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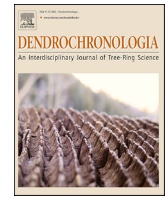

Original article

Contrasting climate signals across a Scots pine (*Pinus sylvestris* L.) tree-ring network in the Middle Volga (European Russia)

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A R T I C L E I N F O

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A B S T R A C T

Since the late-19th century, the Middle Volga has played a major role in the supplying grains and other agricultural products to European Russia. The study area is located in the south of sub-boreal forest in the north and in the forest-steppe in the south. Due to large seasonal differences in rainfall, agriculture in the region, especially in its southern part, strongly depends on hydroclimate variability. According to climate model forecasts, the frequency and intensity of droughts in the Middle Volga are expected to increase due to ongoing warming. Here we introduce 16 new Scots pine tree ring width (TRW) chronologies (*Pinus sylvestris* L.) from the region and use a dendroclimatological approach to determine what climatic factors drive radial growth. Our analysis revealed contrasting climate signals across the network of sites with chronologies from the north showing weak correlation with May temperature and precipitation ($r = -0.27$ and $r = 0.28$, respectively), while the southern sites demonstrated stronger relationships with climate in the first half of the vegetation season (May to July temperature, $r = -0.26$ to -0.43; May and July precipitation, $r = 0.29$–0.35). The northern sites did not demonstrate a strong growth response to the self-calibrated Palmer drought severity index (scPDSI) whereas the southern group was more drought sensitive had a strong drought response and positively correlates with scPDSI for the period from previous July to the current October ($r = 0.27$–0.56). Based on this strong relationship between southern TRW and scPDSI we reconstruct June-September scPDSI using the most sensitive sites (T04S, T06S, T08S) for the period from 1830 to 2014. The model explains 31% of variance. Our reconstruction shows droughts in 19th century: in 1831–33, 1851, 1853, 1859, 1863–65, 1880, 1891–92, 1897–98 and in 20–21th centuries: in 1906, 1921, 1936, 1939, 1967, 1975, 1996, 2010.

1. Introduction

In the year following the 1891–92 Russian famine, Lev Tolstoy wrote, “Having lived part of this summer in the rural wilderness of the Samara province and having witnessed the terrible disaster that befell the people as a result of three lean years, especially this one, I consider it my duty to describe, as far as I can truthfully, the plight of the rural population of this region and to call all Russians to serve assistance to the affected people” (Tolstoy, 1873). Just three decades later in 1921, another Russian writer, Maxim Gorky, appealed to the civil community for assistance to help the population of the Middle Volga that were once again facing severe malnutrition and famine brought about by drought and failed harvests. Although the League of Nations, the Red Cross, and many volunteers, including Fridtjof Nansen, made enormous contributions to combat this disaster, five million people perished from hunger and disease. In the 19th and 20th centuries, severe droughts in the Middle Volga region occurred in 1891–92, 1897–98 (Borisenkov and Pasetsky, 1988, 2003; Drozdov, 1980; Loginov et al., 1976), 1936, 1939, 1942 (Loginov et al., 1976), 1996, and 2010 (Strashnaya et al., 2011; Cherenkova, 2012; Meshcherskaya et al., 2011; Zolotokrylin et al., 2013), thus, droughts appear to be a common feature in this predominant agricultural landscape and can have a swift and dramatic impact on the livelihood of the region’s inhabitants. Therefore, the need for information on the frequency, severity, and spatial pattern of drought is important not only to better understand anomalies in the hydroclimate system, but also to guide regional planning initiatives and the adaptation of local economies towards mitigating the impact of drought.

Previous tree-ring studies in the Middle Volga have mainly focused on dendroecology (Krasnobaeva, 1986, 1972; Yarkutkin, 1968, 1974; Krasnobaeva and Mityashina, 2006), including the impact of

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anthropogenic factors on pine forests (Demakov and Smykov, 2009; Demakov and Isaev, 2015a, 2015b), and dendroarchaeological dating of historic wooden structures and artefacts such as Sviyazhsk and the Kazan Kremlin (Tishin, 2006, 2008; Matskovsky et al., 2016; Tishin et al., 2018). Recently, the Middle Volga was included in large-scale drought reconstructions of the East European plain (Solomina et al., 2017; Cook et al., 2020), however, Cook et al. (2020) focus on the general pattern of droughts in a vast territory of European Russia and do not specifically analyze the strength of the regional climatic signal or verifies the reconstruction using the historical and instrumental data in particular regions such as the Middle Volga area. Solomina et al. (2017) described the droughts in European Russia as well but did not provide quantitative reconstructions. Thus, the recent studies did not provide more detailed tree-ring information for the specific Middle Volga region, including primarily the differences in spatial characteristics in the climatic signal embedded in tree-rings, or its stability in time. In this paper, we present a tree-ring network from the Middle Volga consisting of 16 new Scots pine (*Pinus sylvestris* L.) chronologies, and identify what climate factors drive radial growth of pine across the study area and explore the geospatial variation in the radial growth response over a ~250 000 km^2 territory.

2. Materials and methods

2.1. Study area

The study area (56–52° N, 46–52° E) is located within the East European Plain and covers parts of the republics of Tatarstan, Chuvashia and Mari El, and the Penza, Orenburg and Samara regions. In the north, the vegetation is covered by sub-boreal pine or broad-leaved-coniferous sub-taiga forest, whereas mixed temperate broad-leaved forests dominate in the central part of the area (Fig. 1a). In the south, these associations are replaced by broad-leaved forest-steppes and meadow steppes. The western and southwestern parts of the study area are located within the Upper Volga Upland, and towards the east where Bugulminsko-Belebeevskaya hills reach elevations of 420 m asl (Fig. 1b). The central part of the study area lies the valleys of the Volga and Kama rivers, and in total, the study area stretches 500 km from north to south and east to west.

The climate of the study area is temperate continental with a predominance of westerlies and a gradual increase in the continentality towards the south. This is particularly expressed by higher summer temperature and decreasing rainfall from north to south (Alisov, 1956). Monthly mean temperature in the region is + 23 °C in July and − 16 °C in January (Bardin et al., 2019). The mean monthly sum of precipitation during the vegetation season between April to October decreases from north (355 mm in Kazan) to south (259 mm in Saratov). On average, the driest months during the vegetation period are typically March and April with a monthly sum of precipitation around 30–33 mm/month. The wettest months are June to August when precipitation totals reach 62–65 mm/month in the north and 48–52 mm/month in the south (Fig. 2).

