

Plant phenological data and tree-rings as palaeoclimate indicators in south-west Finland since AD 1750

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Abstract Plant phenological data and tree-rings were tested for their palaeoclimatic value in south-west Finland since AD 1750. The information from fragmentary, partly overlapping, partly non-systematically biased plant phenological records of 14 different phenomena (a total of 3,144 observations) was combined into one continuous time series of phenological indices. All site- and phenomenon-specific series were standardized to present an average of zero and standard deviation of one. The mean phenomenon-specific series were then averaged as arithmetic means for annually resolved time series representing the variability in the particular plant phenomenon. Consequently, each phenomenon-specific mean series was based on spatially normalized site-specific index series. These series were compared to each other,

living-tree and subfossil tree-rings, and to early and modern meteorological time series. Phenological indices showed strong positive correlation with February to June temperatures. On the other hand, the correlations between phenological indices and precipitation data were around zero. Analysis using time-dependent running correlations showed non-stationary relationship between the tree-rings and phenological indices and observed spring temperatures. The skill of phenological data for reconstructing the spring temperatures was statistically proved.

Keywords Early climatological observations · Palaeoclimatology · Phenology · Temperature · Tree rings

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Introduction

Phenology can be defined as the field of research which studies the relationship between biological phenomena, for example bud burst and flowering of plants and migration of birds, and climatic factors such as temperature and the intensity of light, and which investigates seasonal and annual rhythms and variation in the timing of the events (Häkkinen 1999). Records from high latitude regions, where seasonal contrasts are relatively large, are of special interest since, at present, the most dramatic climate change is occurring in the arctic and boreal regions (Hassol 2004). According to routine meteorological observations, spring and annual mean temperatures in Finland have been significantly increasing during the last 150 years (Tuomenvirta 2004). One of the crucial consequences of the warming will be disturbances in the annual cycle of plants, especially in the onset of the active period in spring. Long term, continuous, phenological records offer an excellent possibility to study

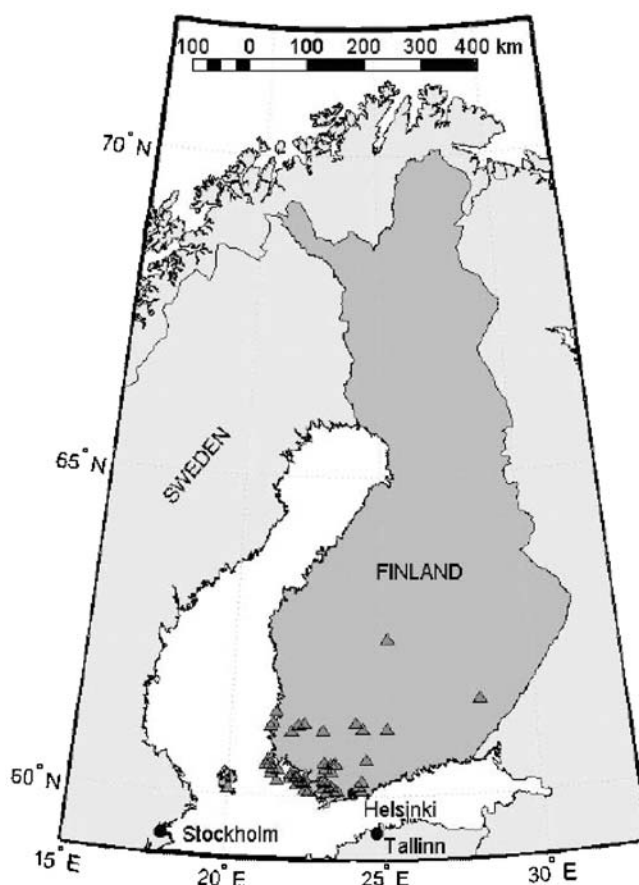


Fig. 1 Localities where phenological observations were made in the study of Linkola (1924)

the relationship between climate factors and the timing of phenological events.

The systematic collection of plant phenological observations started in Finland in 1846 by the Finnish Society of Sciences and Letters (Lappalainen and Heikinheimo 1992; Häkkinen 1999). These records have been used in many studies in the relationship between temperature and the annual cycle of plant, and especially the data after the year 1895 (Lappalainen 1994; Heikinheimo and Lappalainen 1997; Häkkinen et al. 1995, 1998; Häkkinen 1999; Linkosalo 2000). The history of collection of plant phenological observations in Finland, however, began as early as the mid-eighteenth century on the initiative of the Swedish botanist Carl von Linné (Lappalainen and Heikinheimo 1992; Häkkinen 1999). This data has not, however, been regularly used in climate-indicator studies. One reason may be the fragmentary and discontinuous nature of this data compared to modern phenological time series, and the other reason the lack of regional meteorological data.

Fortunately, old time series of the climatological measurements are available from Turku, south-west Finland, for the period 1748–1823 (Holopainen 2004). Temperature and precipitation data from these early climatological series can

be utilized in the analysis of the annual cycle of plants. More interestingly, a previous study of the climatological data of Turku indicates that spring temperatures in south-west Finland during the period 1748–1823 were 0.7°C colder than during the period 1961–1990 (Holopainen 2004). This is an interesting result, as the spring mean temperatures in Finland have increased in a relatively linear fashion during the last 150 years (Tuomenvirta 2004). Thus, the early climatological records from Turku provide an excellent basis to study the relationship between temperature and precipitation, and the timing of phenological events since the 1750s.

