In the southern and especially south–western Sweden, weather is controlled by North Atlantic jet stream reflecting the influence of North Atlantic circulation on North European climates (Mares et al., 2002; Casty et al., 2005). A negative phase of the North-Atlantic Oscillation (NAO) results in decreased cyclonic activity over northwestern Europe, and is associated with negative precipitation anomalies resulting in lower water content of the forest fuels, and subsequently, higher fire hazard. However, the association of the high R^2 area with south eastern coast of Sweden, an area with generally lower precipitation and humidity during the vegetation period (Nilsson, 1996), indicated that local climate was responsible for sub-regional fire activity. We base this conclusion primarily on the analysis of the earlier and longer fire record (1942–1975). The analysis over 1996–2002 period suggested a different picture, the area with high R^2 values being located at the south–western coast of Sweden, close to Kattegat and Skagerrak straights. The later period was very limited in length (seven years), which made it difficult to thoroughly discuss temporal and spatial changes in climate forcing of fire regimes.

Calibrated PDSI was the best predictor of total forest area burnt in southern Sweden over 1942–1975. Despite the fact that PDSI was not the most data intensive index and it used only monthly series of average temperature and total monthly precipitation, it overperformed other indices by a margin of at least 10% (Table 1). We believe its superior performance in southern Sweden could be due to peak of fire activity there being associated with early part of the fire season (Fig. 2) and adequate representation of water balance of still relatively open and not fully forested areas, which are subject to grass fires. Several methodological issues might decrease performance of other indices. Calculation algorithm for MDC assumed fully recharged soil water reserves in April of each year (Girardin and Wotton, 2009), and DI index was analyzed for the period with average temperatures above 10 °C. Assuming that seasonal pattern of fires during 1996–2008 was representative of the one during 1942–1975, both indices might therefore have poor representation of actual water balance during the period of the maximum fire activity early in the fire season. Another reason for sub-optimal performance of DI in Southern Sweden was the consideration that the average temperatures in the early part of the fire season in this part of the country are still relatively low: e.g. average temperature for Lund (55°42′N 13°12′E) in April and May are 5.7, and 10.8 °C, respectively (SMHI 2010). This could prevent DI, originally developed to assess a ratio between actual and potential evapotranspiration, to adequately reflect water balance of forest fuels. Poor performance of SPI and monthly precipitation series probably indicated that adequate estimation of fire hazard required also temperature data.

In northern Sweden, early season DI was the best regressor for the annually burnt forest area over 1942–1975, corresponding R^2 values reaching 73.3%. We hypothesize that additional information provided by monthly cloud cover chronologies might help improve predictive power of this index in relation to other indices. An analysis of North European climate data did not reveal a stable relationship between temperature and cloudiness (Kaas and Frich, 1995), which in the context of the present study indicates that cloudiness might provide a unique contribution to the estimates of fire hazard. Cloud cover is likely related to large-scale pressure patterns which, in turn, are linked to frequency and duration of blocking ridges in the upper troposphere. Periods with blocking ridges typically lead to increased fire hazard, due to prolonged drying of forest fuels (Skinner et al., 1999; Gedalof et al., 2005).

Northern Sweden is characterized by considerable snow accumulation during winter and indices considering precipitation exclusively as rain (PDSI and calibrated PDSI), might have inferior performance (Akinremi et al., 1996). Available data on fire seasonality indicated that the onset of the dominant fire-prone period in