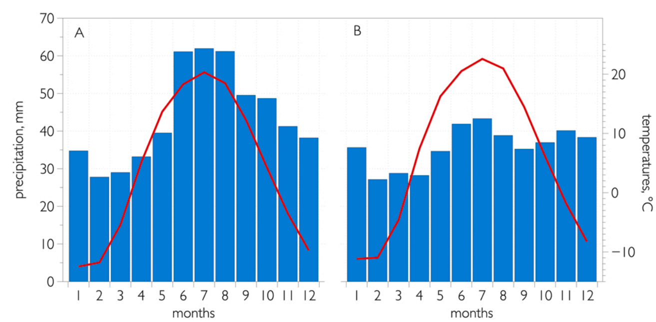

Fig. 2. Mean monthly temperature (red line) and sum of precipitation (blue bars) for the Middle Volga region, CRU TS 4.03 (Harris et al., 2014). **A,** the northern half of the study area between 56° and 53° N, 44–53° E, and **B**, the southern half of the study area between 53° and 51° N, 44–53° E. Monthly climatology was calculated for the period 1901–2017.

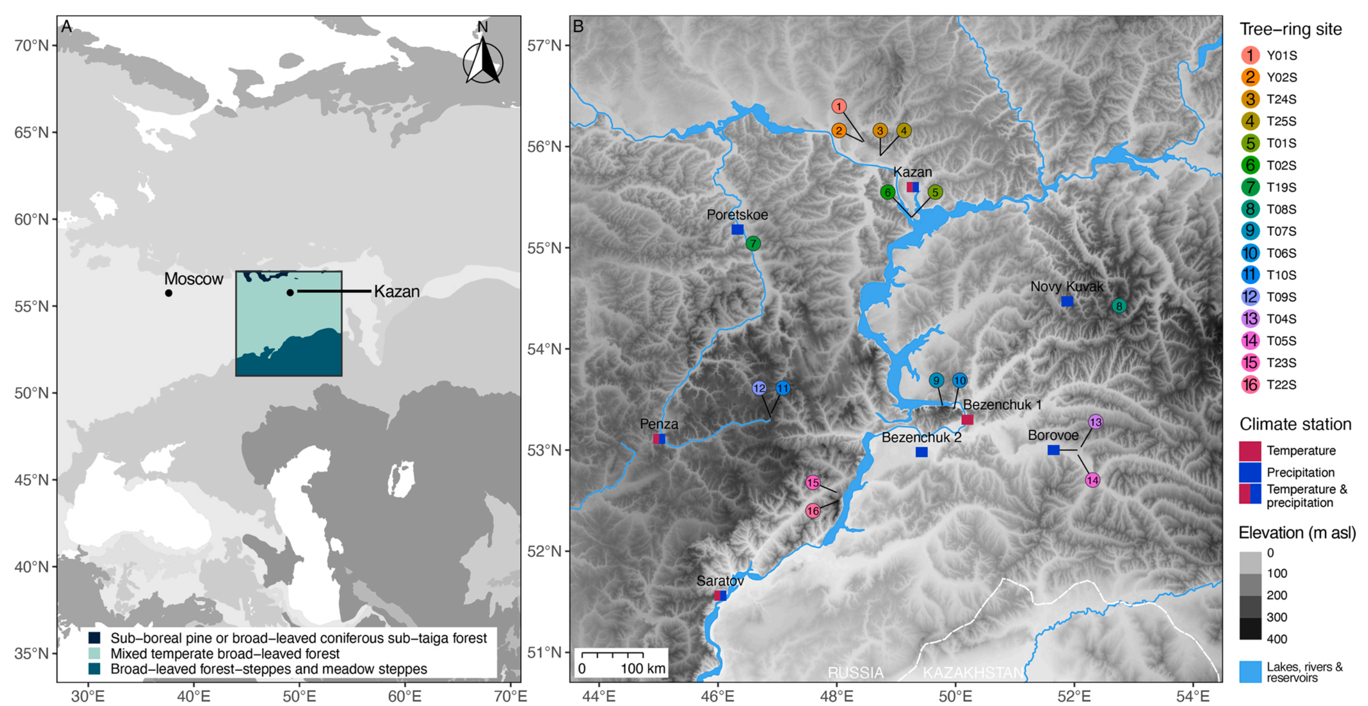

Fig. 1. Geographical setting and environmental characteristics of the study area. **A**, Location and spatial coverage of the three main habitat types within the study area, **B**, Elevation map showing the location of the 16 sites in the Middle Volga tree-ring network, nearby weather stations used in the study, and surface water bodies.

2.2. Tree-ring data and chronology development

In general, forest stands in the study area are constrained in size and age due to anthropogenic impacts (land clearing/agriculture conversion, timber extraction, fire) therefore to avoid disturbance-related growth patterns all tree-ring sites were located within natural reserves and national parks situated away from densely populated or industrial areas. Increment cores of mature, healthy, and dominant/co-dominant Scots pine trees (*Pinus sylvestris* L.*)* were collected from 16 sites using a Pressler borer following standard dendrochronological procedures (Cook and Kairiu¯kštis, 1990), and with the permission of respective land holders and forestry services. For each site, between 15 and 40 trees were sampled and two cores extracted from the opposing sides of the stem at a height of 1.3 m above ground (Table 1, Supplementary Materials). Increment cores were analyzed in the Tree-Ring Laboratory of the Institute of Geography, Russian Academy of Sciences, following conventional techniques described in Speer (2010). Samples were sanded and the surface scanned at a resolution of 2400 dpi using an Epson Expression 120000XL scanner, and measurements derived from the digital images using Cybis CooRecorder and CDendro software to the nearest 0.001 mm (Larsson and Larsson, 2017). Visual and statistical cross-dating of the samples was performed using TSAP-Win (Rinn, 2010) and COFECHA (Grissino-Mayer, 2001; Holmes, 1983), respectively.

Biologically induced non-climatic growth trends were removed from the raw tree-ring measurements by dividing the actual growth value for each year by the value of a point approximating function for each respective year. In our case, a 100-year-long cubic smoothing spline was used to remove age- or disturbance-related growth trends (Cook, 1985) using the ARSTAN program to detrended and standardize each tree ring series. Following the detrending procedure, site chronologies were calculated using a robust biweight mean without autoregressive modeling. The signal quality of the site chronologies was assessed using mean sensitivity (MS), mean inter-series correlation coefficient (Rbar), and the expressed population signal (EPS). Rbar and EPS calculated over 31-year moving intervals with an overlap of 30 years (Fritts, 1976; Wigley et al., 1984).

Table 1
Meteorological data used for the analysis of climatic signal in living TRW chronologies (Bulygina et al., n.d.).