From south-west Finland, Linkola (1924) presented plant phenological data collected from 1750 to 1923 and calculated the mean and the annual variation in days of the onset of 14 phenomena. The observations included indigenous, garden, and agricultural species. In this paper, early plant phenological data along with tree-rings are used to test their sensitivity as palaeoclimate indicators in south-west Finland since 1750. In Finland, ring-widths of Scots pine have been used to reconstruct summer temperatures (Lindholm 1996; Eronen et al. 2002; Helama et al. 2002; Helama 2004). Advantages of the tree ring data are the long

Table 1 Total number of observations and observation sites per species during the years 1750–1924

| Phenomena | Observations | Sites |
|---|--------------|-------|
| Flowering of hepatica (<i>Hepatica nobilis</i>) | 200 | 23 |
| Flowering of wood anemone (<i>Anemone nemorosa</i>) | 236 | 27 |
| Bud burst in birch (<i>Betula pendula</i>) | 273 | 30 |
| Flowering of heather (<i>Calluna vulgaris</i>) | 148 | 20 |
| Flowering of bird cherry (<i>Prunus padus</i>) | 329 | 33 |
| Flowering of coltsfoot (<i>Tussilago farfara</i>) | 140 | 14 |
| Fruiting of wild strawberry (<i>Fragaria vesca</i>) | 176 | 24 |
| Flowering of apple tree (<i>Malus domestica</i>) | 285 | 30 |
| Haymaking | 141 | 22 |
| Rye, coming into ear (<i>Secale cereale</i>) | 246 | 32 |
| Flowering of rye (<i>Secale cereale</i>) | 293 | 33 |
| Rye harvesting (<i>Secale cereale</i>) | 297 | 32 |
| Oat sowing (<i>Avena sativa</i>) | 264 | 32 |
| Oat harvesting (<i>Avena sativa</i>) | 116 | 22 |
| Total | 3,144 | |

time periods and the lack of missing data compared with early plant phenological records.

First of all, we describe the phenological data used, including data from tree rings and early and modern meteorological data. Then, a description of the procedures for combining the plant phenological records into one continuous time series since 1750 is made, including regional homogenization of this data. A statistical analysis between the onset variations and temperature and precipitation over the past three centuries using early and modern meteorological datasets is shown, likewise the comparison between plant phenological data and the tree-ring data. The final conclusive goal is to statistically prove the usefulness and feasibility of the early plant phenological data for palaeoclimatic purposes, especially for high-quality seasonally-resolved climate reconstructions.

Materials and methods

Modern climate data

The weather station in Turku is located in the vicinity of the sites of the early phenological plant observations and was thus chosen to represent the modern climatic data. Temperature measurements are available from 1873 onwards. Calculation and homogenization of monthly temperature means are presented and discussed in detail by Tuomenvirta (2004). Monthly sums of precipitation measurements are available from 1891 until present. Because three types of precipitation gauges have been used since the 1880s, correction factors (%) determined for the different gauges by Heino (1994) and Solantie and Junila (1995) were applied for present-day precipitation data in order to homogenize the monthly values.

Early climatological and phenological data

Calculation and homogenization of daily temperature data for the period 1748–1800 from Turku are presented and discussed in detail by Holopainen (1999). The complete climatological records from Turku for the period 1730–1827 are described by Holopainen (2004), with presentation and discussion of monthly temperature data from 1748–1823 and monthly precipitation data from 1749–1800.

The main phenological data used in this study were the records compiled into one dataset by Linkola (1924). The Julian onset dates of 14 phenomena were entered into a digital database system, which covered the periods 1750–1807, 1816–1897, and 1903–1923 (1924). The longest gap in data was due to the war between Sweden and Russia in 1808–1809 (The Finnish War). Some of the missing phenological data in Linkola (1924) (during the interval 1898 to 1902) were complemented from a relational database by the Finnish Meteorological Institute (Lappalainen and Heikinheimo 1992). Unfortunately, the observations from the year 1912 are missing. This gap was filled by existing data of the bud burst in birch from the localities in the study by Linkola (1924) (T. Linkosalo, private communication, 2005). A graphical presentation of the spatial distribution of the observation sites of the study of Linkola (1924) is made in Fig. 1.

Regional normalization of phenological data

Methods for combining phenological time series have been applied in several studies (Häkkinen et al. 1995; Linkosalo et al. 1996; Linkosalo 2000; Schaber and Badeck 2002; Chuine et al. 2004). (Häkkinen et al. 1995) presented four methods for combining separate fragmentary phenological time series into a single long reliable series. A combined time series of

bud burst in birch (*Betula pendula* Roth) was constructed to illustrate the application of the methods. It is important to note that the preceding study was based on the combination for a single species of plant. While several phenological events were observed in the eighteenth and the beginning of nineteenth centuries, many of the time series span only a few years. Hence, our challenge is to combine separate records of different plant species into a single long continuous series.

A network of phenological observation sites represents a variety of years, latitudes, altitudes, aspects of continentality (proximity of the Baltic Sea), and microclimates (Table 1). Therefore, in order to avoid possible biases due to the variability of data availability each year, each phenological series of observation dates were transferred into dimensionless phenological indices. We first standardized all site- and phenomenon-specific series so that they present an average of zero and standard deviation of one. The mean phenomenon-specific series were averaged as arithmetic means for annually resolved time series representing the variability in the particular plant phenomenon. As a result, each phenomenon-specific mean series was based on normalized site-specific index series. These series were compared to each other, to tree-ring index series and to early and modern meteorological time series. Finally, mean phenological index was computed as an average of all available phenomenon-specific index series.

