Linking tree rings, summer aridity, and regional fire data: an example from the boreal forests of the Komi Republic, East European Russia

Igor Drobyshev and Mats Niklasson

Abstract: To evaluate the potential use of tree-ring data as a proxy for fire activity at the scale of a large boreal region, we analyzed a set of regional tree-ring chronologies of Siberian larch (*Larix sibirica* L.), a spatially implicit annual fire record, and monthly climate data for the Komi Republic for the period 1950–1990. In most years, annually burned area was below 0.001% of the republic's forested area and reached up to 0.7% during fire-prone years. Principal components (PC) of summer aridity resolved 64.2% of the annual variation in the number of fires, 12.2% in the average fire size, and 59.2% in the annually burned area. In turn, tree-ring PCs explained 65.2% of variation in fire-related weather PCs. Dendrochronological reconstruction of the annual number of fires and of the log-transformed annually burned area predicted 27.0% and 40.1% of the high-frequency variance of these variables, respectively. Coefficient of efficiency, a measure of reconstruction usefulness, reached 0.081 (number of fires) and 0.315 (annual area burned), supporting the obtained index as a realistic proxy for regional fire activity. Decadal variation in coefficient of efficiency values suggested improved monitoring accuracy since 1960 and more effective fire suppression during the last studied decade (1980–1990).

Résumé : Dans le but d'évaluer le potentiel des données dendrochronologiques comme substitut pour l'activité du feu à l'échelle d'une vaste région boréale, nous avons analysé un ensemble de courbes dendrochronologiques régionales du mélèze de Sibérie (*Larix sibirica* L.), des données annuelles spatialement implicites sur les feux et des données mensuelles sur le climat pour la région de la république de Komi pour la période de 1950 à 1990. La plupart des années, la superficie brûlée annuellement représente moins de 0,001 % de la superficie boisée de la république et augmente jusqu'à 0,7 % lors des années plus favorables au feu. La composante principale reliée à l'aridité estivale explique 64,2 % de la variation annuelle dans le nombre de feux, 12,2 % de la dimension moyenne des feux et 59,2 % de la superficie brûlée annuellement. De son côté, la composante principale reliée aux données dendrochronologiques explique 65,2 % de la variation dans la composante principale reliée au climat propice au feu. La reconstitution dendrochronologique du nombre annuel de feux et le logarithme de la superficie brûlée annuellement prédisent respectivement 27,0 % et 40,1 % de la variance à haute fréquence de ces variables. Le coefficient d'efficacité, une mesure de l'utilité d'une reconstitution, atteint 0,081 (nombre de feux) et 0,315 (superficie brûlée annuellement), ce qui indique que l'indice ainsi obtenu est une représentation réaliste de l'activité du feu à l'échelle régionale. La variation décennale de la valeur du coefficient d'efficacité indique que la précision des relevés s'est améliorée depuis 1960 et que la répression des feux a été plus efficace au cours de la dernière décennie étudiée (1980–1990).

[Traduit par la Rédaction]

Introduction

Fire is usually considered to be one of the major natural disturbance factors in boreal forests (Zackrisson 1977; Bergeron and Dansereau 1993; Furyaev 1996; Niklasson and Granström 2000). It significantly affects the properties of the earth's atmosphere (Dixon and Krankina 1993; Goldammer and Furyaev 1996; Conard and Ivanova 1997; Flannigan et al. 1998) and has a strong impact on temporal and spatial patterns of biodiversity, soil–plant interactions, and soil microbial activity (Zackrisson 1977; Crete et al. 1995; Granström 1996; Wardle et al. 1998; White et al. 1998; DeLuca et al. 2002). Thus, a better understanding of the interplay between the factors affecting the natural fire-regime pattern in boreal forests is important.

Variation in fire regimes has been documented at different temporal and spatial scales (Bergeron and Archambault 1993; Swentam 1993; Flannigan et al. 1998; Veblen et al. 1999). Regional climatic and topographic conditions ultimately define the properties of vegetation cover and biomass accumulation rate. The weather controls fuel conditions, ignition possibility, and fire propagation rate (Johnson 1992; Granström 1993). At decade- and century-long time scales, human control of forest use introduces an additional variation into fire behavior and in many cases masks the climatic

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I. Drobyshev.[1] SUFOR Project, Department of Plant Ecology, Ecology Building, Sölvegatan 37, Lund University, S-223 62 Lund, Sweden.
M. Niklasson. SUFOR Project, Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences (SLU), Box 49, 230 53 Alnarp, Sweden.

[1] Corresponding author (e-mail: Igor.Drobyshev@ekol.lu.se).

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Fig. 1. The Komi Republic, showing the locations of the climate stations (circles) and sites with available *Larix sibirica* chronologies (boxes), which were used in the study.

and (or) weather signal in fire chronologies (Johnson et al. 1990; Niklasson and Granström 2000). This is particularly the case for the European boreal forests, where a long history of human activities and, especially, a long history of fire suppression (Lehtonen et al. 1996; Parviainen 1996; Pyne 1996; Pitkanen and Huttunen 1999) effectively hinder the analysis of natural fire behavior under the current climate.

In the present paper we consider an annually resolved and spatially implicit record of fire activity in the forests of the Komi Republic, one of the most eastern boreal regions of European Russia, where large areas of natural forest still exist (Korchagin 1940; Kozubov et al. 1999; Kozubov and Taskaev 1999). Because of the large area of the republic (415 900 km^2), most of which is covered by natural boreal forest, a strong link could exist between weather variation and fire activity. To find evidence for this link and to consider the value of tree-ring data as a proxy for fire-related weather, we contrast the annual record of fire activity in Komi against climate data sets and published regional larch (*Larix sibirica* L.) chronologies (Schweingruber et al. 2000). Specifically, we address the following questions: (1) Can the fire record of the Komi Republic be used as a reliable proxy for the natural fire activity at the regional scale? (2) How does regional fire behavior relate to annual weather variation when considered at a monthly resolution? (3) Can tree-ring data be related to the annual pattern of fire activity at the scale of a large boreal region?

The use of daily data for the analysis of fire behavior is clearly preferable to the use of monthly and annually resolved data sets (Campbell and Flannigan 2000; Nash and Johnson 1996). However, tree-ring data typically contain climate signals at much coarser temporal scales, which makes the dendrochronological reconstructions of fire behavior inherently difficult. In this paper, we did not attempt a reconstruction of fire activity directly from tree-ring data. Instead, we approach the problem by establishing a link between fire and weather parameters and by reconstructing fire-related weather variables from tree-ring chronologies.

