ГЕОМОРФОЛОГИЯ, 2022, том 53, № 3, с. 74–82

РЕКОНСТРУКЦИИ НА ОСНОВЕ ПАЛЕОБИОЛОГИЧЕСКИХ МЕТОДОВ

УДК 551.89:551.583.7 (470.316+470.317)

ДЕНДРОКЛИМАТИЧЕСКИЙ ПОТЕНЦИАЛ СТАБИЛЬНЫХ ИЗОТОПОВ УГЛЕРОДА В ЦЕЛЛЮЛОЗЕ ГОДИЧНЫХ КОЛЕЦ *Pinus sylvestris* L. В ЯРОСЛАВСКОЙ И КОСТРОМСКОЙ ОБЛАСТЯХ

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Поступила в редакцию 30.03.2022 г.
После доработки 10.04.2022 г.
Принята к публикации 15.04.2022 г.

Стабильные изотопы углерода в годичных кольцах деревьев могут служить индикатором прошлых климатических и экологических изменений. Однако климатический сигнал, который выражается в этом индикаторе, варьирует в зависимости от региона и вида деревьев. С этой точки зрения, Европейская часть России все еще остается малоизученным регионом, где почти нет исследований зависимости изменений изотопного состава древесины от климатических параметров. В данной работе приводятся первые результаты подобного исследования для живых деревьев сосны обыкновенной (*Pinus sylvestris* L.) в Тверицком бору Ярославля. Было измерено соотношение стабильных изотопов углерода (δC^{13}) в древесной целлюлозе отдельных годичных колец, извлеченных из пяти деревьев, и рассчитаны коэффициенты корреляции δC^{13} с метеорологическими параметрами за 2010–2020 гг. Показано, что δC^{13} в древесной целлюлозе имеет значимую взаимосвязь с температурой с мая по сентябрь ($r = 0.63$, $p = 0.037$), с осадками с мая по сентябрь ($r = -0.77$, $p = 0.051$) и с индексом суровости засухи Палмера с мая по сентябрь ($r = -0.65$, $p = 0.032$). Эти результаты являются первым прямым доказательством того, что δC^{13} в древесной целлюлозе сосны обыкновенной в Ярославле может служить показателем колебаний влажности теплого периода. Для того, чтобы сделать выводы о стабильности климатического сигнала в этом регионе на протяжении всего XX века, необходимы дополнительные измерения. Также в статье описываются две новые древесно-кольцевые хронологии, основанные на археологических и архитектурных материалах из Ярославской (1438–2019 гг.) и Костромской (1283–2012 гг.) областей. Согласно полученным результатам о климатической чувствительности δC^{13} в древесной целлюлозе, эти хронологии могут служить материальной основой для реконструкций влажности годичного разрешения в регионе.

Ключевые слова: сосна обыкновенная, дендрохронология, Европейская часть России, засуха, индекс суровости засухи Палмера

DOI: 10.31857/S0435428122030099

1. INTRODUCTION

Classical dendroclimatic reconstructions based on tree-ring width (TRW) or maximum latewood density (MXD) data are usually limited to extreme environments, where tree growth is controlled by one strong limiting factor. In non-boundary environments stable isotopes can surpass classical tree-ring proxies, as they are less dependent of ecoclimatic conditions and hence usually have significant correlations with climatic data (Gagen et al., 2004; Frank et al., 2015; Esper et al., 2016, 2018). Stable isotope ratios in tree rings can be a good proxy for climatic changes in the past, being a substitute or a complement for other proxies (Loader et al., 2013; Helama et al., 2021). East European Plain is located in temperate climate where dendroclimatic signal in tree-ring width of conifers is mixed and sometimes non-significant (Matskovsky, 2016; Solomina et al., 2017; Hughes et al., 2019; Kuznetsova et al., 2022). Therefore, the development of more climate-sensitive tree-ring proxies on this territory is of primary importance.

The process of photosynthesis is responsible for the assimilation of atmospheric CO_2 by the tree (Hartl-Meier et al., 2014). CO_2 fixation and, as the result, the stable isotopes ratio in tree rings depends on the regime of moistening, air humidity, temperature and illumination of the territory (Nikolov et al., 1995; Fredeen, Sage 1999; Bunce, 2000). Due to various climatic controls of isotope fractionation, various climatic parameters have been reconstructed using stable carbon isotopes ratios: temperature in Central Asia (Treydte et al., 2009), Turkey (Heinrich et al., 2013), Finland (Gagen et al., 2007), Altai (Sidorova et al., 2013); river flow in Siberia (Waterhouse et al., 2000), droughts in Europe (Kress et al., 2010), Altai (Jiang et al., 2020), and China (Kang et al., 2022); relative humidity in China (Liu et al., 2018), fire frequency in Oregon, USA (Voelker, 2019); sunshine duration (Loader et al., 2013) and cloud cover (Gagen et al., 2011) in Scandinavia.