Index series were further reversed. Doing so, positive correlations occur between warm springs and phenological indices. If phenological index series were not reversed, correlations between spring temperatures and phenological index series are negative. This kind of presentation could easily lead to confusion since the rate of plant development is positively dependent on temperature.

The method presented here closely resembles methods often used in dendrochronological studies where tree-specific overall growth differences are minimized by dividing the annual values by the series mean value (Fritts 1976; Cook et al. 1995). Chuine et al. (2004) applied the regional normalization by first choosing their longest series as the reference series, then scaling all the other series to present the same average date as a long reference series over the common recorded period, and finally combining the available dataset. We acknowledge the benefits of this method but were, however, not able to apply the procedure in this study due to relatively short segment lengths: no phenological site-specific record was long enough to stand as a base series for other site-specific series to be compared with.

Tree-ring data

Tree-ring material of Scots pine (*Pinus sylvestris* L.) has been collected from the same region as the phenological

and climate data. The data comprises of living-tree as well as subfossil tree-ring series and covers the last 800 years. Tree-ring data thus forms an ideal counterpart for the phenological records greatly complementing the present plant-climate comparison.

Cores from living trees along the shore of Lake Kaitajärvi and Lake Vähä-Melkutinjärvi (60°40'N, 23°35' E) were extracted by an increment borer. Subfossil samples were collected from tree trunks (megafossils) from the bottom sediment of the same lakes. Disks were cut by saw after lifting the trunks to the surface and sampled trunks were returned into the lake.

Ring-widths were measured to the nearest 0.01 mm. Series of ring-widths were carefully cross-dated (Fritts 1976) using several numerical procedures (Holmes 1983; Van Deusen 1990) in addition to visual comparison of the plotted measurement series on the computer screen. Individual ring-width series of trees were indexed in the process called tree-ring standardization (Fritts 1976; Cook 1985; Helama et al. 2004) in order to remove the age-size related trend in radial growth. This was done using negative exponential curve, linear regression line or line through the series mean (Fritts et al. 1969). Indices were derived from the modeled curve by division. Due to high serial correlation, indices were prewhitened using Box and Jenkins (1970) methods of autoregressive and moving average time series modeling (Cook 1985; Monserud 1986; Guiot 1986; Biondi and Swetnam 1987). The order of the autoregressive-moving average process was determined using Akaike's (1974) Information Criteria. Prewhitening transforms autocorrelated series into a series of serially independent observations. These indices were used here for our climate-growth analyses over the past 250 years.

Biometeorological signal detection

The relationships between the phenological series, tree-rings and climatic variables were determined using the Pearson correlation coefficient. Linear transfer functions were derived by least squares to reconstruct climate from phenological time series (Fritts 1976; Guiot 1990). The data from the modern meteorological record of Turku (here, 1873–1924) was used for calibration, and the data from the early meteorological observations of Turku (1750–1823) was used to verify the constructed transfer model. In order to demonstrate the skill of reconstruction of the phenological data, Pearson correlations, reduction of error (RE) and coefficient of error (CE) -statistics were used (Fritts 1976; Briffa et al. 1988). RE and CE are the measures of the variance in common between the observed and reconstructed climatic variables and any positive value of RE or CE indicate of a reasonable skill in the reconstruction.

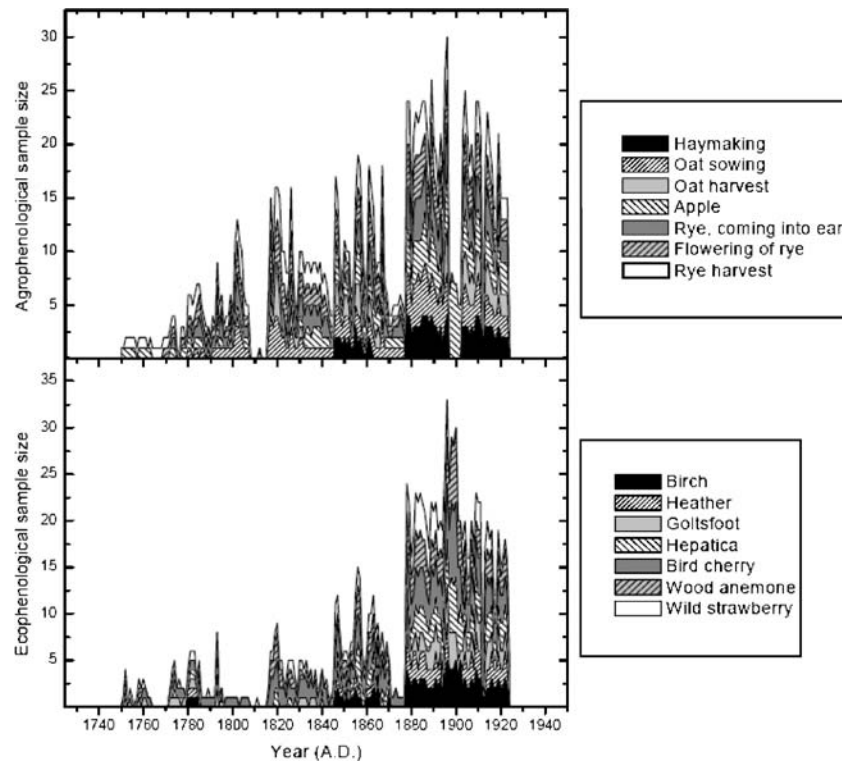


Fig. 2 The number of observations in agrophenological (*upper plot*) and ecophenological data (*lower plot*), as a function of time, 1750–1924