Material and methods

Study area

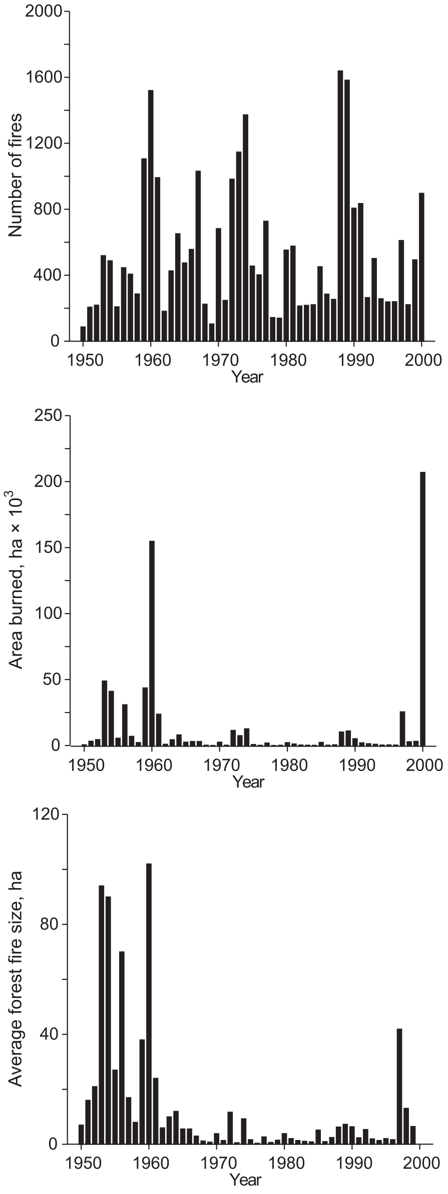
The Komi Republic lies within arctic, Atlantic–arctic and Atlantic–continental provinces (Republic of Komi 1997, Fig. 1). Annual average temperature varies between 1 °C in the southern part of the republic and –6 °C in its northern part, with the respective lengths of the growing season (days with average daily temperature above 10 °C) being between 110 and 45 days. Annual total precipitation decreases from 700 mm in the south to 450 mm in the north. Accumulation of thick snow cover (70–80 cm) is characteristic of the winter period, which lasts 130–200 days. For most of the Komi Republic, there are between 4 and 8 days with high forest fire hazard annually (Khairullin 1997).

The Komi Republic is the most forest-rich region in the northeastern part of European Russia (Fig. 1). It occupies 4.159 million km^2 (Komi 1981). The forested area totals around 30.0 million ha, which constitutes 4.1% of all Russian forested areas and 3.9% of exploitable timber (Kozubov and Taskaev 1999). Middle and northern taiga forests prevail in the vegetation cover of Komi, with the exception of the mountainous part of the republic where forest–tundra and tundra ecosystems develop (Kozubov et al. 1999). Boreal vegetation is dominated by two pine species (*Pinus sylvestris* L. and *Pinus sibirica* Du Tour), Siberian spruce (*Picea obovata* Ledeb.), and Siberian fir (*Abies sibirica* Ledeb.). Birch (*Betula pubescens* Ehrh.) forests form the early stages of postfire succession (frequently with abundant *Populus tremula* L.). In the Ural mountains, *Betula pubescens* subsp. *tortuosa* Ehrh. climax-type stands form at the tree-line. Mires, mostly raised bogs, make up 3.2 million ha, or 8% of the republic's territory (Kozubov and Taskaev 1999). A considerable amount of the republic territory (14.6%) is formally protected through the establishment of nature preservation areas.

Fire suppression activity and regional fire records

About 95% of the area of the republic belongs to the State Forest Fund, which manages the forest through a system of local forest enterprises ("leskhoz"). These units provide the raw data for official forestry statistics. Duties of the foresters employed in these enterprises include monitoring of various natural phenomena such as fires, blowdowns, and other possible hazards to timber production. In 1998, the average area of a leskhoz was 875 000 ha, and the monitoring area for a single forester was 420 km^2 (Kozubov and Taskaev 1999). In the majority of the cases such enormous areas under formal supervision of a local forester reduced the quality of the fire record. A large proportion of all fires, however, is recorded by airborne brigades established within the Russian Forest

Fig. 2. Fire activity in the Komi Republic for the period 1950–2000.



Service in the 1930s (Kozubov and Taskaev 1999). Official forest fire statistics are believed to underestimate fire-associated forest disturbance (Pyne 1996; Shvidenko and Nilsson 2000). Large forested areas, an insufficient number of employees in fire-fighting brigades (784 for the whole republic in 1998, Kozubov and Taskaev 1999), and a poor road network considerably limit the possibilities for fire suppression. According to the official regulations, all types of fire events are registered within three categories: underground, ground, and crown fires, all of which can occur on forested, unforested, and non-forest land (Shvidenko and Nilsson 2000). In the present study, we assume that the vast majority of the fires recorded were crown or ground fires in the forested areas.

Three features of the regional fire regime, routinely reported in Russian forestry statistics on an annual basis, include (1) number of recorded fires within an area, (2) average fire size, and (3) total area burned annually. The strength of climate signal in each of these parameters can vary. “Number of fires” appears to be the value that is most independent of fire-control measures. However, it may be more influenced by variation in monitoring intensity. “Average fire size” can be affected by fire control and changes in spatial fuel distribution as a result of timber harvesting. Fire suppression efforts surely influence the dynamics of “total area burned annually”. The annual record of forest fires for the period 1950–2000 was obtained through the Forestry Committee of the Komi Republic. Records of in-the-air hours for fire fighting and monitoring airplanes for 1979–1994, provided by the Forestry Committee, and overall timber production values for the 1950–94 (Kozubov and Taskaev 1999) were also analyzed.

Climate data

Hourly data sets from four World Meteorological Organization (WMO) climate stations for June through August for the period 1946–1993 (Vose et al. 1992; Razuvaev et al. 1995) were employed. The stations were Ust’-Cil’Ma (WMO No. 23405); Pechora (23418); Troicko-Pecerskoe (23711); Syktyvkar (23804); and Jaksha (no WMO No.) (Fig. 1). Homogeneity of climatic data was checked through the Mann–Kendall statistical test for randomness on each paired station set. Both monthly average temperature and the sum of monthly precipitation were checked within three “seasons” as defined in the routine HOM of the Dendrochronological Program Library (Holmes 1999). With respect to the precipitation data, tests proved homogeneity of the data at the most stringent 90% level among all pairs of stations, with the exception of the Troicko-Pecerskoe and Syktyvkar pair (95%). With respect to the temperature data, all pairwise comparisons showed homogeneity at the 90% level.

Spearman correlation coefficients were used to check for linear relationships among different variables.

For each month and for 10-day periods, the Seljaninov hydrothermal coefficient (SHC; Shvidenko et al. 1998) was calculated as

$$\mathrm{SHC} = \mathrm{SHC} = \frac{10\sum P}{\sum T}$$

where ΣT and ΣP were the sums of temperature (in degrees Celsius) and precipitation (in millimetres), respectively, for a given time period.