According to the new data from annually-resolved, long-lasting, tree-ring-based isotope records, long-term hydroclimate trends, as well as interannual variations, can be better captured using stable isotopes than by TRW or MXD (Büntgen, 2022). In that study, Ulf Büntgen argued that limitations of “growth-dependent” (like TRW or MXD) parameters relate to natural processes of adaptation to long-term climate changes, whereas “growth-independent” carbon and oxygen isotopic ratios from tree-ring cellulose can capture environmental variation well beyond the segment length of individual tree-ring samples. This is another argument for an extensive development of such proxies in different regions over the Globe.

Dendroclimatological studies based on stable isotopes in tree rings from Europe are numerous. As an example of recent progress in this region, stable carbon and oxygen isotopes in oak wood have been used to reconstruct droughts in central Europe over the past 2000 years with annual resolution (Büntgen et al., 2021). However, in the European part of Russia, studies using proportion of stable carbon isotope C^{13} (δC^{13}) in tree rings for climatic reconstructions are still rare. For instance, there is a study on the reconstruction of moisture conditions based on δC^{13} in tree rings of archaeological wood from Yaroslavl (Panyushkina et al., 2016). But there are still no data on the climate signal in δC^{13} in this region. Neither there are studies comparing δC^{13} in tree rings of living trees to meteorological observations.

In this paper we make first steps to fill this gap. We collected tree-ring samples from living pines (*Pinus sylvestris* L.) in Yaroslavl city, we measured and cross-dated these samples to build tree-ring-width (TRW) chronology. Then we measured δC^{13} in five individual trees for the period from 2010 to 2020 and compared these records to meteorological data to explore paleoclimatic potential of this proxy. Moreover, we constructed long tree-ring chronologies for Yaroslavl and Kostroma regions based on archaeological and architectural materials to show the possible extension of tree-ring-based climatic reconstructions in the region.

2. MATERIALS AND METHODS

2.1. Tree-ring materials. We sampled ten living pines in the Tveritsky forest in the city of Yaroslavl (57.65° N, 39.93° E) in September 2020 (site code A22S). Two samples from each tree were taken at breast height with a common increment corer (ø 6 mm), and two additional samples with a large diameter increment corer (ø 10 mm). They were placed in plastic containers for transportation to the laboratory of dendrochronology (Institute of Geography, Moscow).

Materials for the extension of tree-ring chronologies into the past in Yaroslavl and Kostroma regions come from archaeological excavations and old wooden buildings. Materials for the Kostroma chronology come from the archaeological excavations in the city of Kostroma and from the wooden buildings from the Kostroma Region. They include samples from the church in Andreevskoye village (58.16° N, 41.30° E), two buildings from the Museum of Wooden architecture of Kostroma Region: house of Skobyolkin and the church of Ilijah the Prophet. The other materials come from the excavations (2013–2018) of fair buildings in the center of Kostroma city (57.77° N, 40.93° E): Melochniye ryady, Maliye Myasniye ryady, Muchniye ryady. Kostroma archaeological and architectural materials were connected to the present by cross-dating with living pines from the Kologriv district of Kostroma region (58.83° N, 44.32° E, AD 1860–2012).

Materials for the Yaroslavl chronology come from the archaeological excavations in the city of Yaroslavl and from the wooden buildings from Yaroslavl region. They include samples from the church of St. John on the Ishnya river (57.18° N, 39.36° E), from four wooden houses in Porechye-Rybnoye village (57.09° N, 39.39° E), and the house in Cheluskintsev st., 7 in Yaroslavl. The other materials come from the excavations of 2020–21 in the center of Yaroslavl, Volzhskaya embankment, 1. Yaroslavl chronology was connected to the living pines from Yaroslavl (AD 1869–2019) and from Borisoglebsk district of Yaroslavl region (57.27° N, 39.15° E, AD 1864–2013).

The materials used for the development of the Yaroslavl and Kostroma tree-ring chronologies were described in details earlier (Engovatova et al., 2022).