Results and discussion

Biometeorologically similar phenological series

Phenological observations can be subdivided into two categories, agro- and ecophenological, based on their origin and relation to human activity. The number of agrophenological observations is larger than the ecophenological observations (Fig. 2), probably reflecting the importance of agricultural activities to contemporaries. The subdivision cannot, however, be clearly demonstrated by means of visual

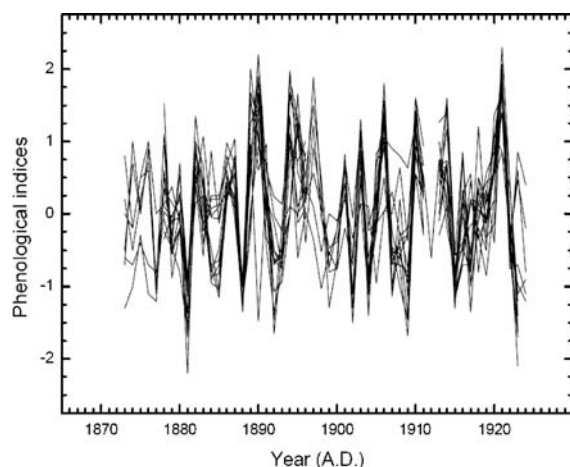


Fig. 3 Fourteen different phenological time series (see Table 1) over the interval of modern meteorological data, 1873–1924

or statistical comparison of the year-to-year variability. All 14 different phenological index series share a fair amount of common variability, as can be seen in Fig. 3. Mean inter-correlations (1873–1924) among agrophenological, ecophenological and all available phenomenon-specific index series are 0.59, 0.55 and 0.53, respectively. The highest level of inter-correlation among agrophenological indices is probably due to the greater sample size in these series (Fig. 2), thus resulting in a slightly more reliable phenomenon-specific index series. The high level of mean inter-correlation of all series (0.53) indicates a successful regional normalization of the phenological onset dates. The high level of common variability among the phenomenon-specific index series already demonstrates the feasibility of averaging these series into one mean phenological time series.

The origin of the common variability of the phenomenon-specific series is set out in Table 2. All the phenological series correlate well with the modern spring temperatures (Table 2a). The phenological index series and monthly temperatures show high correlations in March, April, May or June. Correlations between the phenological index series and monthly precipitation sums are clearly lower (Table 2b). Especially, May and June precipitation sums are, in general, negative. This could be an indication of adverse influence of cloudy rain days on temperatures; such a relationship has been previously demonstrated in Finland by Heino (1994). As the primary influence on plants would in such a case originate from temperature

Table 2 Correlations between the phenological and tree-ring series and various monthly temperature (A) and precipitation (b) variables of previous (small letters) and concurrent year (capital letters) of growth over the period of modern meteorological observations