Tree-ring data

We selected four sets of larch (*L. sibirica*) chronologies developed from locations within the Komi Republic and published online as a part of WSL-Birmensdorf Tree Ring Data set (Schweingruber et al. 2000). They included KEDVLANO (64°15′N, 53°34′E; 1674–1991), NYUCHPLA (60°42′N, 51°23′E; 1649–1991), NONBLASI (65°36′N, 50°38′E; 1603–1990), and KOZHLASI (65°27′N, 60°35′E; 1588–1990) chronologies (Fig. 1). We obtained raw single-tree chronologies and averaged them to make composite larch chronologies. A set of chronologies taken for analysis included earlywood width and density, latewood width and density, and minimum and maximum density chronologies.

To remove the nonclimatic trends in width increments, single series were detrended through the use of negative ex-

Table 1. Results of six regression analyses examining the relationship between summer aridity and fire activity in the Komi Republic.

No.	Factors in a single regression analysis	b	SE of b	p value
Dependent variable: no. of fires				
1	Intercept	1 875.385	203.380	$<10^{-6}$
	SHC	–27.530	4.175	$<10^{-6}$
	Adjusted $R^2 = 0.642$; $F = 43.479$			
2	Intercept	524.355	40.663	$<10^{-6}$
	Climatic PC 1	250.056	34.964	$<10^{-6}$
	Climatic PC 3	–158.353	45.925	0.014
	Climatic PC 5	–107.814	42.314	0.051
	Adjusted $R^2 = 0.642$; $F = 24.901$			
Dependent variable: average forest fire area				
3	Intercept	61.748	16.598	0.001
	SHC	–0.977	0.341	0.007
	Adjusted $R^2 = 0.153$; $F = 8.227$			
4	Intercept	14.868	3.894	0.001
	Climatic PC 1	8.325	3.358	0.019
	Climatic PC 5	–4.897	4.077	0.237
	Adjusted $R^2 = 0.122$; $F = 3.771$			
Dependent variable: total area burned annually				
5	Intercept	14.05	0.845	$<10^{-6}$
	SHC	–0.132	0.173	$<10^{-6}$
	Adjusted $R^2 = 0.587$; $F = 57.90$			
6	Intercept	7.582	0.196	$<10^{-6}$
	Climatic PC 1	1.160	0.168	$<10^{-6}$
	Climatic PC 3	–0.553	0.221	0.017
	Climatic PC 5	–0.360	0.204	0.146
	Adjusted $R^2 = 0.592$; $F = 20.36$			

Note: Summer aridity is expressed as the Seljaninov hydrothermal coefficient (SHC) (analyses 1, 3, and 5) and as principal components (PC) derived from monthly temperature and precipitation data (analysis 2, 4, and 6). Data is for the period 1950–1990. Total annual area burned was log transformed prior to analysis.

ponential and linear functions and autoregressed within the ARSTAN program (Grissino-Mayer et al. 1997). A cubic smoothing spline was applied to preserve 50% of the variance contained in the measurement series at a wavelength of 128 years and 99% at the wavelength of 40.6 years. Residual chronologies were used for the subsequent analyses. For the period 1946–1990, the raw data included on average 54 single-tree series (min. 44, max. 56) for the earlywood width chronology, 27 (min. 24, max. 29) series for the earlywood density chronology, 54 (min. 48, max. 56) series for the latewood width chronology, 27 (minx. 24, max. 29) series for the minimum density chronology, 54 (min. 44, max. 56) series for the latewood density chronology, 54 (min. 44, max. 56) series for the total ring width chronology, and 27 (min. 24, max. 29) series for the maximum ring density chronology. Signal to noise (Wigley et al. 1984) ratios varied between 6.11 in the minimum density chronology and 15.52 in the earlywood width chronology.

Analysis of tree growth and climate relationships

Response function analysis (Cook and Kairiukstis 1990) was applied to find the monthly weather variables that were significantly affecting pine growth. The analyses were performed with the help of the DendroClim program (Biondi 1997), whichS uses mean monthly temperature and total monthly precipitation from the June in the previous year to August in the current year (a total of 15 months) for the period 1946–1990. The analysis used averaged monthly average temperatures and the sums of monthly precipitation from Ust'-Cil'Ma, Pechora, Troicko-Pecerskoe, and Syktyvkar climate stations.

Analysis of fire and climate relationships

The use of principal components analysis (PCA) (Kruskal and Wish 1978) on the weather data helped avoid autocorrelation both between values of the same weather variable (typically positive) and between temperature and precipitation records of the same months (typically negative). The PCA routine, based on the correlation matrix, extracted principal components of weather variation (weather PCs) from the monthly sums of precipitation and average air temperatures for the summer months June–August. Five principal components were extracted. To obtain a clear pattern of the factor loadings, they were normalized and rotated according to the Varimax algorithm (Clarkson and Jennrich 1991). Explanatory power of PCs with respect to the annual record of number of fires and burned area was checked in a stepwise multiple regression analysis (Sokal and Rohlf 1995). At this stage, multiple regression was used exclusively as a selection tool to filter out

Fig. 3. Factorial structure of weather principal components (PC) selected in stepwise multiple regression analysis. T, P, and numbers refer to monthly temperature and precipitation values and the respective calendar months. The lines represent separate PCs, which accounted for 23.26% (PC 1), 18.32% (PC 3), and 11.91% (PC 5) of the total variance.

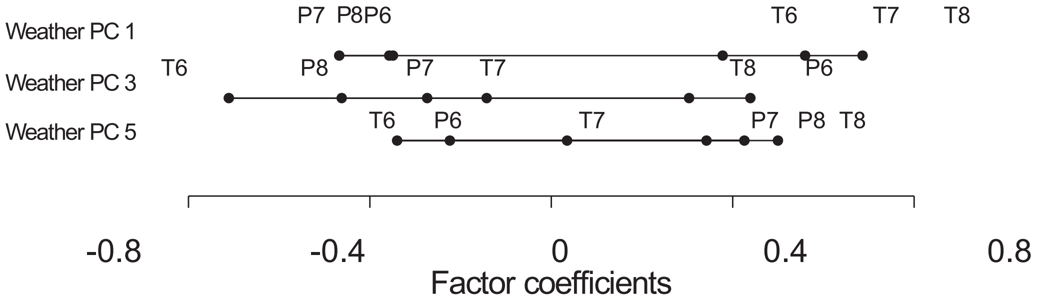
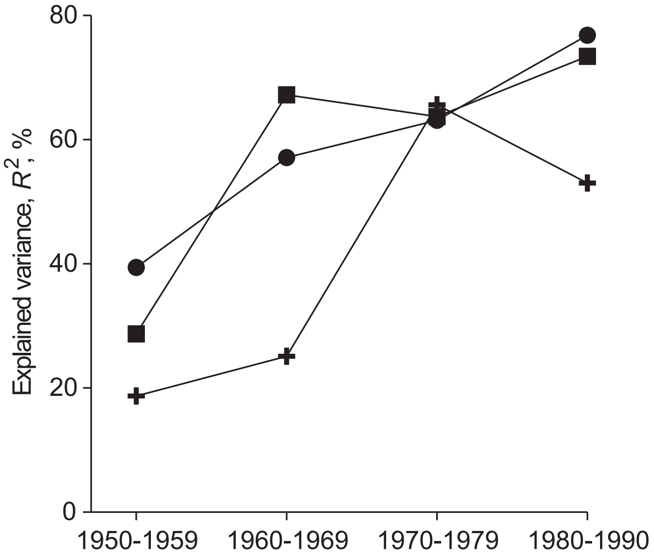