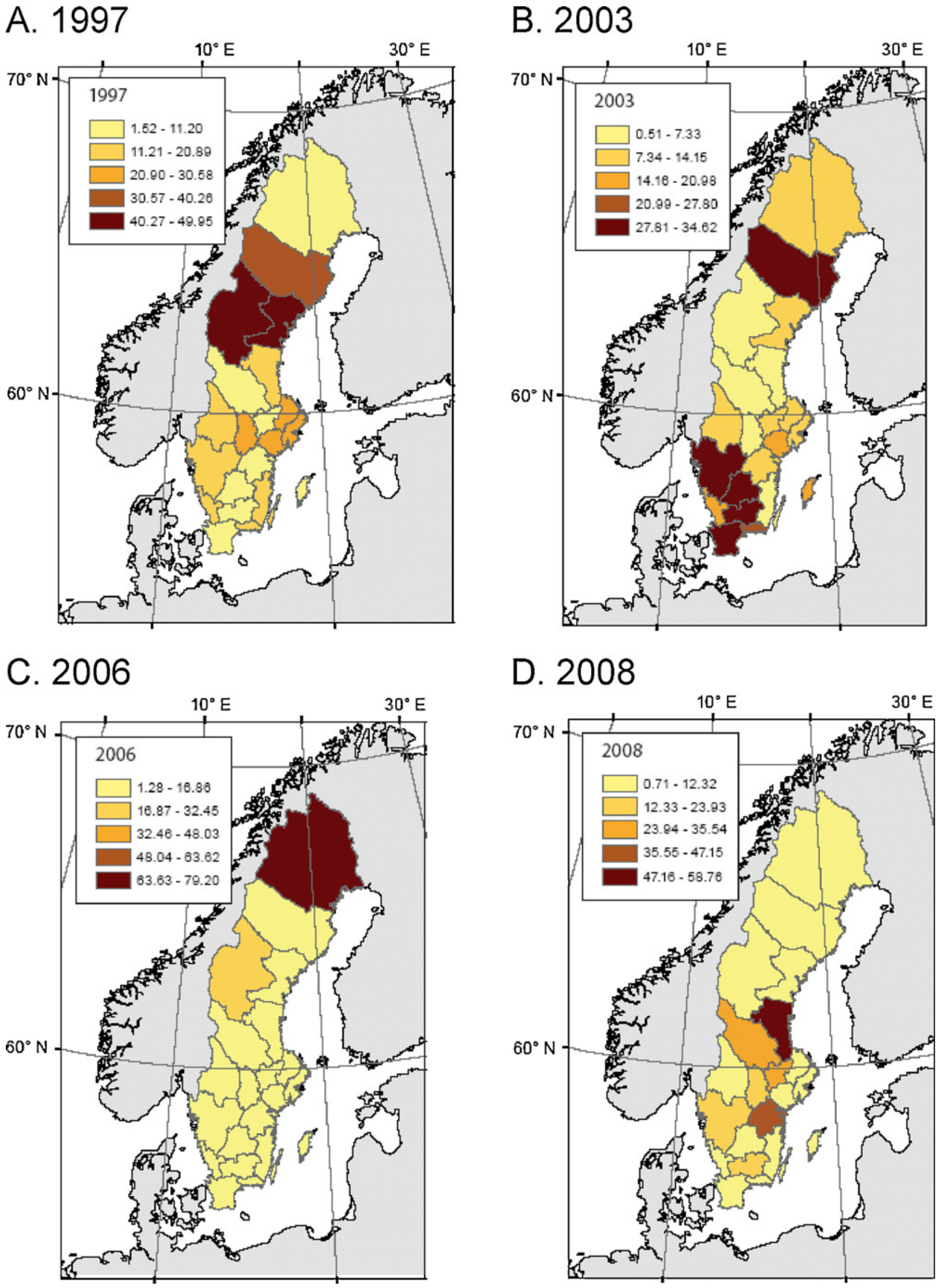


Fig. 8. Deviations from average fire activity (in %) at county level in four the most fire-prone years during 1996–2008: 1997, 2003, 2006, and 2008.

northern Sweden happens in the second half of the growing season. Strong relationship between early season DI and fire activity apparently reflected an important role of water deficit, accumulating over the first part of the fire season, in controlling late season fire activity.

Over 1942–1975, fire activity in northern Sweden showed better correlation with fire weather indices, as compared to Southern Sweden. Seasonal fire pattern might be responsible for these differences. Apparently, peak in fire hazard in the second half of the fire season is better represented by the studied indices, than fire hazard early in the fire season. We suspect that the early season fire activity is largely a product of grass fires spreading into the forests. These may require milder drought episodes as compared to actual forest fires. Additionally, higher population density and generally lower absolute amount of area burnt in the south might result in higher amount of human-related noise in climate-fire relationships and further reduce the amount of explained variability in the southern Swedish fire record.