2.2. Tree-ring-width measurements and cross-dating. Laboratory preparation, measurements and further analysis were carried out in the laboratory of dendrochronology of the Institute of Geography RAS, Moscow. Increment cores were glued on the wooden beams with perpendicular fiber direction (Stokes, Smiley, 1968), and then sanded. Cuts from archaeological wood were sanded. In some cases, when tree rings were hard to distinguish after sanding, they were cleared by a razor blade. Then the samples were scanned using a flatbed scanner, Epson Expression 1680, with a resolution range of 1500–3200 dpi. Ring widths were measured using CooRecorder software (Larsson, Larsson, 2016). This program calculates distances between successive coordinates of the points that were placed automatically or manually by an operator on the tree-ring borders. Detailed step-by-step protocol of obtaining TRW measurements is available on the web page of Cybis company (http://www.cybis.se/forfun/dendro/helpcoorecorder7/index.htm). Individual TRW series were transformed into decadal Tucson format using CDendro software (Larsson, Larsson, 2016). Process of cross-dating was carried out in programs CDendro and COFECHA (Grissino-Mayer, 2001). Cross-dated tree-ring series were then standardized using negative exponential or negative or zero slope linear function via ratio in dplR package in the R environment (Bunn, 2008; R Core Team, 2021). The chronologies quality of was estimated by means of the Expressed Population Signal (EPS, Briffa, Jones, 1990), applying a 30-year moving window. EPS values larger than 0.85 were used as a threshold representing the periods of the chronologies suitable for reconstruction (Wigley, 1984).

2.3. Stable carbon isotopes measurements. Cross-dated cores were cut with a stationery knife under a binocular – either single rings or separately earlywood (EW) and latewood (LW) were cut. The cut samples were transferred to the Laboratory of Radiocarbon Dating and Electron Microscopy of the Institute of Geography RAS. Alpha-cellulose from each sample was extracted using a modified Jayme-Wise isolation method (Boettger et al., 2007). δC^{13} were measured from the alpha-cellulose samples using the precisION IRMS mass spectrometry analyser (Isoprime, UK) combined with the Vario Isotope Cube elemental CHNS analyzer (Elementar, Germany) relative to a high purity reference gas (CO_2) calibrated according to IAEA standard materials (IAEA-CH3-cellulose, IAEA-600-caffeine). The Casein B2155, Urea B2174 and Sorghum Flour B2159 (Elemental Microanalysis, UK) standards were used as working laboratory standards and for constructing the calibration curve.

2.4. Meteorological data. Monthly mean temperature and sums of precipitation at Yaroslavl weather station (WMO code 27330) for the period 2010–2020 were taken from the website (http://www.pogodaiklimat.ru/history/27330.htm).

Monthly values of self-calibrated Palmer Drought Severity Index (scPDSI) were obtained from the University of East Anglia Climatic Research Unit product version 4.05 (Barichivich et al., 2021). This is a gridded dataset with spatial resolution of 0.5°. The values from the nearest grid-point to Yaroslavl were taken (57.75° N, 39.75° E).

3. RESULTS AND DISCUSSION

3.1. Tree-ring width chronology for living trees. TRW chronology for living pine trees growing in Yaroslavl covers the period AD 1869–2019. The period with EPS values larger than 0.85 starts in AD 1905, where it is covered by measurements from nine to eleven trees (fig. 1). This chronology is the base for sampling individual rings for δC^{13} measurements and for cross-dating of architectural materials in the region.

3.2. Long chronologies of archaeological and architectural materials. Cross-dating of 89 samples allowed us to develop the Kostroma TRW chronology which covers the period AD 1283–2012 (fig. 2). It was successfully cross-dated with the Kirillov and Vologda TRW chronologies (Karpukhin, Matskovsky, 2012) (AD 1085-2012, t-value = 11.0). The highest sample replication is for the 17th century, while the replication in 18th and 19th centuries can be easily increased by materials we have collected from various wooden buildings in the region. The replication for the 20th century could be increased by samples from living trees in the region. Earlier part of the chronology (13–15th centuries) is harder to straighten by additional samples, as the archaeological wood from this period is rare.

Yaroslavl TRW chronology consists of 81 samples and covers the period AD 1438-2019 (fig. 2). It was cross-dated with the Kostroma chronology (t-value = 4.8) and Vologda chronology (t-value = 7.7). The most problematic period for the chronology is the 19th century, as it is not easy to get access to architectural wood for this period. On the other hand, it will be easier to extend this chronology into the past, as there are a lot of archaeological materials from Yaroslavl city starting from the 12th century.

Despite lower t-values for the mean chronologies, individual samples from Yaroslavl are usually easily cross-date against the Kostroma chronology, while it is hard to cross-date them against the Vologda chronology. At the same time, individual samples from Kostroma are often easily cross-dated with the Vologda chronology. All the three regions are located in the boreal forest area (taiga), but Yaroslavl and Kostroma are located on the southern ecological border of taiga (southern taiga), while Vologda is located in the middle taiga. We argue that such cross-dating connections may be explained by differing climatic sensitivity of trees in these forests: more moisture sensitive trees in Yaroslavl region and more temperature-sensitive trees in Kostroma region. These considerations may refine previously defined geographical boundary between mostly temperature-sensitive and mostly moisture-sensitive trees (Matskovsky, 2012; 2016) as passing between Yaroslavl and Vologda (around 58.5° N). Kostroma region, which is located to the east of Yaroslavl region and to the south of Vologda region, should be considered as a transitional region for the climatic signal in tree-ring width of co-