Fig. 4. Variation in the strength of the relationship between official fire statistics and weather as expressed though the Seljaninov hydrothermal coefficient (SHC) for the period 1950–1995. Data represent the amount of variation explained by a linear regression model separately for four periods. See Table 1 for the statistical details of the analyses. Boxes, number of fires; crosses, average area of fire; circles, total area burned annually.



weather PCs that did not significantly resolve fire-related weather variation. PCA, multiple regression analysis, and canonical correlation analyses (see later) were performed in the Statistica software package (StatSoft, Inc. 1999).

Reconstruction of fire activity from tree rings

Values of larch chronologies for current, immediately preceding, the following years for all composite chronologies were transformed into independent variables via PCA. Selection of fire-related components of growth variability was done through multiple regression, with annual number of fires and annually burned area as the dependent variables.

In an attempt to find linear relationships between selected weather PCs and selected tree-growth PCs, the results of these two PCAs were combined in the canonical correlation analysis. The aim of this type of correlation analysis is to assess the linear relationships between two sets of variables (Darlington et al. 1973). This analysis defines the canonical roots by calculating the so-called canonical sums, each representing the result of the weighting of the original variables within each group, and summing them up. These roots may be viewed as "correlational pathways", the significance of which can be evaluated independently. According to the structure of the statistical routine, the maximum possible number of roots equals the number of variables in the smallest group. In such a way, canonical roots were calculated between the set of tree-ring PCs and the set of weather PCs to obtain an index of fire-related annual weather variation. Specifically, a yearly estimate of fire-related weather was obtained by summing up scores of canonical roots, calculated from tree-ring PCs with the help of the canonical coefficients:

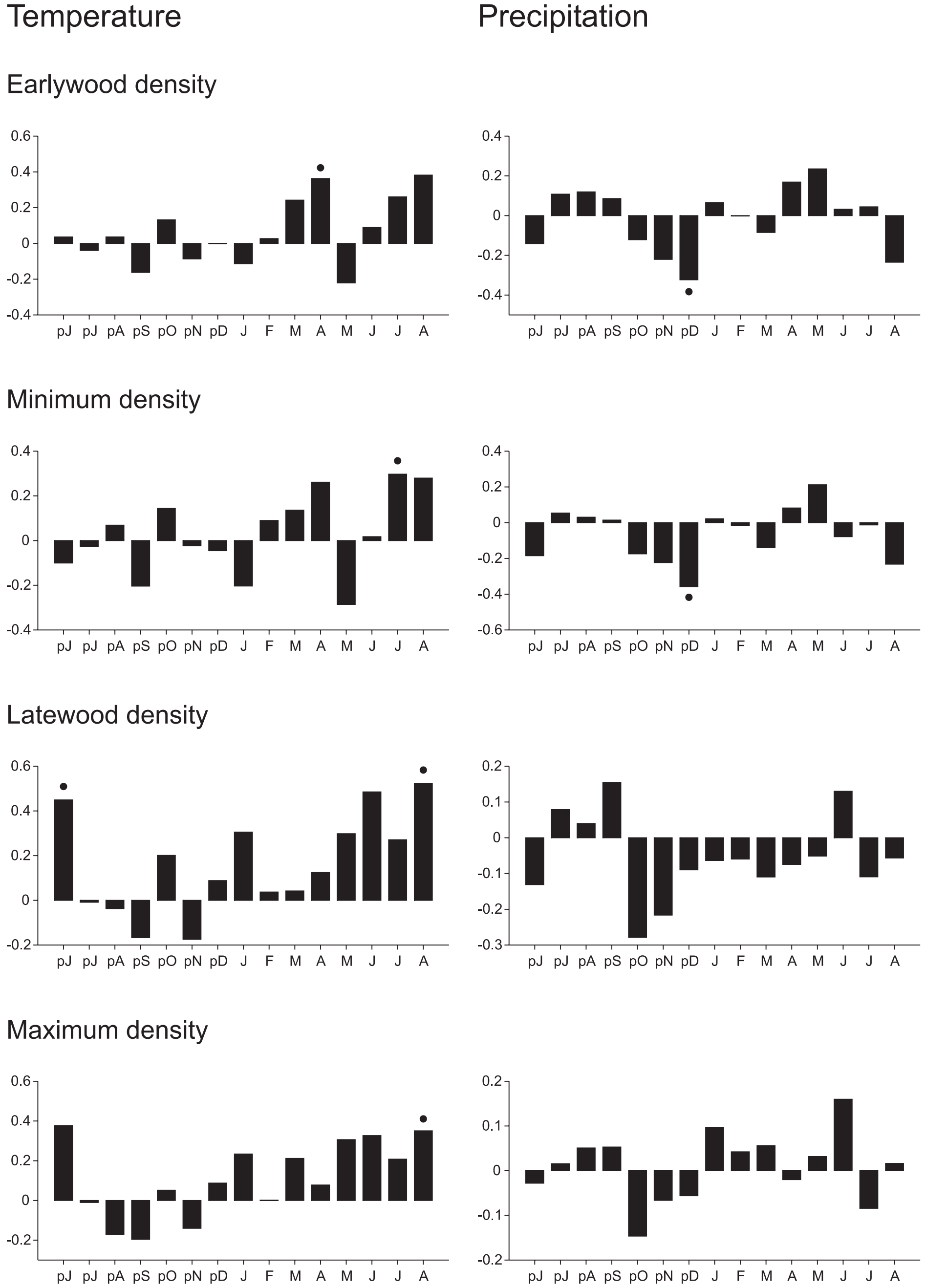
$$\text{Tree-ring estimate} = \sum_{i=1}^{N} R_i = \sum_{j=1}^{K} a_{j1}\mathrm{PC}_{j1} + \sum_{j=1}^{K} a_{j2}\mathrm{PC}_{j2} + \ldots + \sum_{j=1}^{K} a_{jN}\mathrm{PC}_{jN}$$

where R is a canonical root, a_{ij} is a canonical coefficient of the ith canonical root of the jth tree-ring PC, N is the total number of canonical roots, and K is the total number of tree-ring PCs. During a reconstruction, we focused on the annual number of fires and logarithmically transformed annually burned area. Log transformation of the latter variable was done to filter out the effect of fire suppression on the absolute values in the record.