| | Flowering of coltsfoot | Flowering of hepatica | Flowering of wood anemone | Flowering of bird cherry | Flowering of heather | Bud burst of birch | Fruiting of wild strawberry | Flowering of apple tree | Oat sowing | Oat harvesting | Hay making | Rye, coming into ear | Flowering of rye | Rye harvesting | Tree rings |
|------------|------------------------|-----------------------|---------------------------|--------------------------|----------------------|--------------------|-----------------------------|-------------------------|------------|----------------|------------|----------------------|------------------|----------------|------------|
| A) | | | | | | | | | | | | | | | |
| T_sep | -0.32 | -0.19 | -0.25 | -0.27 | -0.15 | -0.26 | -0.11 | -0.06 | -0.20 | 0.16 | -0.21 | -0.16 | -0.20 | -0.16 | -0.13 |
| T_oct | 0.21 | 0.25 | 0.15 | 0.08 | 0.10 | 0.06 | 0.05 | 0.00 | 0.21 | 0.28 | 0.08 | 0.11 | 0.07 | 0.05 | 0.07 |
| T_nov | 0.06 | 0.14 | 0.09 | 0.13 | 0.13 | 0.08 | 0.01 | -0.05 | 0.19 | 0.18 | 0.03 | 0.14 | 0.04 | 0.13 | -0.05 |
| T_dec | 0.10 | 0.24 | 0.19 | 0.33 | 0.23 | 0.26 | 0.22 | 0.16 | 0.23 | 0.04 | -0.02 | 0.32 | 0.12 | 0.17 | 0.04 |
| T_JAN | 0.48 | 0.39 | 0.40 | 0.22 | 0.25 | 0.17 | 0.24 | 0.04 | 0.32 | -0.11 | 0.21 | 0.30 | 0.13 | 0.21 | 0.17 |
| T_FEB | 0.57 | 0.41 | 0.51 | 0.40 | 0.18 | 0.37 | 0.28 | 0.22 | 0.59 | 0.54 | 0.43 | 0.41 | 0.26 | 0.44 | 0.42 |
| T_MAR | 0.72 | 0.70 | 0.76 | 0.51 | 0.33 | 0.45 | 0.31 | 0.35 | 0.64 | 0.28 | 0.36 | 0.59 | 0.39 | 0.39 | 0.44 |
| T_APR | 0.70 | 0.70 | 0.79 | 0.77 | 0.51 | 0.73 | 0.52 | 0.55 | 0.81 | 0.44 | 0.51 | 0.71 | 0.56 | 0.49 | 0.47 |
| T_MAY | 0.28 | 0.42 | 0.46 | 0.83 | 0.87 | 0.81 | 0.77 | 0.75 | 0.38 | 0.64 | 0.62 | 0.69 | 0.68 | 0.65 | 0.17 |
| T_JUN | -0.05 | 0.03 | 0.15 | 0.35 | 0.59 | 0.26 | 0.64 | 0.52 | 0.21 | 0.60 | 0.55 | 0.36 | 0.66 | 0.67 | -0.15 |
| T_JUL | 0.10 | 0.01 | 0.04 | 0.08 | 0.00 | 0.05 | -0.02 | 0.16 | 0.14 | 0.43 | 0.26 | -0.05 | -0.01 | 0.35 | 0.03 |
| T_AUG | -0.05 | 0.05 | -0.06 | 0.25 | 0.22 | 0.18 | 0.28 | 0.32 | 0.08 | 0.29 | 0.03 | 0.14 | 0.26 | 0.35 | 0.01 |
| B) | | | | | | | | | | | | | | | |
| P_sep | -0.07 | -0.09 | 0.03 | 0.09 | -0.15 | 0.04 | -0.38 | -0.03 | 0.00 | -0.22 | -0.33 | -0.07 | -0.26 | -0.32 | 0.24 |
| P_oct | -0.39 | -0.20 | -0.17 | 0.00 | 0.17 | -0.10 | -0.02 | 0.13 | -0.10 | 0.14 | -0.04 | 0.15 | 0.08 | 0.05 | 0.02 |
| P_nov | -0.16 | -0.14 | -0.13 | 0.09 | -0.02 | 0.02 | 0.13 | 0.04 | 0.13 | 0.14 | -0.04 | 0.16 | 0.09 | 0.11 | -0.56 |
| P_dec | -0.38 | -0.25 | -0.29 | -0.07 | -0.13 | -0.03 | -0.17 | -0.13 | -0.01 | 0.14 | -0.06 | -0.02 | -0.03 | -0.03 | -0.30 |
| P_JAN | 0.37 | 0.17 | 0.36 | 0.01 | 0.03 | 0.12 | -0.04 | -0.07 | 0.13 | -0.22 | -0.09 | 0.20 | -0.01 | -0.09 | -0.03 |
| P_FEB | -0.01 | 0.14 | 0.09 | 0.11 | 0.02 | 0.12 | -0.16 | 0.09 | 0.04 | 0.10 | -0.09 | 0.11 | -0.06 | -0.05 | 0.03 |
| P_MAR | -0.24 | -0.28 | -0.08 | -0.11 | 0.13 | -0.09 | 0.15 | -0.04 | 0.01 | 0.21 | 0.26 | 0.00 | 0.20 | 0.28 | -0.24 |
| P_APR | 0.03 | -0.01 | 0.02 | 0.19 | 0.22 | 0.21 | 0.20 | 0.25 | -0.08 | 0.27 | 0.32 | 0.15 | 0.21 | 0.18 | 0.04 |
| P_MAY | -0.13 | 0.01 | -0.05 | -0.29 | -0.24 | -0.25 | -0.18 | -0.20 | -0.27 | -0.16 | 0.04 | -0.26 | -0.29 | -0.20 | 0.18 |
| P_JUN | 0.00 | 0.03 | -0.05 | -0.09 | -0.14 | -0.10 | -0.17 | -0.16 | -0.11 | -0.14 | -0.28 | 0.09 | -0.11 | -0.36 | 0.16 |
| P_JUL | 0.06 | -0.17 | 0.06 | 0.05 | -0.15 | 0.10 | -0.06 | -0.04 | 0.25 | -0.22 | -0.22 | 0.04 | -0.01 | -0.13 | -0.06 |
| P_AUG | 0.15 | -0.21 | 0.05 | -0.07 | 0.03 | -0.14 | -0.20 | 0.03 | -0.14 | -0.30 | -0.29 | -0.09 | -0.17 | -0.29 | 0.07 |
| c) | | | | | | | | | | | | | | | |
| tree-rings | 0.59 | 0.51 | 0.56 | 0.38 | 0.16 | 0.40 | 0.16 | 0.10 | 0.39 | 0.17 | 0.39 | 0.28 | 0.22 | 0.17 | |

Values in italics are the highest correlations within a column

Table 3 Correlations between the phenological and tree-rings series and mean temperatures of various 3- to 5-monthly seasons over the period of (A) early (1750–1823) and (B) modern (1873–2004) meteorological records