Site code	Temperature	Precipitation	Latitude (° N)	Longitude (° E)
Y01S	Kazan, 1901–2015	Kazan, 1936–2010	56.049	48.462
Y02S	Kazan, 1901–2015	Kazan, 1936–2010	56.045	48.440
T24S	Kazan, 1901–2015	Kazan, 1936–2010	55.909	48.733
T25S	Kazan, 1901–2015	Kazan, 1936–2010	55.908	48.732
T01S	Kazan, 1901–2015	Kazan, 1936–2010	55.300	49.260
T02S	Kazan, 1901–2015	Kazan, 1936–2010	55.300	49.260
T19S	Kazan, 1901–2015	Poretskoe, 1966–2015	55.042	46.595
T08S	Kazan, 1901–2015	Novy Kuvak, 1901–1983	54.427	52.757
T07S	Bezenchuk, 1904–2014	Bezenchuk, 1951–2014	53.440	49.780
T06S	Bezenchuk, 1904–2015	Bezenchuk, 1951–2015	53.406	49.973
T10S	Penza, 1901–2014	Penza, 1966–2014	53.363	46.896
T09S	Penza, 1901–2014	Penza, 1966–2014	53.321	46.891
T04S	Bezenchuk, 1904–2014	Borovoe, 1905–1990	53.030	52.110
T05S	Bezenchuk, 1904–2014	Borovoe, 1905–1990	52.954	52.059
T23S	Saratov, 1901–2015	Saratov, 1966–2015	52.580	48.000
T22S	Saratov, 1901–2015	Saratov, 1966–2015	52.500	48.040
Kazan	+	+	55.600	49.280
Borovoe		+	53.000	52.050
Novy Kuvak		+	54.470	51.880
Poretskoe		+	55.180	46.330
Saratov	+	+	51.560	46.040
Bezenchuk	+		53.300	50.200
Bezenchuk		+	52,98	49,43
Penza	+	+	53.110	45.010

2.3. Climate data and statistical analysis

To compare the individual site chronologies with climate we used instrumental data for temperature (T) and precipitation (P) from the nearest meteorological station. Minimum and maximum distances between site and station range from 0.5 to 96 km. (Fig. 1, Table 1) from January of the previous year to October of the current year (Fig. 1, Table 1). Due to the limited temporal coverage of station data, especially for precipitation, we also used CRU_TS 4.03 T and P grid point data with a resolution of 0.5° x 0.5° closest to the coordinates of each site for the common period from 1901 to 2014 (Harris et al., 2014). CRU_TS 4.03 scPDSI (Osborn et al., 2017) and the Meshcherskaya-Blazhevich drought index (D) was used to compare regional chronologies with an additional aridity parameter (Meshcherskaya A. V. et al., 2011; Meshcherskaya et al., 1978; Meshcherskaya and Blazhevich, 1997). The Meshcherskaya-Blazhevich drought index represents the part of the Middle Volga area affected by droughts when $T > T_{mean} + 1°C$ and $P < 0.8 * P_{mean}$ (where T – temperature, T_{mean} – mean monthly temperature, P – precipitation, P_{mean} – mean monthly precipitation) for the period from 1901 to 2013.

Spatial trends observed in the climate response analysis where confirmed using PCA.

The Pearson coefficient of correlation (r) was used to determine the statistical relationships between radial growth and monthly climate data (Fritts, 1976; all correlations mentioned in the paper are significant at a level of $p < 0.05$). Principal Component Analysis (PCA) was used to determine if the individual site chronologies could be grouped into regional clusters and assist in interpreting the results of the response analysis. Most chronologies cover a common period from 1837 to 2014 (177 years) except for T23S that was only 110 years long that excluded from PCA to ensure a more robust result. Consequently, we divided the site chronologies into two regional groups, Middle Volga north (MV_{north}) and Middle Volga south (MV_{south}), according to similar climatic response patterns and the results of principal component analysis. These two master-chronologies were composited by calculating the arithmetic by means of simple averaging (Section 3.3).

3. Results and discussion

3.1. Middle Volga site chronologies

Tree-ring metrics describing site-specific growth characteristics and the signal quality of each site chronology are presented in Table 2. Across the study area, the mean annual increment varied from 0.6 to 2.7 mm $year^{-1}$, mean sensitivity ranged between 0.12 and 0.3, and the longest chronology of 266 years extends from 1749 to 2014 (T01S). First-order autocorrelation ranged between 0.35 and 0.66 with a mean of 0.56 indicating that growth in the previous year had some connection to and influence on radial growth in the following year. Inter-series correlation for each site ranged from 0.35 to 0.88, standard deviation varied between 0.46 and 1.6 (units), and EPS values typically fell below the arbitrary threshold of 0.85 when replication was lower than 24 series.

Table 2
Descriptive statistics of the 16 Middle Volga Scots pine tree ring width chronologies.

Site code	Chronology length (years)	Mean sensitivity (MS)	Interseries correlation (rbar)	Mean annual increment (mm)	Standard deviation (mm)	Temporal span (EPS >0.85)
T01S	266	0,20	0,53	1.591	0.463	1900–2014
T02S	207	0,18	0,65	1.27	0.848	1833–2014
T04S	213	0.162	0.351	1.51	1.004	1860–2014
T05S	218	0.203	0.58	1.12	0.773	1850–2015
T06S	188	0,24	0,60	1.34	0.73	1880–2014
T07S	229	0,21	0,67	0.74	0.46	1865–2014
T08S	207	0,23	0,63	1.21	0.893	1860–2015
T09S	227	0,21	0,56	1.25	0.775	1840–2014
T10S	216	0,24	0,56	1.36	0.761	1850–2014
Y01S	213	0,21	0,56	1.47	0.75	1827–2014
Y02S	189	0,30	0,63	1.32	0.72	1851–2014
T19S	179	0.123	0.64	2.07	1.298	1890–2015
T22S	201	0.186	0.672	1.62	1.6	1870–2015
T23S	111	0.184	0.849	1.91	0.941	1960–2015
T24S	268	0.165	0.886	0.601	0.57	1800–2016
T25S	252	0.212	0.807	1.43	0.727	1845–2016

3.2. Climate response of site chronologies

69% of Scots pine ring-width chronologies in the Middle Volga region correlated negatively with May to July temperature of the current year (r = −0.26 to −0.43), and with previous year August temperature (r = −0.26 to −0.37) (Table 2a, Supplementary Material). Several sites demonstrated weak positive correlations with temperature of previous and current January possibly reflecting the importance of snowpack development and retention for providing adequate source of soil moisture at the beginning of the growing season (previous year: T07S, T24S, Y01S, r = 0.26–0.28; current year: T08S, T23S, r = 0.26–0.30). In general, the southern sites were more sensitive to temperature than the northern sites as only three of seven sites in the north showed significant correlations with current May and previous January (previous year: T24S, Y01S, r = 0.26–0.29; current year Y02S, T01S r = −0.26 to −0.28), while in the south, seven of eight sites demonstrated negative correlations with current May (T04S, T05S, T06S, T07S, T08S, T10S, T22S; r = −0.28 to −0.39), five sites correlate negatively with current June (T04S, T05S, T06S, T08S, T22S; r = −0.30 to −0.43), two shared relationships with current July (T04S, T06S, r = −0.29 to −0.33), while only a few sites showed a negative response with the previous year (Fig. 1a and Table 2a, Supplementary Material).