The estimates of number of fires and annually burned area were derived from tree-rings PCs in the form of the reconstructed values of fire-related weather PCs. By doing so, we later verified reconstruction by using the whole record of the annual number of fires actually recorded and the annually burned area (1950–1990). To check the reconstruction quality with respect to high-frequency variation, we used linear regression. The bootstrap method (Efron and Tibshirani 1994) was applied to produce estimates of variation in the values of regression coefficients. Empirical 2.5 and 97.5 percentiles of the distribution were obtained through resampling half (n = 20) the original distribution 1000 times.

Predictive power for the low-frequency signal was assessed through the coefficient of efficiency (CE) (Nash and Sutcliffe 1971; Briffa et al. 1988), a statistic similar to reduction-of-error statistics (Fritts 1976). It was defined as

Fig. 5. Pearson's correlation coefficients (vertical bars) between larch density residual chronologies and temperature and precipitation for the 1946–1990 interval. Significant variables ($p < 0.05$) tested separately with the response function analyses are marked with a dot. Along the *x*-axis, "p" stands for the previous-year monthly variables.



$$\mathrm{CE} = 1.0 \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{N} (y_i - \bar{y}_i)^2}$$

where y_i is the measured value of the fire statistic in a year i, $\hat{y}_i$ is the predicted value of the tree-ring estimate of fire activity in year i, and $\bar{y}_i$ is the mean value of the fire statistics. A positive value of this statistic implies that the reconstruction is "useful", and negative values in most cases point to an unsatisfactory result of the reconstruction. Before applying CE statistics, reconstructed indexes and actual variables were normalized. Since the reconstruction exercise was intended to check for among-year variation in fire activity and not for absolute values of number of fires, no checks were carried out with respect to means of "measured" and reconstructed distributions.

Results

Fire statistics

In the Komi Republic, the periods of increased fire activity, as seen in the record of the annual number of fires, occurred once

Table 2. Factorial structure of tree-ring principal components (PC) selected for the canonical analysis.

Tree-ring variables	PC 3	PC 5	PC 7	PC 8
Earlywood density				
Lag 0	**–0.941**	0.142	0.038	–0.048
Lag 1	0.048	0.040	0.025	**0.956**
Minimum density				
Lag 0	**–0.938**	–0.072	0.018	–0.025
Lag 1	0.012	0.016	–0.011	**0.939**
Latewood density				
Lag 0	–0.121	**0.949**	0.004	0.001
Lag –1	0.001	–0.002	**0.948**	0.010
Maximum density				
Lag 0	0.064	**0.953**	–0.033	0.058
Lag –1	–0.056	–0.027	**0.952**	0.001

Note: Variables presented are those with at least one factor loading greater than 0.7 (shown in bold).

every 10–15 years and lasted for 2–3 consecutive years (Fig. 2). Data on the annual number of fires and the average size of a forest fire revealed 1953, 1954, 1956, 1959, 1960, and 2000 as years with total area burned being above 0.1% of the forested area of the republic. The year 2000 was marked as a year with exceptionally high fire activity, when the area burned reached 207 000 ha.

We found no correlation between annual number of fires and harvested volume of timber (Kozubov and Taskaev 1999) for the period 1950–1998 ($r = 0.206$, $p = 0.155$, $n_{\text{years}} = 49$). However, for the same period, harvested volume was negatively related with the average size of a forest fire ($r = –0.521$, $p = p < 10^{-4}$, $n_{\text{years}} = 49$) and with the total area burned annually ($r = –0.308$, $p = 0.031$, $n_{\text{years}} = 49$). A strong and positive correlation existed between average fire size and usage time for fire monitoring and fire-fighting airplanes for the period 1970–1994 ($r = 0.615$, $p = 0.001$, $n_{\text{years}} = 25$). For the same period, usage time was strongly correlated with annual number of fires ($r = 0.702$, $p < 10^{-4}$, $n_{\text{years}} = 25$).

Analyses of fire and climate relationships

SHC calculated from the average temperature during 3 months in summer (June–August) and total sum of precipitation for the same period was the most closely related to the fire variables (Table 1).

We described the aridity of the summer months by extracting PCs from the monthly temperature and precipitation data for the period June–August. In the PCA, a component was retained for further analyses if its eigenvalue was ≥0.7. The PCs were used as the independent variables in the stepwise multiple regression analyses, with the fire variables as the dependent variables (Table 1). The correlation between weather variation and fire variables was higher with respect to annual number of fires and annually burned area than it was with respect to average fire size. Because of this, average fire size was dropped from the analysis at this point. Weather PCs 1, 3, and 5, which were significantly related to number of fires and burned area, were preserved for further analyses. These PCs accounted for, respectively, 23.26%, 18.32%, and 11.91% (that is, 53.49% in total) of the total variance in original monthly weather data for the 3 months in summer.

The structure of the first weather PC (Fig. 3) highlighted the fact that in Komi there is a strong negative relationship between amount of precipitation and temperature at the scale of the summer season. The structure of the third PC implied that it was inversely related to the aridity in June, the temperature and precipitation values for this month being located on the opposite ends of the axis. The strength of the correlation between weather PCs and fire data varied considerably over the period studied (Fig. 4). The most obvious trend was an increase in the climatically resolved fire record since the first decade of observations.

Analysis of tree growth and climate relationships and selection of tree-ring PCs

Response function analyses pointed to the spring and summer temperatures as well as winter precipitation as being factors significantly related to the pattern of ring-density distribution in larch (Fig. 5). By setting a 0.5 threshold on the eigenvalue of a PC to be retained for further analysis, nine PCs were extracted in the PCA of all available larch chronologies and their respective ±1 lag. Screening of tree-ring PCs in multiple regression analysis showed PCs 3, 5, 7, and 8 being related to the fire variables. These PCs accounted for 34.0% of the total variation in the tree-ring data set. Factorial structure of the selected PCs showed that all density chronologies were the main contributors to the variation along the respective axes (Table 2).