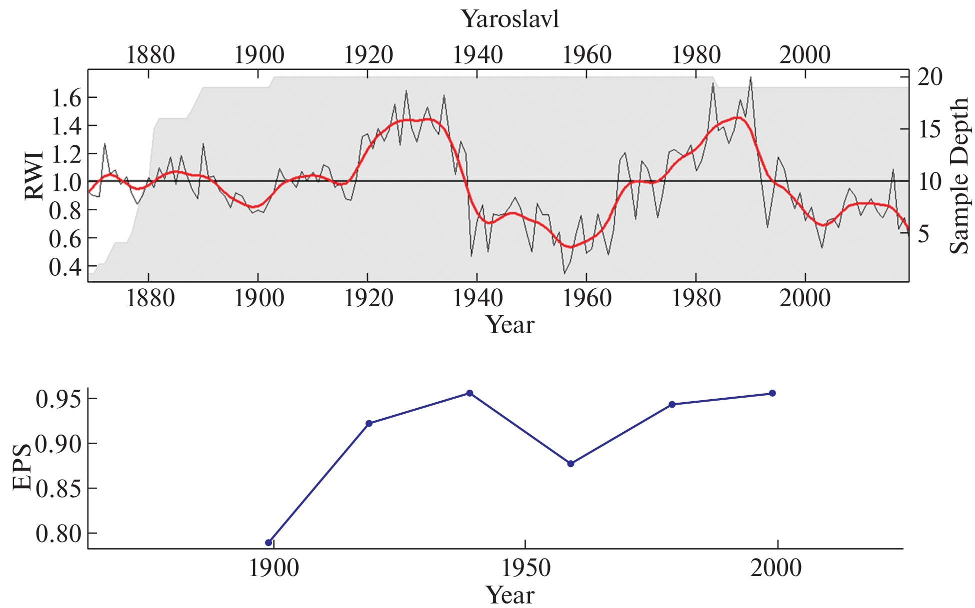

Fig. 1. TRW chronology for living trees growing in Tveritskiy forest, the city of Yaroslavl. Upper panel shows tree-ring indices (black line) smoothed by 32-year spline (red line) and sample replication (grey shading). Lower panel shows EPS values for 50-yr periods with 25-yr overlay.

Рис. 1. Хронология ширины годичных колец живых деревьев, растущих в Тверицком бору Ярославля. Сверху показаны индексы прироста (черная линия), сглаженные 32-летним сплайном (красная линия) и наполненность образцами (серая штриховка). Снизу показаны значения EPS за 50-летние периоды с наложением в 25 лет.

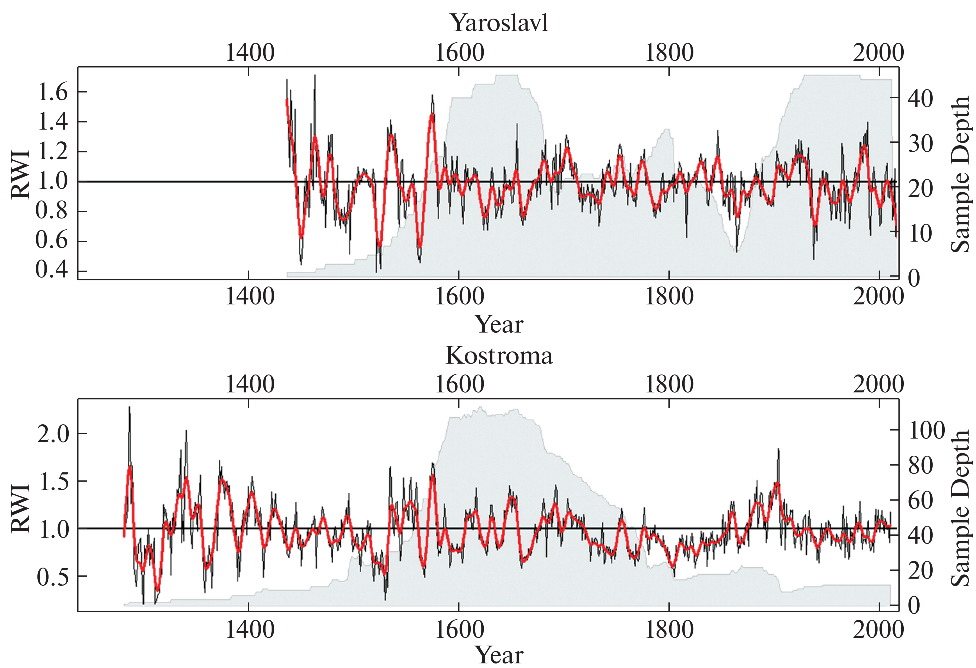

Fig. 2. Yaroslavl (upper panel) and Kostroma (lower panel) TRW chronologies and their replication. Designations as in the fig. 1.