The relationship between the TRW chronologies and precipitation in the Middle Volga was more heterogeneous compared to the temperature response, although for most sites a similar spatial pattern existed i.e., 100% of southern sites have significant correlations with precipitation of the current and the previous year compared to 57% of the northern sites. In the north, two of seven sites positively correlated with precipitation for current May (T01S, Y02S; r = 0.26–0.38), one with current March (T19S, r = 0.31), and three with previous July (T01S, T22S, Y02S, r = 0.26–0.31). In the south, five sites had positive significant correlations with current May (T04S, T05S, T06S, T08S, T10S r = 0.26–0.40), three sites with current June and July (T04S, T05S, T06S, r = 0.26–0.39), two sites with current March (T05S, T23S, r = 0.30–0.33), while several sites had positive significant correlations with precipitation of the previous vegetation season (Fig. 1b and Table 2a, Supplementary Material). Despite the positive correlation with January temperature, the TRW chronologies did not correlate strongly with winter precipitation suggesting that snowpack preservation was more important than snowfall amount for promoting radial growth in the studied trees.

Most southern sites demonstrated significant positive correlations with scPDSI from April to October of the current year (r = 0.28–0.53), and from June to October of the previous year (r = 0.29–0.40) (Fig. 1c and Table 2a, Supplementary Material). Although the correlation between scPDSI and TRW was not very high, for most sites, relationships were stronger and more spatially coherent than those found with temperature or precipitation. In comparison, northern sites did not correlate with scPDSI giving a better understanding of climate-growth relationships on the southern edge of the pine area with the exception of Y02S that showed a positive correlation with summer scPDSI (r = 0.33–0.36).

3.3. Common and divergent growth signals across the network

PCA of 15 detrended and site-averaged TRW chronologies over the 1837–2014 common period revealed that just over half of the variance (51%) was accounted for by the first two factors (PC1 = 39% and PC2 = 12%). Co-orientation of all loadings along the PC1 axis confirmed common growth patterns and a common factor forcing radial growth among all Middle Volga sites (Fig. 3A). Along the PC2 axis, the loadings clearly distinguished two opposing groups (Fig. 3B). This clustering corresponds to the latitude of the chronologies with PC2 loadings revealing a north/south division between 54° N and 55° N that roughly corresponds to the transition zone between temperate forest and steppe biomes. The shortest chronology, T23S and not included in the PCA, correlated strongly with other sites from MV_{south} and for this reason it was included with MV_{south}. T09S, located centrally, was not assigned a strong loading score on PC2 which may be related to the fact that trees at this site were regularly tapped for resin. Consequently, it is likely that growth patterns at T09S were influenced by this process resulting in poor correlation on the second PC axis and for this reason it was excluded from further analysis.

Two northern sites, T24S and T25S, and one southern site, T05S (Fig. 3), are positioned close to the northern cluster but still show site-specific growth dynamics. As well as T24S and T25S, T05S is close to the southern group, but has specific growth dynamic. Based on their position along the PC2 axis we may assume that T24S and T25S chronologies are more temperature sensitive and less drought sensitive and T05S is more drought sensitive, but growth dynamic is biologically different from other sites due to local ecomorphological specifics. Two sites T04S and T05S locates close to each other on the sand dunes, but T05S growths on the top of the dune and it might affect to the growth dynamics.

3.4. Climatic signal in the TRW chronologies

From sites divided into northern and southern groups according to PC2 loadings, we selected chronologies showing negative correlations with temperature and positive correlations with precipitation to build two regional chronologies, Middle Volga north (MV_{north}) and Middle Volga south (MV_{south}) (Fig. 4, Table 1 Supplementary Material). In the north, only two sites correlated with climate (T01S and T02S), whereas

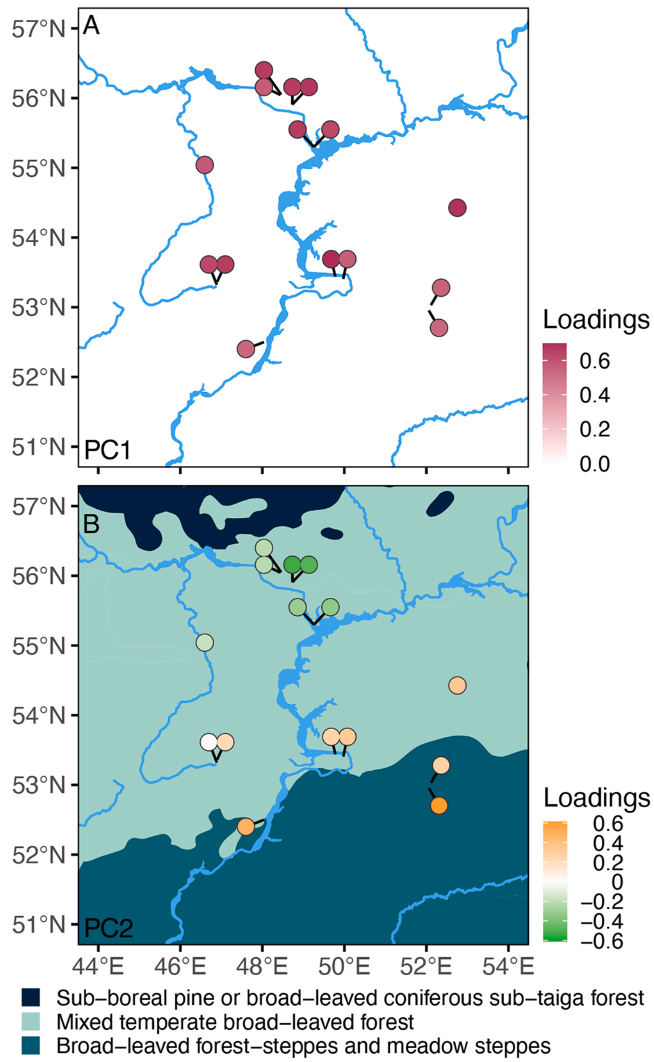

Fig. 3. Spatial characteristics of loading scores for the first two principal components (PC) for tree-ring chronologies in the Middle Volga. **A**, loading scores for the first PC (39% explained variance), and **B**, shows the loading scores for the second PC (12% explained variance). PC calculations were made for the common period, 1837–2014.

in the south, five sites were considered (T04S, T05S, T06S, T08S, T22S) (Table 2, Supplementary Material). MV_{north} demonstrated moderately weak negative correlations with May temperature ($r = -0.27$), a positive correlation with May precipitation ($r = 0.28$) and did not show any meaningful correlation with temperature or precipitation of the previous year (Fig. 4, Table 2b, Supplementary Material). In comparison with MV_{north}, correlation analyses between MV_{south} and monthly climate parameters showed a large improvement. The southern regional chronology demonstrated correlations with temperature and precipitation in the first half of the vegetation season of the current year (May-July temperature $r = -0.32$ to -0.43; May and July precipitation, $r = 0.32$ and 0.35) (Fig. 4, Table 2b, Supplementary Material). In addition, tree-ring chronologies from the south were correlated with previous July temperature ($r = -0.26$) and precipitation ($r = 0.29$) (Fig. 4, Table 2b, Supplementary Material).