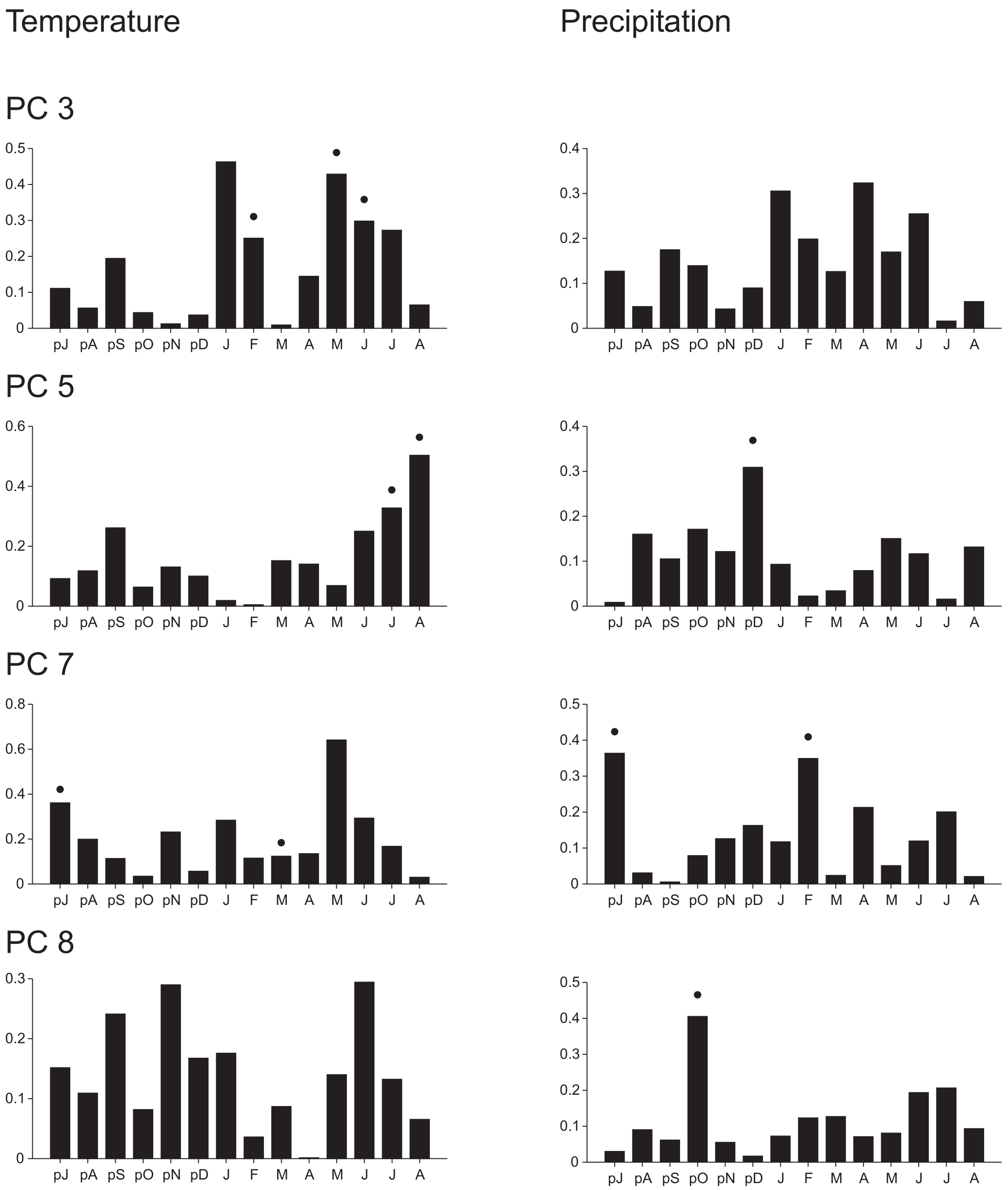
The climate signals embedded in the density PCs were coherent with the ones in the density chronologies (Fig. 6). In addition, correlation and response function analyses showed that the PCs contained information about weather during different parts of the current-year fire season. Late-spring and early-summer temperatures were significantly related to PCs 3 and 7, and mid- and late-summer temperature to PC 5. Significant precipitation impact on the PCs was observed for precipitation in the summer, autumn, and winter preceding the current growing season.

Reconstruction of fire activity from tree rings

Canonical correlation analysis was employed to assess the possible linear relationships between sets of weather and tree-ring PCs (Table 3). Although only the first canonical root was found to be significant ($p < 10^{-6}$), the second root had a relatively low p value of 0.14, which might indicate the existence of several "correlation pathways" in the studied system (see statistical analyses section). Indeed, climatic PC 1 and tree-ring PC 5 were the main contributors to the first canonical root that likely represented the weather pattern of high and late summer. As to the second root, climatic PCs 5 and 3 and tree-ring PCs 7 and 8 were the most influential. The structure of the climatic PC 3 (Fig. 3) and the response function analysis of tree-ring PC 7 suggested that the second root was related to the weather pattern during the early summer. As a result, extracted canonical roots might contribute in an additive fashion to the estimate of annual fire activity. Based on this reasoning, scores from two canonical roots were preserved for the subsequent analyses.

A score of canonical root (R) was calculated for a particular year from the tree-ring PCs with the help of the canonical coefficients (Table 2). Since two roots were used in the analyses, two scores (one for each root) were calculated and

Fig. 6. Absolute values of the Pearson's correlation coefficients (vertical bars) between tree-ring principal components and temperature and precipitation for the 1946–1989 interval. Significant variables ($p < 0.05$) tested separately with the response function analyses are marked with a dot. Along the *x*-axis, "p" stands for the previous-year monthly variables.



then added to each other to obtain a tree ring based estimate of fire-related weather (see subsection Reconstruction of fire activity from tree rings). In such a way, a chronology of tree-ring estimates of fire-related weather was obtained for the period 1950–1990 (Fig. 7).

The reconstructed index accounted for, respectively, 27.3% and 39.8% of the high-frequency variation in actual number of fires and log-transformed annually burned area for the period 1950–90 (Fig. 8), the *b* coefficients in regression equations staying positive within 95% of their bootstrap-derived distributions. The reconstruction showed some skill in predicting the low-frequency variation of the respective variables, the CE statistics reaching 0.081for the reconstruction of number of fires and 0.315 for annually burned area. Plotting the annually burned area against a measure of reconstruction skill for a year, measured as the value of CE for a single year, revealed worse performance of the reconstructed index during the years with low and intermediate levels of fire activity compared with years with increased fire activity (Fig. 9A). Considerable variation in CE values was found over different parts of the verification period (Fig. 9B).

Discussion

Regional fire activity and quality of the fire record

The pattern of fire activity in the Komi Republic appears to contain a strong climatic signal, although fire suppression has definitely exercised some control over forest fires during the period studied. The interannual variability in area

Fig. 7. Comparison of the dendrochronological reconstruction of fire activity in the Komi Republic (pointed at by arrow) and the actual record of the number of fires and annually burned area. Running 3-year averages are shown for all curves.

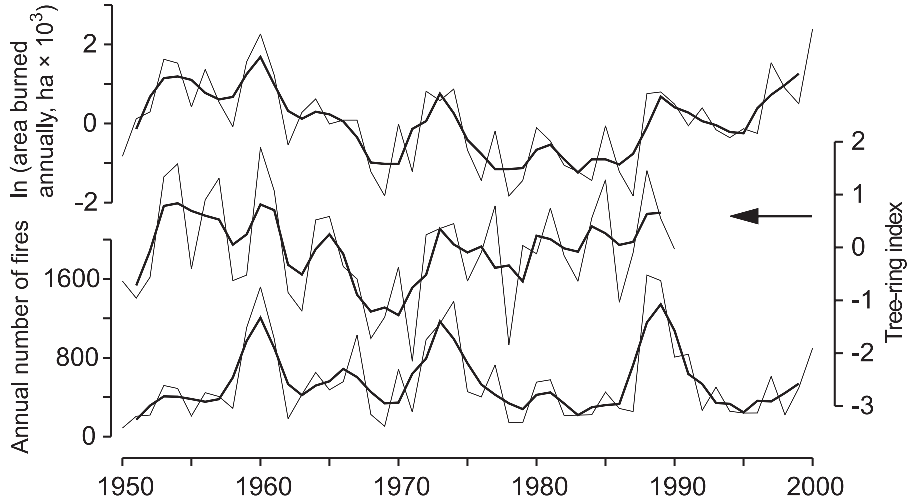


Table 3. Canonical analysis of climatic and tree-ring principal components (PC).