Рис. 2. Ярославская (сверху) и Костромская (снизу) хронологии ширины годичных колец и их наполнение образцами. Усл. обозначения см. рис. 1.

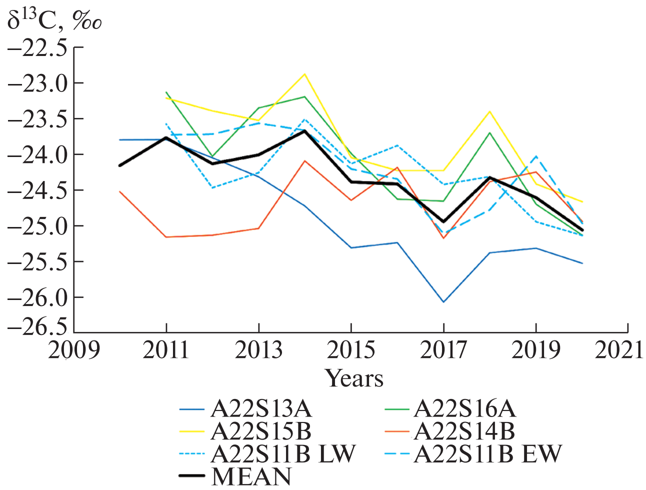

Fig. 3. δC^{13} values measured in the cellulose of tree rings. Coloured lines show series from individual cores. Solid lines show the measurements from the whole ring, dotted line shows the measurements from latewood, dashed line shows the measurements from earlywood. Black line shows the MEAN series of all the measurements.

Рис. 3. Значения δC^{13}, измеренные в целлюлозе годичных колец. Цветные линии показывают серии из отдельных кернов. Сплошные линии – кольцо целиком, короткий пунктир – поздняя древесина, длинный пунктир – ранняя древесина. Черная линия – усредненный ряд для всех измерений.

nifers. The difference in soil conditions may also be a factor that alters primary climatic signal between Yaroslavl and Kostroma forest stands.

3.3. Variations of stable carbon isotopes in tree rings. Measured values of δC^{13} in cellulose of the sampled tree rings are shown in the fig. 3. Ten to 11 rings have been measured entirely from four cores; EW and LW in ten rings of one core. Correlation analysis was carried out between the series of measurements (table 1). Basically, all the initial measurements correlate well with each other and with the MEAN (averaged) series, except for the core A22S14A, which showed insignificant and even negative correlation values due to the presence of a positive trend. The δC^{13} values in latewood are less correlated with the MEAN series than the δC^{13} values in earlywood. This is logical considering that earlywood makes up most of the annual ring. The maximum correlation with the MEAN series has the core A22S16A. When removing the linear trend from all the series, the minimum correlation with the MEAN series has the core A22S13A, the maximum correlation has the core A22S16A. The differences between δC^{13} values in the individual trees might be related to the micro-habitat, genetics or non-climatic disturbances in the forest stands (Robertson et al., 2002). Generally, changes in δC^{13} values in tree rings are not related to the age of tree, especially out of the juvenile period of the first 10–15 rings. However, tree-ring isotope series can contain low-frequency non-climatic trends (Loader et al., 2013). Sometimes the differences between δC^{13} values in the individual trees could also be explained by the slower growth of tree towards the canopy (Loader et al., 2012). In further studies, an increased replication of measurements in every year might resolve the significance and the nature of the differences in δC^{13} values between the individual trees.

Interannual variability of the δC^{13} values for each tree (mean standard deviation = 0.6) is higher than inter-sample variability for each year (mean standard deviation = 0.57). This fact, along with the good synchronicity of the measurements, indicates the presence of a common signal, which we may expect to be of climatic nature.

3.4. Co-variations of stable carbon isotopes and meteorological parameters. We correlated the MEAN series of δC^{13} measurements with meteorological parameters – summer temperature, precipitation and scPDSI (May to September period). Correlation coef-

Table 1. Correlation coefficients between δC^{13} series. The coefficients for the initial series are shown above the diagonal, for the detrended series (linear trend removed) – below the diagonal. Statistically significant values are shown in bold font ($p < 0.05$)

Таблица 1. Коэффициенты корреляции между рядами δC^{13}. Коэффициенты для исходных рядов показаны над диагональю, для рядов с убранным линейным трендом – под диагональю. Статистически значимые значения выделены полужирным шрифтом ($p < 0.05$)