Similar to the temperature and precipitation, the northern (MV_{north}) chronology did not demonstrate a strong response to scPDSI. The TRW of the southern group (MV_{south}) has a strong drought response and positively correlated with scPDSI for the period from previous July to the current October ($r = 0.27$–0.56) (Fig. 4, Table 2b, Supplementary Material).

3.5. scPDSI reconstruction

For reconstruction of scPDSI, the PCreg program was used (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). All 16 Volga TRW Arstan standard (std) chronologies were loaded into the program, and 3 chronologies were programmatically selected as predictors (T04S, T06S, T08S, significance level is $p < 0.01$). Based on these sites, a reconstruction of JJAS scPDSI was produced for the period 1830–2014 reflecting when all three sites showed an EPS> 0.85 using principal component regression approach with Eigenvalue cutoff, predictands were not pre-whitened. The model reproduces well the amplitude and extreme values of scPDSI observations for the various split calibration and verification periods. RE and CE are positive in all cases, $R^2 = 0.3$, the Pearson's correlation of the actual versus estimated scPDSI $r = 0.6$, adjusted $R^2 = 0.3$ (Table 3). The model almost identically reproduces the actual scPDSI values for different periods of calibration and verification: for the full period from 1901 to 2014 $R^2 = 0.3$, the Pearson's correlation of the actual versus estimated scPDSI $r = 0.5$, adjusted $R^2 = 0.3$, for the periods from 1901 to 1957 and vice versa RE and CE are positive, the model explains 31% of the variability of the data set. (Fig. 5).

We compared our JJAS scPDSI reconstruction with measured JJAS scPDSI (Fig. 7) to investigate climatic conditions in several years when reconstructed scPDSI underestimated the instrumental data. We choose 2 years: 1944 and 1945 ($scPDSI_{rec}$=3.18 vs $scPDSI_{act}$=1.14 and $scPDSI_{rec}$=3.26 against $scPDSI_{act}$=1.15 respectively, quartile 0.25 =−1.001). Fig. 7 shows the differences between mean monthly precipitation in 1944 and 1945 and the average climatology for the period, 1905–1990 for Borovoe weather station, as well as the temperature for the period from 1901 to 1990 from grid-point data (CRU TS 4.03). We conclude that underestimation is based on the higher amount of precipitation in May-August of the current year (Fig. 7).

Our reconstruction shows droughts in 19th century: in 1831, 1832,

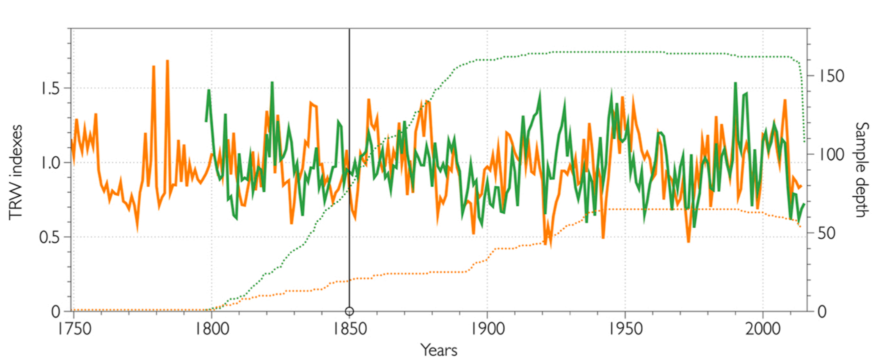

Fig. 4. TRW regional chronologies MV_{north} and MV_{south}. Solid lines – TRW indices, dotted lines – sample depth, the black vertical line – EPS> 0.85, for the MV_{north} EPS> 0.85 from 1850 to 2015 CE and MV_{south} (EPS> 0.85) from 1850 to 2016 CE.

Table 3
Calibration and verification statistics for the tree-ring reconstruction of the JJAS Palmer Drought Severity Index (scPDSI) using TRW chronologies T04S, T06S, T06S.

	Calibration	Verification	Calibration	Verification	Calibration period
	1901–1957	1958–2014	1958–2014	1901–1957	1901–2014
r	0.566	0.580	0.597	0.561	0.559
R^2	0.302	–	0.357	–	0.312
Adjusted R^2	–	–	–	–	0.305
CE	–	0.102	–	0.186	–
RE	–	0.202	–	0.243	–
DW	1.102-	–	1.838	–	1.1934
Percent variance explained	30.2		35.7 -		31.2

1833, 1851, 1853, 1859, 1863, 1864, 1865, 1880, 1891, 1892, 1897, 1898 and in the 20th and 21st centuries: in 1906, 1921, 1936, 1939, 1967, 1975, 1996, 2010 (Fig. 6, $scPDSI_{act} \leq -0.81$, quartile 0.25). Most of the estimated drought years agree with the actual scPDSI data for the Middle Volga region (Table 4, Fig. 6, $scPDSI_{act} \leq -0.81$, quartile 0.25).

We compared the most severe droughts during the 20th and 21st century, reconstructed using TRW with temperature, precipitation and drought indices measured scPDSI and the Meshcherskaya-Blazhevich drought index (D) from July to September (Fig. 8). D is commonly used to monitor moisture conditions in Russian grain-producing regions. The calculation of the index is based on a joint analysis of anomalies of a given value for monthly values of air temperature and precipitation and an estimate of the area of their distribution. As a drought index, the share of the region's area as a percent is considered, where the air temperature is 1 °C or more above average, and the amount of precipitation is 20% or more less than average (Meshcherskaya A. V. et al., 2011). In our work, we used the values of the index to verify the results of dendroclimatic analysis (Fig. 8) A comparison of the reconstruction in the historical period (19th century) is given in Section 3.6. Fig. 8 illustrates similarities between our scPDSI reconstruction and almost all hydroclimatic extremes over the 20th century for the Middle Volga. In most cases drought was associated with a low amount of precipitation and high temperature range. The pine growth reduction is also found in regional MV_{north} and MV_{south}, especially in the years 1906, 1921, 1936, 1939, 1996 and 2010 suggesting that even for trees growing under optimal environmental conditions (i.e., MV_{north}) react to extreme drought and demonstrate the growth reduction.