| | Flowering of coltsfoot | Flowering of hepatica | Flowering of wood anemone | Flowering of bird cherry | Flowering of heather | Bud burst of birch | Fruiting of wild strawberry | Flowering of apple tree | Oat sowing | Oat harvesting | Hay making | Rye, coming into ear | Flowering of rye | Rye harvesting | Tree rings |
|-----------|------------------------|-----------------------|---------------------------|--------------------------|----------------------|--------------------|-----------------------------|-------------------------|------------|----------------|------------|----------------------|------------------|----------------|------------|
| A) | | | | | | | | | | | | | | | |
| T_Feb-Jun | 0.16 | 0.63 | 0.49 | 0.39 | 0.64 | 0.27 | 0.69 | 0.71 | 0.47 | 0.76 | – | 0.70 | 0.75 | 0.69 | 0.21 |
| T_Feb-May | 0.17 | 0.68 | 0.49 | 0.40 | 0.56 | 0.32 | 0.55 | 0.67 | 0.45 | 0.71 | – | 0.69 | 0.66 | 0.59 | 0.26 |
| T_Mar-Jun | 0.34 | 0.66 | 0.35 | 0.48 | 0.57 | 0.37 | 0.67 | 0.78 | 0.64 | 0.46 | – | 0.73 | 0.81 | 0.75 | 0.20 |
| T_Mar-May | 0.38 | 0.73 | 0.36 | 0.52 | 0.45 | 0.46 | 0.49 | 0.74 | 0.65 | 0.34 | – | 0.76 | 0.73 | 0.62 | 0.27 |
| T_Apr-Jun | 0.43 | 0.57 | 0.23 | 0.54 | 0.93 | 0.45 | 0.78 | 0.86 | 0.75 | 0.29 | – | 0.68 | 0.83 | 0.75 | 0.01 |
| B) | | | | | | | | | | | | | | | |
| T_Feb-Jun | 0.70 | 0.67 | 0.80 | 0.81 | 0.66 | 0.75 | 0.66 | 0.67 | 0.79 | 0.73 | 0.69 | 0.79 | 0.70 | 0.75 | 0.44 |
| T_Feb-May | 0.75 | 0.71 | 0.81 | 0.77 | 0.55 | 0.73 | 0.55 | 0.57 | 0.78 | 0.63 | 0.60 | 0.74 | 0.57 | 0.63 | 0.51 |
| T_Mar-Jun | 0.62 | 0.69 | 0.79 | 0.87 | 0.79 | 0.80 | 0.76 | 0.77 | 0.75 | 0.68 | 0.70 | 0.85 | 0.81 | 0.78 | 0.36 |
| T_Mar-May | 0.72 | 0.76 | 0.84 | 0.85 | 0.68 | 0.81 | 0.62 | 0.68 | 0.76 | 0.54 | 0.59 | 0.82 | 0.66 | 0.63 | 0.46 |
| T_Apr-Jun | 0.40 | 0.50 | 0.60 | 0.88 | 0.87 | 0.82 | 0.87 | 0.83 | 0.63 | 0.80 | 0.75 | 0.81 | 0.88 | 0.84 | 0.21 |

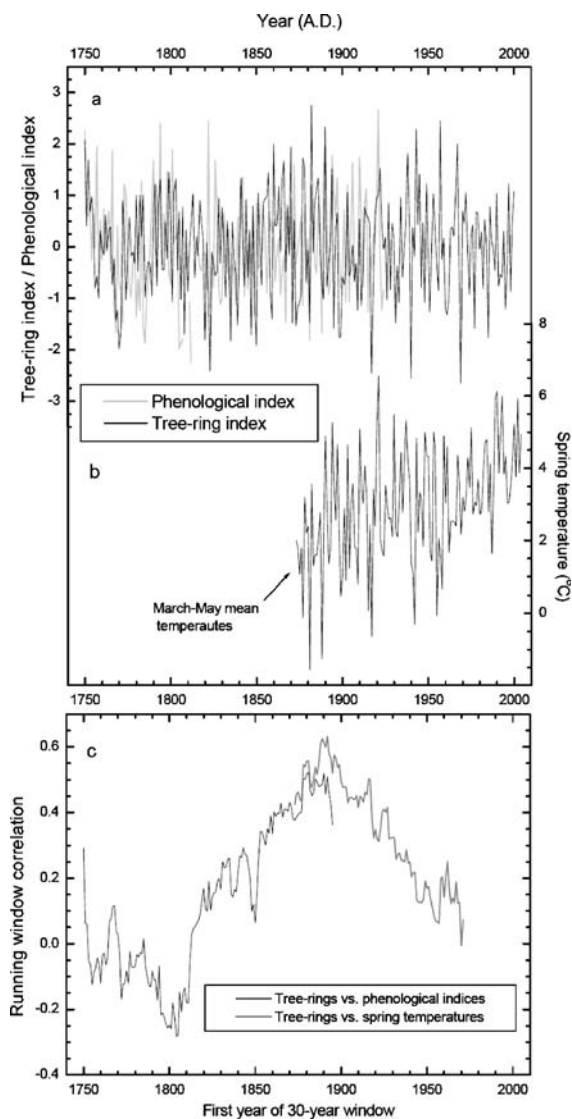


Fig. 4 Comparison of phenological and tree-ring indices for the past 250 years (a) with observed spring temperatures in Turku meteorological station (b). Running correlation with 30-year window shows greatly non-constant relationship between the tree-rings and phenological indices and observed spring temperatures (c)

control, one could conclude that precipitation had no long-term impact on the plant phenological series in this study.