	13A	16A	15B	14A	11B LW	11B EW	MEAN
13A	–	**0.708**	**0.695**	–0.184	0.461	**0.858**	**0.777**
16A	0.159	–	**0.931**	–0.025	**0.753**	**0.687**	**0.927**
15B	0.176	**0.842**	–	0.024	**0.729**	**0.632**	**0.911**
14A	0.079	0.411	0.455	–	0.189	0.057	0.149
11B LW	–0.381	0.471	0.438	**0.654**	–	0.478	**0.793**
11B EW	0.608	0.243	0.150	0.546	–0.128	–	**0.848**
MEAN	0.337	**0.788**	**0.764**	0.538	0.517	0.580	–

ficients between the MEAN series of δC¹³ and mean May to September temperature (T V–IX) are $r = 0.63$ ($p = 0.037$) and $r = 0.29$ ($p = 0.39$) for the initial and detrended data respectively (fig. 4). Correlation coefficients between the MEAN series of δC¹³ measurements and total May to September precipitation (P V-IX) are $r = -0.77$ ($p = 0.0051$) and $r = -0.59$ ($p = 0.059$) for the initial and detrended data respectively. Correlation coefficients between the MEAN series of δC¹³ measurements and May to September scPDSI (V-IX) are $r = -0.65$ ($p = 0.032$) and $r = -0.64$ ($p = 0.036$) for the initial and detrended data respectively. Our results agree with the recent studies (Esper et al., 2018; Lukač et al., 2021), where significant correlations of δC¹³ with temperature, precipitation and soil moisture were found for different pine species in Sweden and Montenegro, respectively. In our case the highest correlations were found between δC¹³ and precipitation. However, the primary climatic factor that controls δC¹³ may change with microsite conditions (Esper et al., 2018), as well as in time (Lukač et al., 2021).

We see exchanging influence of summer temperature and precipitation on isotopic composition of tree cellulose. For example, in 2014 low precipitation and average temperature led to higher δC¹³ values, while in 2017 low temperature and average precipitation led to lower δC¹³ values. Both temperature and precipitation influence air moisture, thus affecting stomatal conductance, which alters carbon discrimination (Warren et al., 2001; Farquhar et al., 1989). Soil moisture, as expressed in scPDSI, contrary to temperature and precipitation has significant correlation values with δC¹³ both for the initial and detrended series. Moreover, while the values of temperature and precipitation come from the nearby weather station, scPDSI values were acquired from a gridded dataset, which does not include this weather station. Soil moisture measurements from a nearby location are expected to correlate better with the δC¹³ values.

For the analyzed period of 2010–2020 we see pronounced trends in all the series: δC¹³ and summer temperature (negative), precipitation and scPDSI (positive). A part of the correlation of the series, hence, is due to this trend. The trend in δC¹³ may be due (at least partly) to the reduction of atmospheric δC¹³ due to admixture of fossil fuel CO_2 (Suess effect), and due to a changing physiological response of trees to increasing atmospheric levels of CO_2 (McCarroll et al., 2009). However, even detrended δC¹³ series show significant correlation values with scPDSI, which reaffirms climatic sensitivity of δC¹³ values in tree-ring cellulose. Here we used simple linear detrending as the length of our series is relatively short. However, more sophisticated methods are used to account for Suess effect in longer time series of δC¹³ variations (Keeling, 1979; Belmecheri, Lavergne, 2020).

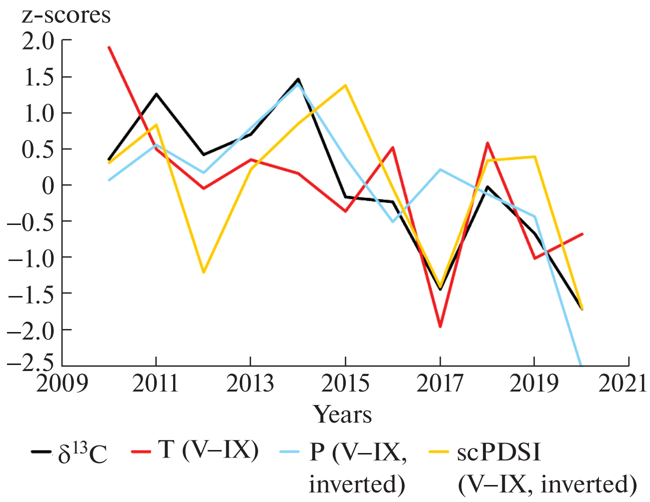

Fig. 4. Comparison of δC¹³ and climatic parameters. Black line shows δC¹³ MEAN series, red line shows temperature (V–IX), blue line shows precipitation(V–IX), yellow line shows scPDSI (V-IX). All the series were transformed to z-scores.