According to instrumental records and written sources, 1906 was an extremely dry year in the Volga region with the onset of severe drought in April and lasting through the summer months (Strashnaya et al., 2011). This year was bad throughout the Eastern part of Russia and Europe (Monthly weather chronicle, n.d.). 1921 was one of the driest in the past century in the whole Europe from the Great Britain to Ukraine (van der Schrier et al., 2021). According to our reconstruction, the drought spread out much further to the east up to the Middle Volga region. In other recorded drought years, 1921, 1936, 1975 and 2010 were found and correspond to the driest years recorded in the Middle Volga region during the 20th and 21st century (Strashnaya et al., 2011).

The particular interest for analysis is 2010, when abnormally high temperature and infrequent rainfall events were observed in the centre of European Russia in the second half of summer (Strashnaya et al., 2011). This was due to an extremely stable high pressure system positioned over European Russia from early July to mid-August blocking the eastward movement of western disturbance, bringing cooler weather. During July 2010, Moscow experienced an all-time high maximum air temperature, breaking the previous record of 35.6 °C, set on July 11, 1996. In 2010, nighttime temperature was also abnormally high with the "tropical night" indicator (minimum nighttime temperature <20 °C) for numerous meteorological stations exceeding the July average by 20 °C. In Moscow, 16 tropical nights were recorded, far surpassing the monthly average of 0.5 per year. The precipitation rate in the central and southern parts of the EPR was 100–200 mm lower over the summer (Solomina et al., 2017).

In an earlier study (Solomina et al., 2017), seven out of 14 oak and pine TRW chronologies from European Russia (700–1000 km west of the Middle Volga) showed growth suppression in 2010, in the Kostroma and Yaroslavl regions in the north, and Tula region in the south (including Yaroslavl, Kaluga, Tver and Moscow). For a regional chronology built from seven TRW sites from Kaluga, Tver and Moscow regions, the increment of pine in 2010 was not abnormal compared to the increments for the period 1779–2014. The following ring, 2011, was narrow (> 1 standard deviation), but the range of growth depression was relatively small. Most likely, the lack of noticeable increment decrease in 2010 occurred due to the fact that the intense heat began in the second half of the summer, and probably after the majority of the radial growth and tree-ring formation had already occurred resulting in the increase was abnormally low in the following year (Solomina et al., 2017). Similarly, chronologies in the Middle Volga demonstrated a growth reduction in 2011 as well.

3.6. *Comparison between the scPDSI reconstruction and historical data*

We compared our tree-ring based scPDSI reconstruction with historical chronicles and other local records (Schepkin, 1886; Bagaley, 1892; Ermolov, 1892; Loginov et al., 1976; Drozdov, 1980; Borisenkov and Pasetsky, 1988, 2003; Strashnaya et al., 2011). Our reconstruction identified numerous drought events during the 19th century that included the years 1831–33, 1851, 1853, 1859, 1863–65, 1880, 1891–92, 1897–99 (Fig. 6, $scPDSIact \leq -0.81$, quartile 0.25). After screening historical records (Borisenkov and Pasetsky, 1988, 2003) and early meteorological data (Bulygina et al., n.d.) several find potential climatic anomalies that could be related to growth reductions across the Middle Volga pine network.

Thus, in 1830, the summer was "excessive heat and drought in the south of Russia", the winter from 1830 to 1831 was especially cold. In 1831 hailstorms, dry fogs, "suffocating state of the air" were noted ("Empire Special Occasion Tables," n.d.; "List of prices for the basic necessities of life in the empire," n.d.)). In 1832, the cold weather in spring was followed by a severe drought and heat in June and July. Also, the autumn of 1832 was abnormally cold, and it could have had an additional effect on the pine growth of the following year (1833) (Varandinov, 1858). In 1833, the unusual cold weather in spring switched to unprecedented heat and drought in the southern Russia, including the Middle Volga (Varandinov N.N., 1858). The spring of 1851 in the Volga region was dry and the winter of 1850–1851 was unstable and frost was replaced by thaw (Empire weather conditions, n.d.).

Historical records also confirm the spring-summer drought (from April to June) in the Volga region in 1853 following a late frost in May. In the middle of summer, rainy and damp weather set in (Empire weather conditions, n.d.) that might also affect the tree growth. In 1859, a snowless winter was observed in the southern provinces of Russia, and a severe drought was recorded in the Volga region in summer ("Empire Special Occasion Tables," n.d.). Spring in 1863 was extremely dry and cold delaying the onset of germination in winter wheat crops ("North Post," n.d.). The winter of 1863–1864 was "fickle" with frequent thaws, spring came late, and summer was rainy (TSGIA, n.d). 1859 was also dry in the most provinces of Russia ("North Post," n.d.). The winter of 1879–1880 was with little snow, and the spring drought in the Volga