From the point of view of palaeoclimatology, it is of interest to know whether the relationship between meteorological and phenological observations also existed back in the earlier intervals of the studied records. Early meteorological observations (1748–1827) in the study region provide an excellent opportunity to compare the relationship between the climate and phenological records (Table 3). We tested the assumption of constancy of the relationships, and conclude that, despite the fewer observations and several uncertainties in the earlier phenological observations, the phenomenon-specific index series do correlate fairly well with the spring temperatures over both periods. Correlations are somewhat higher over the period of modern meteorological observa-

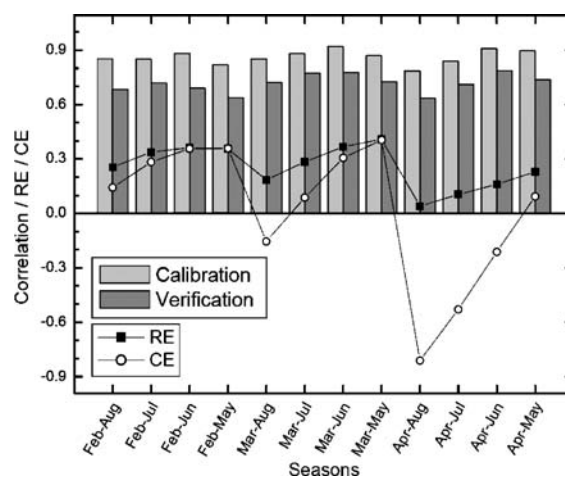


Fig. 5 Calibration and verification statistics for reconstructed spring temperatures. Correlations between actual and reconstructed temperatures as well as reduction of error (RE) and coefficient of error (CE) statistics measure the reliability of the reconstruction

tions, but the difference between early and modern periods is more or less marginal. The difference between the periods was most apparent when the phenomenon-specific series contained the smallest number of observations during the late 1700s and early 1800s, but this does not violate the assumption of common growth signal or potential of averaging of the phenomenon-specific index series. Overall, the results indicate that the phenological series could indeed be reliable indicators of past climates.

Tree-rings and climate

Similar to the phenological index series, tree-rings of Scots pine also show a positive correlation with the spring temperatures of modern meteorological records in the study region (Table 2a). This is of relevance to palaeoclimatology, as the common biometeorological signal in the phenological and tree-rings series indicates that the records could potentially be used in an integrated model for the interpretation or reconstruction of past spring temperatures. The comparison shows that nearly all phenomenon-specific series actually correlate rather well with the tree-rings over the same period (Table 2c). Relationship between the tree-rings and spring temperatures over the period of early meteorological observations is not, however, as clearly defined as could be expected based on the correlations over the late 1800s and early 1900s temperature records (cf. Table 3).

More detailed examination between tree-ring and mean phenological index series (Fig. 4a,b) point to the non-stationary nature of the relationship of tree-rings to phenological data and spring temperatures. Relatively high positive correlation between tree-rings and other records does occur sporadically, but the correlation actually varies greatly as a function of time (Fig. 4c). As the mean phenological index could be taken as a proxy for spring

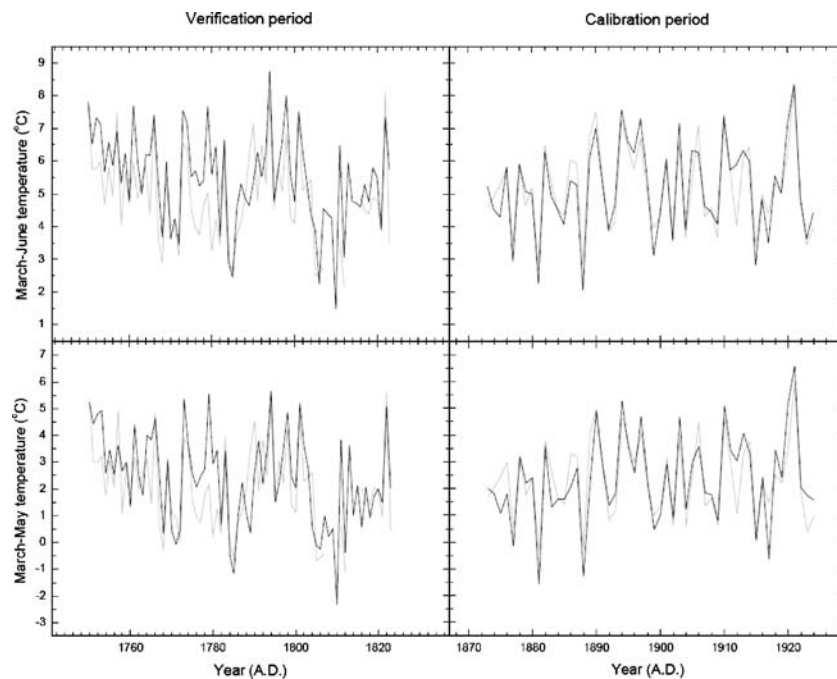


Fig. 6 Comparison of actual (*black line*) and reconstructed temperature variability in south-west Finland during the calibration (interval of modern meteorological data) and verification (interval of early meteorological data) periods

temperatures in the region (Tables 2, 3), the comparison in Fig. 4 actually facilitates the evaluation of the covariability between tree-rings and spring temperatures over the past 250 years. This examination indicates positive but low, even slightly negative correlation between tree-ring and spring temperatures between 1750s and 1850s, after which the relationship became more prevalent. Then again, towards the end of the 1900s the relationship clearly levels off. Interestingly, this variation in the relationship could explain the observation of Laitakari (1920), who found high and positive correlation between Scots pine tree-rings and April temperatures in southern Finland, and also why such a relationship has not been described more often.