Рис. 4. Сравнение рядов δC¹³ и климатических параметров. Черная линия – средние значения δC¹³ за каждый год, красная линия – температура мая-сентября, синяя линия – инвертированные значения осадков мая-сентября, желтая линия – инвертированные значения scPDSI (индекса суровости засухи Палмера) мая-сентября. Все серии нормированы.

We conclude that δC¹³ values in tree-ring cellulose of *Pinus sylvestris* in Yaroslavl region is a moisture sensitive proxy that has statistically significant connection to summer precipitation and temperature (probably through evaporation), as well as to soil moisture. Other studies revealed differing climatic signal in δC¹³ for this species – from summer sunshine in Northern Finland (McCarroll, Pawellek, 2001) to summer (June-July) precipitation at the Northern Caucasus (Brugnoli et al., 2010). Our findings confirm the interpretation of previously studied δC¹³ series extracted from archaeological materials (Panyushkina et al., 2016) as a moisture sensitive proxy record.

However, the length of the studied δC¹³ record does not allow us to make conclusions about the stability of climatic signal in this proxy throughout the 20th century. Longer isotopic records acquired from well-dated tree rings of Yaroslavl region will shed light on this question. Additionally, investigation of the relationship between well-replicated early- and latewood δC¹³ series and meteorological parameters will allow to better capture the seasonality in these proxies.

4. CONCLUSIONS

The main conclusions of this study are the follo-wing:

– the series of δC¹³ measurements from five trees showed good co-variability;

– δC^{13} values in tree-ring cellulose of *Pinus sylvestris* in Yaroslavl region show positive correlation to summer (May to September) temperature, negative correlation to May to September precipitation and May to September scPDSI for the analysed period of 2010–2020;

– the constructed long chronologies for Yaroslavl (AD 1438-2019) and Kostroma (AD 1238–2012) regions are potential sources of materials for future δC^{13} measurements and long annually resolved reconstructions of moisture conditions in the region;

– cross-dating of tree-ring width series of archaeological and architectural samples from Yaroslavl, Kostroma and Vologda regions showed that Kostroma is connected to both regions while individual samples from Yaroslavl are hard to cross-date against Vologda samples;

– further studies should consider longer δC^{13} record to confirm our findings for the 2010–2020 period and to explore the stability of climatic signal throughout the 20th century.

Dendroclimatic Potential of Stable Carbon Isotopes in Tree-Ring Cellulose of *Pinus sylvestris* L. in Yaroslavl and Kostroma Regions, European Russia

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Stable carbon isotopes in tree rings may serve as an important proxy of past climatic and environmental changes. However, the climatic signal that is expressed in this proxy vary across regions and species. European Russia is still an understudied region, where a few studies on climatic signal in isotopic composition of wood were undertaken. Here we provide the first results of such study for living Scots pines in the city of Yaroslavl. We measured the ratio of stable carbon isotopes (δC^{13}) in wood cellulose of individual tree rings extracted from five trees, and calculated correlation coefficients of δC^{13} with meteorological parameters. The period analyzed is 2010–2020. We showed that δC^{13} in wood cellulose has a significant relationship with May-September temperature ($r = 0.63$, $p = 0.037$), May-September precipitation ($r = -0.77$, $p = 0.0051$), and May-September Palmer Drought Severity Index ($r = -0.65$, $p = 0.032$). These results are the first direct evidence that δC^{13} in wood cellulose of Scots pine in Yaroslavl may serve as a proxy for the warm period moisture variations. Additional measurements are required to make conclusions about the stability of climatic signal in this proxy throughout the 20th century. We also describe two new tree-ring chronologies based on archaeological and architectural materials from the Yaroslavl (AD 1438–2019) and Kostroma (AD 1283–2012) regions. According to the obtained results on the climatic sensitivity of δC^{13} in wood cellulose, these chronologies may serve as a material base for annually resolved moisture reconstructions in the region.

Keywords: Scots pine, dendrochronology, drought, East European plain, PDSI

ACKNOWLEDGMENTS

The study was supported by Russian Science Foundation grant No. 21-17-00264 (isotopic analysis) and State assignment project No. AAAA-A19-119022190172-5 (FMGE-2019-0004, construction of the Yaroslavl and Kostroma chronologies). The study was completed in the laboratory created by the Megagrant project (agreement No. 075-15-2021-599, 08.06.2021).