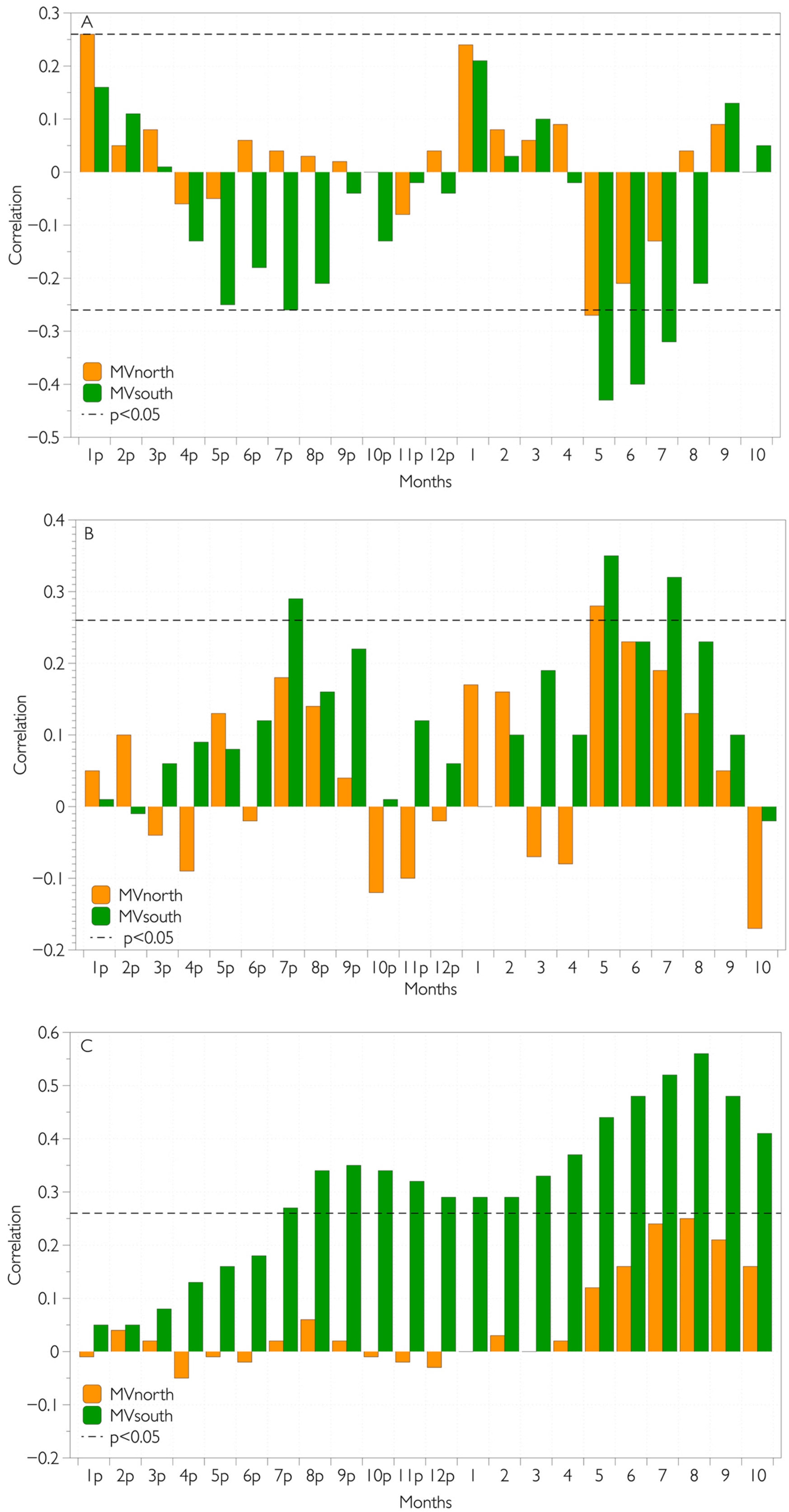

Fig. 5. Correlation results between the two regional TRW chronologies, MV_{north} and MV_{south}, with monthly climate parameters for the period 1901–2014. **A,** Mean monthly temperature, **B**, Precipitation, and **C**, scPDSI. Dashed line shows significance level, $p < 0.05$, X-axis labels with a lowercase *p* indicates correlations with months in the previous year before tree ring formation.

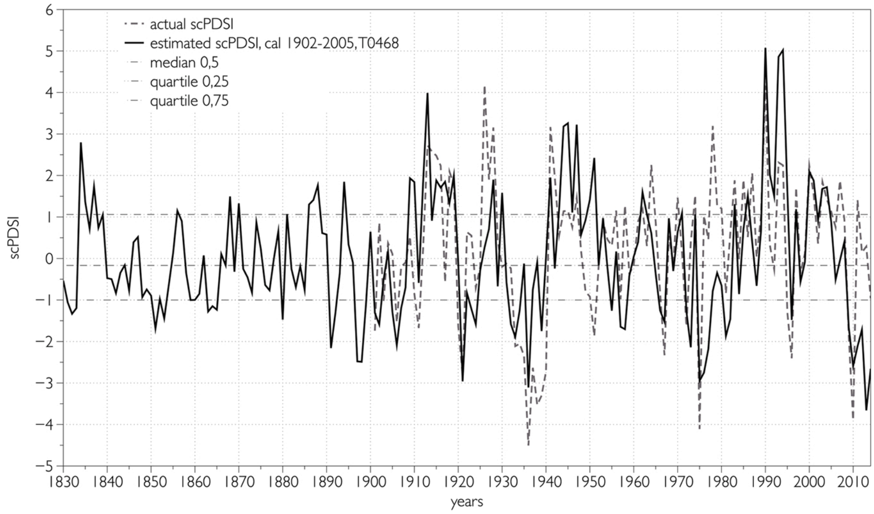

Fig. 6. Measured and reconstructed JJAS scPDSI for the period from 1830 to 2014. The reconstruction is reliable (EPS> 0.85) for the period from 1830 to 2014 CE.

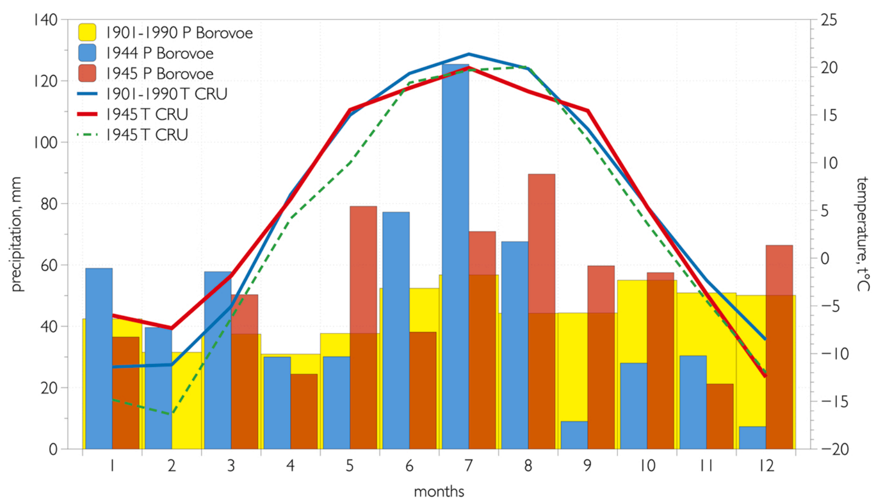

Fig. 7. Mean monthly temperature (Middle Volga south, CRU TS 4.03) and precipitation (Borovoe station data) for 1944 and 1945, and the average climatology for the period 1901–1990.

Table 4
JJAS droughts, reconstructed for the period from 1830 to 2014 CE using tree-ring chronologies T04S, T06S, T08S.

19th century	20th century	21th century
1831	1906	2010
1832	1921	
1833	1936	
1851	1939	
1853	1967	
1859	1975	
1863	1996	
1864		
1865		
1880		
1891		
1892		
1897		
1898		

region almost completely destroyed the harvest of winter crops - this year was the worst harvest in the last 30 years ("Monthly weather chronicle, n.d.).

At the end of 19th century in 1891, 1892, 1897, 1898 in the Middle Volga region, as well as throughout the southern European territory of Russia, droughts were observed during the growing season (Solomina et al., 2017; Strashnaya et al., 2011). According to historical records ("Monthly weather chronicle (288 reviews), n.d.), in 1891 the spring as well as July, August and September were dry. In addition, in the Kazan province, frost damaged the winter wheat crop, the summer was unusually cold, and crops did not sprout the following year. All months of the 1892 growing season were also dry and in the year 1897, it was so dry by the end of July that "the rye was crumbling on the vine" (Monthly weather chronicle, n.d.). Monthly weather chronicle (1891–1914) reports that the year 1898 was arid throughout European Russia. Winter and spring in 1899 were also extremely dry (Monthly weather chronicle, n.d.).