	Root 1	Root 2
Climatic PC		
1	–0.995	–0.078
3	0.033	0.682
5	–0.087	0.717
Tree-ring PC		
3	–0.179	0.396
5	0.941	–0.287
7	0.257	0.602
8	–0.252	–0.542

Canonical R = 0.653
Canonical root 1: $\chi^2 = 57.93$, $p < 10^{-6}$
Canonical root 2: $\chi^2 = 9.607$, $p = 0.142$

Note: Canonical weights of variables are shown for the first two extracted roots. R, canonical root.

burned in Komi and regular occurrence of years with dramatically increased fire activity, responsible for most of the area burned at the decadal scale, are features that are in line with long-term reconstruction of fire regime in the boreal forest in Fennoscandia (Niklasson and Granström 2000). A similar pattern of regional fire activity has also been reported from North American boreal forests (Nash and Johnson 1996; Stocks et al. 2002). A dramatic peak in burned area in 1960 (1.548 million ha) was caused by extremely dry weather (SHC for this year being equal to 28.7 vs. the long-term average of 48.1) and probably the subsequent reorganization of forest management in the republic (Kozubov and Taskaev 1999). After 1960 (with the exception of the year 2000), the area burned has not exceeded 50 000 ha annually.

For the period 1950–2000, the mean annual burned fraction (ABF; sensu Ward et al. 2001) has been 0.05% of the republic's forested area. A long-term average fire cycle, which is time required to burn an area equal in size to the area under consideration (Johnson and Van Wagner 1985; Johnson and Gutsell 1994), would in this case equal ca. 2000 years. When compared with fire history data from the Komi Republic and Fennoscandian boreal fire histories, this figure certainly indicates an effect of fire suppression for the period studied. Fire-history data from an area in the south-eastern part of the Komi Republic (Jaksha area, Fig. 1; Drobyshev et al. 2004) showed the range of past fire cycles to vary from 60 to 220 years. Given that fire cycles in the Fennoscandian part of the boreal forest typically vary from 50 to 120 years (Zackrisson 1977; Niklasson and Granström 2000; Lehtonen and Huttunen 1997), this result points to the impact of fire suppression in the republic.

The fire record itself was likely affected by variation in the monitoring activity. A strong positive correlation between airplane usage time and average fire area pointed to two things: (1) "immediate" fire hazard mostly affects resource allocation to fire suppression and monitoring activities and (2) climatic signal in the regional fire chronology can be modified by varying the monitoring intensity. It seems consistent with the fact that allocation of resources for airplane operations is typically based on the predicted fire activity, which is in turn modeled as a function of weather in the coming months (S. Pautov, personal communication). As a result, fire detection in years with high fire activity could be more accurate than in years with low fire activity.

Intensity of forest use was also related to the fire record of the republic. We considered timber production as a combined regional-scale proxy for the logistic and financial possibilities for fire suppression (Kozubov and Taskaev 1999). A negative correlation between harvested volume and average size of forest fire indicated a tendency for an increase fire-suppression efficiency as the rate of forest exploitation increased. Alternatively, higher fire hazard may result in increased fire suppression at the expense of harvesting activities in the republic.

Fire activity and weather

Fire activity in Komi was well predicted by the summer aridity expressed by the principal components of the

Fig. 8. Linear regression between tree ring based index of fire activity and fire statistics. A, annual number of fires ($y = 1.19 \times 10^3x - 0.705$, $R^2 = 0.27$); B, ln-transformed annual area burned ($y = 0.579x + 2.14 \times 10^{-3}$; $R^2 = 0.40$) in the Komi Republic. Dotted lines refer to the equations, with the values of regression coefficient being within 95% of their distribution range obtained through bootstrapping of half the original data set.

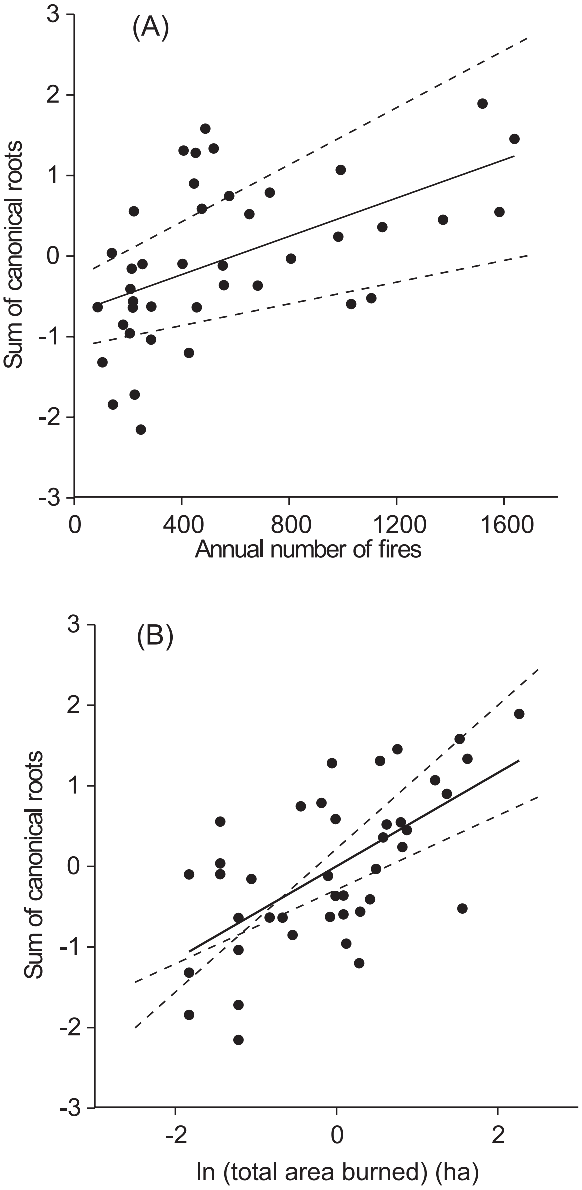
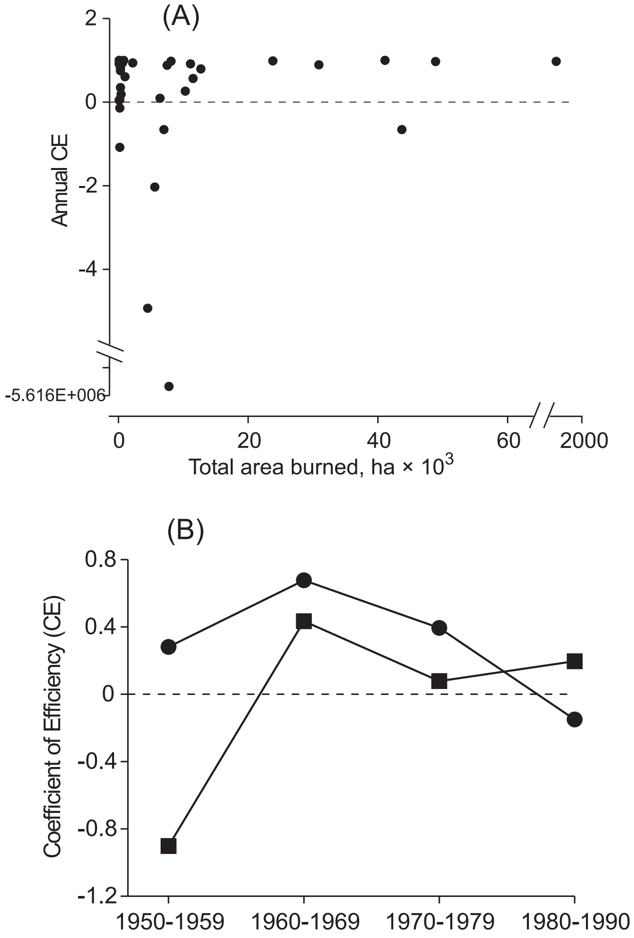