Potential for palaeoclimatology

Plant phenological data have so far in Finland been used for plant physiological, biogeographical and climatic research purposes (e.g., Hari and Häkkinen 1991; Häkkinen et al. 1995, 1998; Häkkinen 1999; Lappalainen and Heikinheimo 1992; Lappalainen 1994; Heikinheimo and Lappalainen 1997; Linkosalo 2000). High positive correlations of the phenological and tree-ring indices against spring temperatures (Table 2a) indicate that the presented time series could also be used for palaeoclimate interpretations. The natural records studied could provide proxies for past temperatures during the intervals when instrumental weather observations did not exist. Any quantitative palaeoclimate reconstruction should not, however, be merely based on correlations, and therefore RE and CE -statistics for model validation were applied in this study. Moreover,

correlations between the studied tree-rings and spring temperatures seem to vary as a function of time, and hence their use in palaeoclimate reconstruction is questionable. It should be noted that the relationship between tree-rings, or any other similar natural time series, may be time-scale dependent (Guiot 1985; Timm et al. 2004), and that the use of present tree-ring datasets for palaeoclimate purposes may become possible after application of more sophisticated calibration methods than those applied here. Furthermore, presented tree-ring data from south-west Finland may correlate in a more straightforward fashion with some other variables, such as soil moisture and large-scale atmospheric indices, e.g., North Atlantic Oscillation (Helama and Timonen 2004). For example, Scots pine tree-rings are known to correlate significantly with early-summer precipitation in south-east Finland (Lindholm et al. 1997; Helama and Lindholm 2003).

Since the number of phenological observations decreases backward in time, the series can be strengthened by averaging all phenomenon-specific series into one mean phenological time series because of their common biometeorological signal. The mean series can then be calibrated and further verified against the instrumental climate records. In order to determine an optimal season for palaeoclimate reconstruction, we performed a calibration-verification test using different multi-monthly mean temperatures. The interval of modern meteorological observations (1873–1924) was used as the calibration period; the interval of early meteorological observations (1750–1823) was withheld from the calibrations and used to verify the mean index based reconstructed spring temperatures.

Based on the correlations over the calibration and verification period, as well as RE and CE statistics, the most reliable reconstructions were derived for the spring temperature time-window from February to May or June, or from March to May or June (Fig. 5). When attempting to reconstruct spring climate for a narrower time-window, for example from March to April or without March, temperatures generally failed due to negative values of CE statistics. Also, visual comparison of the instrumentally observed and reconstructed spring temperatures shows a fair amount of common variability (Fig. 6). Consistency can be observed not only at inter-annual but also at longer, multi-decadal, time-scales. The two records, observed and reconstructed temperature records, match better over the calibration than verification period, a feature which is common for nearly all palaeoclimate reconstruction models due to regression statistics. Apart from statistical issues, dissimilarities may also occur due to a variety of other reasons. Early parts of the meteorological and phenological series contain fewer observations (compared to modern data) made by more or less untrained observers, and therefore information is usually insufficient or does not exist at all. Despite these uncertainties, the eighteenth and nineteenth century phenological observations (at least in the form of regionally normalized phenological mean indices) also provide statistically reliable palaeoclimate information for selected spring months. Applied regional normalization was expected to improve the applicability of the data.

Multi-proxy approach

No one proxy alone is adequate for reconstructing the full spectrum of past climate variability (e.g., Mann 2002). Fortunately, besides the network of plant phenological observations presented in this work, the region of south-west Finland may provide other potential sources for reconstructing past climate. Itkonen and Salonen (1994) reported annually varved sediments from three lakes in the proximity of the study region of this work. Interestingly, the varves in all three lakes showed strong positive correlation with late-winter to early-spring temperatures, nearly in line with the phenological data here. Other potential documentary sources for climate reconstructions could be the rate of grain tithe from the sixteenth and seventeenth centuries, and cryophenological observations since the seventeenth and eighteenth centuries (Vesajoki et al. 1996). Tornberg (1989) described fluctuations of the harvests in south-west Finland from the 1550s to the 1860s. The longest continuous cryophenological observation series is available from northern part of Finland, Tornio, since 1693 (Kajander 1995), but already Johansson (1932) has presented the ice-break-up dates of River Aurajoki, south-west Finland, for the period 1741–1906,

potentially sensitive to spring temperature fluctuations. Along with early ice-break-up series, the continuous recording of the maximum annual extent of ice cover in the Baltic Sea compiled by the Marine Research Institute of Finland could provide useful palaeoclimatic information, starting from the year 1720 (Seinä and Palosuo 1993).

Multi-proxy based reconstruction using several potential sources of natural information could improve and lengthen the palaeoclimate record. This is beyond the scope of this paper, but there is a definite need for such work. The capability of the phenological record constructed here to resolve long-term climate variability is limited due to the short segment lengths and applied regional normalization (see Cook et al. 1995). The multi-proxy model is better suited to time-scale dependent time series, and an example is presented by Moberg et al. (2005).

Conclusions

Plant phenological data have been available from several localities in south-west Finland from the middle of the eighteenth century. Even though the value of these observations is diminished by the shortness of sequences and the uncertainties in the observations procedures involved, they are of importance for palaeoclimatic purposes, especially for high-quality seasonally-resolved climate reconstructions. Given the missing data and sparse data coverage in the latter part the eighteenth century, best results are achieved using regional phenological indices and combining separate fragmentary phenological observation series into one coherent time series. Comparison between phenological indices and temperatures records show that the method can be used to reconstruct spring temperatures. Although tree-ring data did show correlation with spring temperatures similar to phenological indices over the late 1800s and early 1900s, the two proxies could not be combined by means of past climate reconstructions due to the temporally variable nature of growth-climate correlations in the study region.

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