In most cases the reconstructed droughts correspond well with documentary records for the Middle Volga in the 19th century and meteorological data in the 20th century. Although as was found in a few years, a cold spring and/or wet summer may also be responsible for reduced radial growth and narrower tree rings. Thus, we identified the weather in late spring-early summer (especially in May) as a critical period of the formation of the wood of pine in the Middle Volga region.

These conclusions are generally consistent with the results of previous studies on conifer TRW in this area (Efimova et al., 2017;

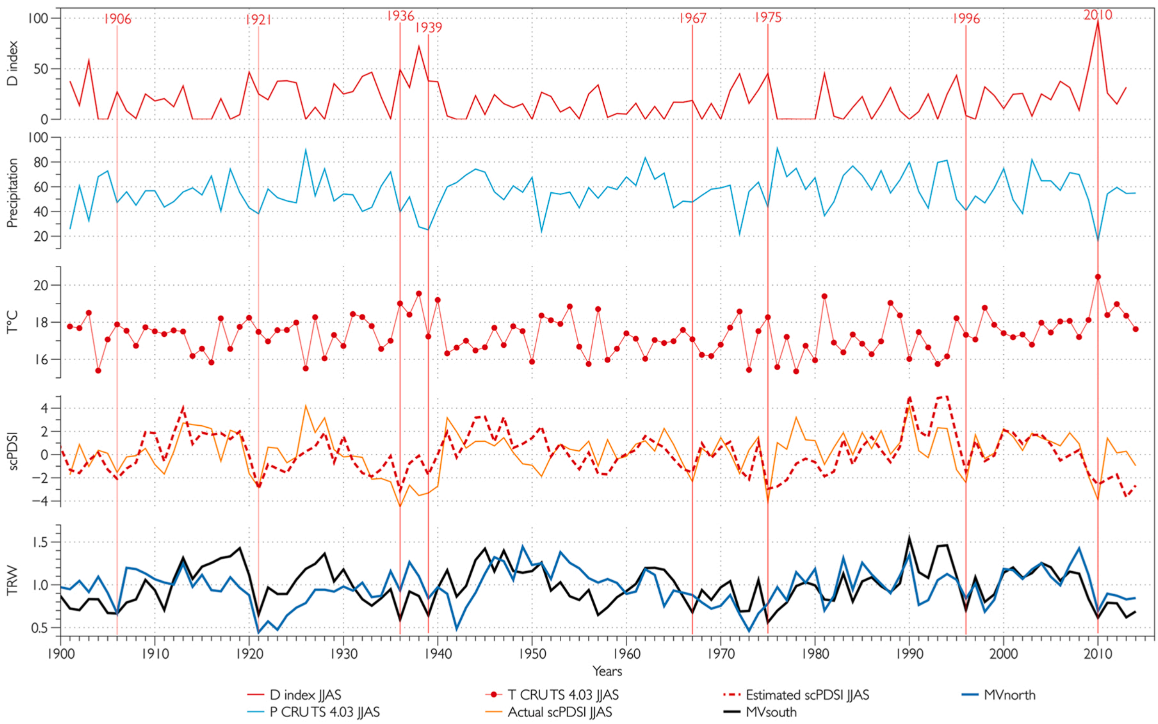

Fig. 8. Meshcherskaya-Blazhevich index (D), the mean monthly precipitation, temperature, actual scPDSI for the period for the period from July to September from 1901 to 2015 in comparison with the reconstructed scPDSI for JJAS and regional master chronologies MV_{north} and MV_{south}. Red vertical lines show severe droughts reconstructed using TRW chronologies T04S, T06S, T08S (scPDSI below the 0.25 quartile).

Timofeev, 2008, 2007; Tishin D. V. et al., 2018; Tishin D.V., 2008). In the Middle Volga the strength of the climate signal of pine tree-ring width increases along the direction from north to south and in this respect, it agrees with general geographical patterns associated with an increase in continentality in the same direction (Gerasimov et al., 1964). Other studies found a similar trend in the Russian Plain (Cook et al., 2020; Solomina et al., 2017). In particular the Cook et al. (2020) study agrees with our results: most of the extreme droughts in the 19th, 20th and 21th century are shown in both reconstructions, our reconstruction scientifically correlate with June-August PDSI reconstruction from the European Russia Drought Atlas (r = 0.65) (Fig. 2, Supplementary Material). However, the findings of Matskovsky et al. (Matskovsky et al., 2020) who used 2 eastern chronologies from the Volga region to validate the VS-Lite process-based model forced by IPCC climate projections in order to assess the pine growth in the region throughout the 21st century disagrees with our results. They concluded that the 21st century conditions will favor tree growth in the region. This conclusion contradicts our results: our data shows that the summer warming started in 1960 s increased the dependence of the pine trees from the precipitation that do not increase enough to compensate the growth of evapotranspiration. Authors noticed that their conclusions might be biased by the Leaky Bucket soil moisture model utilized by the VS-Lite and some other limitations of the model.

4. Conclusions

Pine ring width in the Middle Volga region negatively correlates with the temperature of the growing season of the current (May-July) and the previous (May-August) years. Southern sites are more temperature sensitive than northern forest stands. Pine ring width of the northern forest stands correlates with the current May-June precipitation, while more climate sensitive southern chronologies correlate with precipitation of the whole growing season (May-August) and with the precipitation of the second half of the previous year (July-August). Their sensitivity to climate is related to the increase of continentality in the southern – southern direction. Likewise, pine chronologies from the south of the Middle Volga region have strong significant correlations with scPDSI for the whole vegetation season of the current and previous year while northern forest stands are less drought sensitive and growth in the optimal climatic conditions.

Our study suggests the main reason for pine growth decrease in the Middle Volga is spring – early summer drought, while climatic conditions of the second half of the growing season did not play an important role in radial growth. The hydroclimatic sensitivity of several sites in the Middle Volga tree-ring network provided us the ability to use tree ring data to reconstruct past drought in the region from 1830 to present. Our reconstruction shows droughts in 19th century: in 1831, 1832, 1833, 1851, 1853, 1859, 1863, 1864, 1865, 1880, 1891, 1892, 1897, 1898, 1899 and in 20–21th centuries: in 1906, 1921, 1936, 1939, 1967, 1975, 1996, 2010. Reconstructed drought events were verified using instrumental data and historical archives. Although at the moment our chronology covers rather short period staring in 1830 s, we hope to extend the chronologies back in time using wood from historical buildings and archeological artefacts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2022.125957.

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