Fig. 9. Changes in reconstruction skill expressed by the coefficient of efficiency (CE) as a function of annually burned area in the Komi Republic (A) and in four decades of the studied period (B). In (B) the reconstruction of the number of fires is represented by boxes and annually burned area are represented by circles.



monthly summer temperature and precipitation (Table 1). This result is consistent with conclusions from other studies linking drier weather of the current growing season to increased fire activity in many boreal ecosystems (Payette et al. 1989; Bergeron and Archambault 1993; Johnson and Wowchuk 1993; Swetnam 1993; Nash and Johnson 1996; Kitzberger et al. 1997; Skinner, Flannigan et al. 2002). Weak correlation between number of thunderstorms and fires indicates that ignition frequency is not a limiting factor among factors affecting regional fire behavior in the Komi Republic (I. Drobyshev, unpublished data).

On the interannual time scale, fire-prone periods in Komi, as seen in the dynamics of the annual number of fires, last for 2 or 3 years (Fig. 2). The same length of fire-prone periods was also noted in Siberian forests (Korovin 1996). Such a pattern should rather be determined by atmospheric circulation and not by fuel availability when considering the regional scale. The latter factor is believed to be important in Canadian boreal forests, where amount of fuel together with temporal pattern of lightning (Nash and Johnson 1996) were considered limiting factors for regional-scale fire activity (Campbell and Flannigan 2000). Presently, the role of this interaction is unclear for the Komi forests, although we believe direct weather control to be the most important factor at the scale of the large boreal region. Indirect supporting evidence comes from the strong explanatory power of weather PCs in resolving variance in the annual dynamics of fire activity (Table 1). The correlation between fire record and weather PCs (stronger with respect to number of fires and log-transformed annually burned area and weaker with respect to average fire size) provides a basis for the subsequent reconstruction exercise.

Can tree-ring reconstructions be a decent proxy for regional fire activity?

The study suggests that it is possible to define an indirect relationship between the pattern of density distribution within tree rings and a record of fire activity. We observed a significant correlation between tree-ring PCs, which predominantly preserved variation contained in density chronologies (Table 2), and summer temperatures (Fig. 6). In a continental climate (Stocks and Lynham 1996), the temperature of the growing season positively correlates with summer aridity. Thus, summer aridity should correlate with the pattern of density distribution within a ring. In turn, summer aridity, expressed by the weather PCs, was closely linked to the regional fire activity.

The different time scales at which weather shapes the tree-ring pattern and fire regime is a problem that is hard to conquer when linking tree-ring and annual fire data. However, the monthly climate data, taken as a reasonable compromise, did provide predictive power with respect to annual fire activity in the Komi Republic, which, in turn, was possible to connect to regional density chronologies. The amount of high-frequency variance resolved by the reconstruction index (27% and 40% for number of fires and area burned, respectively) and positive values of coefficient of efficiency (CE = 0.081 and 0.315) implied that the reconstructed index was a reasonably good predictor of high- and low-frequency signal in the actual fire record. The three fire-prone periods around 1960, 1972, and 1987, as seen in the records of the number of fires and log-transformed annually burned area, were visible in the reconstructed chronology. This was a result of a reasonably good reconstruction skill with respect to a year with increased fire activity (Fig. 8 and 9A). The ability for a model to predict the timing of such events is important, since the temporal pattern of large fire episodes represents a crucial property of natural disturbance dynamics in the boreal region. Such episodes provide orders of magnitude higher impact on vegetation and landscape properties as well as on climate, as compared with “average” fire years (Moritz 1997; Johnson 1992; Niklasson and Granström 2000; Stocks et al. 2002). Lower reconstruction skill with respect to the years with average or below-average fire activity was partly due to the logarithmic transformation of the original values, which increased the role of nonclimatic factors and sampling errors during such “non-fire” years.

Variation in the reconstruction skill over the period studied raises questions about the quality of the official fire record (Fig. 9B). We speculate that for the first decade studied the low monitoring accuracy of small and moderate fires led to unsuccessful reconstruction of the annual number of fires. This was in agreement with the low amount of climatically resolved variation in the number of fires for this period (Fig. 4). However, the largest fire events, the principal contributors to the annually burned area, were nevertheless recorded. At that time, the possibilities for fire suppression were probably the least among all decades studied, as can be inferred from the history of the forest industry in Komi (Kozubov and Taskaev 1999). As a result, reconstruction of the annual burned area was “skillful”, with the CE value reaching 0.281. The CE values for both number of fires and area burned stayed positive over the next two decades. It suggested that fire monitoring improved faster than actual fire suppression. During the last decade, the negative value of CE for the annually burned area pointed to fire suppression as a likely factor affecting regional fire activity.

Despite the limited overlap between tree-ring and climate data sets as well as apparent variation in monitoring intensity the obtained dendrochronological reconstructions can be viewed as a realistic proxy for regional fire activity, at least for this boreal region. Possibilities to use tree-ring chronologies for providing a proxy of the regional fire activity have also been reported for the boreal forests of Alberta, Canada (Larsen and MacDonald 1995). In the Komi Republic, a strong coupling between climate and forest-fire activity and the presence of a fire-related climate signal in tree-ring chronologies may give a valuable opportunity to quantify more precisely the human versus climatic forcing on the fire regime. We conclude that a spatially referenced and seasonally resolved approach is likely to improve the quality of tree ring based reconstructions of regional fire dynamics.

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