The origin of highly elevated values of R^2 in regressions between area burnt and all studied indices over 1996–2002 remains unclear. Although we do not exclude the possibility that high explanatory power of indices is a result of strong climate forcing upon modern fire regimes, we express caution in drawing this conclusion, primarily due to very short period analyzed (seven years). Purely statistical effect might partly explain observed pattern. The year 1997 was a large fire year in Sweden and the regression algorithm fitting that year accounted for a considerable part of overall variability in the small data set, thus inflating the R^2 estimate. An example of this effect is the regression pattern between June SPI and area burnt for southern Sweden over 1996–2002 (Fig. 7). However, other indices showed almost perfect fit over the whole gradient of observed values as, for example, DI index for the same area and the period. We do not exclude possibility that improved quality of both climate and fire data might contribute to high R^2 values. Bridging two analyzed periods by obtaining county data for 1976–1995 should be helpful in explaining the sudden increase in explanatory power of fire weather indices.

5.3. *Directions for future work*

Considering the large geographical scale of analyzed fire activity and strong association of burnt areas with climatic indices, it is evident that large scale atmospheric anomalies should be the ultimate drivers of regional fire regimes. Although analysis and discussion of such dynamics is outside the scope of the current paper, we would like to point to two important issues here. First, direct correlation between fire activity and circulation indices may be of little use for these analyses, probably due to difference in their seasonal expressions: fire activity is a primarily late-spring and summer phenomenon in Scandinavia, whereas most of the circulation indices typically describe winter weather (however, see Scherrer et al., 2006). For example, comparison of 1942–1975 and 1996–2008 did not yield significant differences in average Fire Cycle, despite the fact that the former period was generally dominated by negative NAO phase (meaning more fire-prone weather in northern Europe), and the latter-by approximately equal representation of both phases (Mares et al., 2002). Secondly, despite the fact that Scandinavia is a region with strong oceanic influence on weather patterns (Jacobeit et al., 2003), the analyses suggested that fire activity may be strongly controlled by sub-regional weather systems, only indirectly connected to large-scale circulation patterns.

Our study demonstrates that at reasonably large geographical scales (10^3–10^4 km^2) there is generally a strong coupling between climatic variability and forest fire activity, which should provide a solid ground for sub-regional modeling of the future fire hazard. However, lack of information on fuel conditions, ignition frequencies, forest successional pathways, and a considerable variability in temperature and precipitation regimes, documented at decadal and centurial time scales (Alexander et al., 2006), all introduce uncertainties into climate-driven projections of future fire hazard. Modern projections suggest higher precipitation over Scandinavia, although this trend is mostly associated with winter period, with summer precipitation projection indicating regional differences in summer precipitation trends (Hanssen-Bauer et al., 2005). Forest use practices may be equally important in predicting future fire hazard.

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Appendix A.

See Table A1.

Table A1
Input parameters used for calculation of different climatic and bioclimatic indices. All indices used monthly level data. For each index the properties of temporal frame with the highest R^2 values were selected empirically.

Index	Inputs		References
	Time series	Main constants	
DI[a]	Average monthly temperature, total monthly precipitation, average monthly cloud cover	Soil water field capacity, psychrometer constant (65 pa/K), latent heat of vaporization of water (L, $2.5{\cdot}10^6$), short-wave albedo (β, 0.17), solar constant 1360 W m^{-2}, clear-sky transmitivity ($c+d$)	Prentice et al., 1993
SPI	Total monthly precipitation		McKee et al., 1993
PDSI & PDSI$_{cal}$[b]	Average monthly temperature, total monthly precipitation,	Latitude, soil water field capacity, tolerance parameter (10^{-5}).	Palmer, 1965 Wells et al., 2004
MDC	Average monthly temperature, total monthly precipitation, maximum monthly temperature	Day length adjustment factor (L)	Girardin et al., 2004

[a] DI$_{early}$ and DI$_{late}$ are DI indices calculated for the first and the second halves of the vegetation season, respectively. In all cases, the growth season was estimated individually for each year and grid point analyzed.

[b] Calibrated PDSI.

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