REFERENCES

Barichivich J., Osborn T.J., Harris I., van der Schrier G., and Jones P.D. Monitoring global drought using the self-calibrating Palmer Drought Severity Index. In: "State of the Climate in 2020". Dunn R.J.H., Aldred F., Gobron N., Miller J.B., Willett K.M. (Eds.). *Bulletin of the American Meteorological Society*. 2021. Vol. 102. P. 68–70. https://doi.org/10.1175/2019BAMSStateoftheClimate.1

Belmecheri S. and Lavergne A. Compiled records of atmospheric CO2 concentrations and stable carbon isotopes to reconstruct climate and derive plant ecophysiological indices from tree rings. *Dendrochronologia*. 2020. Vol. 63. P. 125748. https://doi.org/10.1016/j.dendro.2020.125748

Briffa K.R. and Jones P.D. In: Methods of Dendrochronology: Applications in the Environmental Sciences, ed E.R. Cook and L.A. Kairiukstis. Dordrecht: Kluwer Academic (Publ.), 1990. P. 137–152.

Brugnoli E., Solomina O., Spaccino L., and Dolgova E. Climate signal in the ring width, density and carbon stable isotopes in pine (*Pinus silvestris* L.) in Central

Caucasus. *Geography, Environment, Sustainability*. 2010. Vol. 3. No. 4. P. 4–16. https://doi.org/10.24057/2071-9388-2010-3-4-4-16

Bunce J.A. Responses of stomatal conductance to light, humidity and temperature in winter wheat and barley grown atthree concentrations of carbon dioxide in the field. *Global Change Biology*. 2000. Vol. 6. P. 371–382. https://doi.org/10.1046/j.1365-2486.2000.00314.x

Bunn A.G. A dendrochronology program library in R (dplR). *Dendrochronologia*. 2008. Vol. 26. P. 115–124. https://doi.org/10.1016/j.dendro.2008.01.002

Büntgen U. Scrutinizing tree-ring parameters for Holocene climate reconstructions. *Wiley Interdisciplinary Reviews*. 2022. Climate Change, e778. https://doi.org/10.1002/wcc.778

Büntgen U., Urban O., Krusic P.J., Rybníček M., Kolář T., Kyncl T., Ač A., Koňasová E., Čáslavský J., Esper J., Wagner S., Saurer M., Tegel W., Dobrovolný P., Cherubin P., Reinig F., and Trnka M. Recent European drought extremes beyond Common Era background variability. *Nat. Geosci*. 2021. Vol. 14. P. 190–196. https://doi.org/10.1038/s41561-021-00698-0

CooRecorder basics – Cybis Dendrochronology [Electronic data] http://www.cybis.se/forfun/dendro/ (access date: 23.04.2022)

Dolgova E. June–September temperature reconstruction in the Northern Caucasus based on blue intensity data. *Dendrochronologia*. 2016. Vol. 39. P. 17–23. https://doi.org/10.1016/j.dendro.2016.03.002

Engovatova A.V., Lazarev A.S., and Matskovsky V.V. *Novye arkheologicheskie nakhodki dlya dendrokhronologicheskoi shkaly po khvoynym porodam dlya Yaroslavskoi i Kostromskoi oblasti*. (New archaeological finds for conifer tree-ring width chronologies of the Yaroslavl and Kostroma regions.) In: The Archeology of the Moscow region. Moscow: Istitute of Archaeology RAS (Publ.), 2022. Vol. 18. P. 91–106. (in Russ.)

Esper J., Holzkämper S., Büntgen U., Schöne B., Keppler F., Hartl C., George S.S., Riechelmann D.F.C., and Treydte K. Site-specificclimatic signals in stable isotope records from Swedish pine forests. *Trees*. 2018. Vol. 32. P. 855–86. https://doi.org/10.1007/s00468-018-1678-z

Esper J., Krusic P.J., Ljungqvist F.C., Luterbacher J., Carrer M., Cook E., Davi N.K., Hartl-Meier C., Kirdyanov A., Konter O., Myglan V., Timonen M., Treydte K., Trouet V., Villalba R., Yang B., and Büntgen U. Ranking of tree-ring based temperature reconstructions of the past millennium. *Quaternary Science Reviews*. 2016. Vol. 145. P. 134–151. https://doi.org/10.1016/j.quascirev.2016.05.009

Farquhar G.D., Ehleringer J.R., and Hubick K.T. Carbon isotope discrimination and photosynthesis. *Annual review of plant biology*. 1989. Vol. 40. P. 503–537. https://doi.org/10.1146/annurev.pp.40.060189.002443

Fredeen A.L. and Sage R.F. Temperature and humidity effects on branchlet gas-exchange in white spruce: an explanation for the increase in transpiration with branchlet temperature. *Trees*. 1999. Vol. 14. P. 161–168. https://doi.org/10.1007/s004680050220

Gagen M., McCarroll D., and Edouard J.L. Latewood width, maximum density and stable carbon isotope ratios of pine as climate indicagtors in a dry subalpine environment, French Alps. 2004. *Arctic, Antarctic, and Alpine Research*. Vol. 36. P. 166–171. https://doi.org/10.1657/1523-0430(2004)036[0166:LWMDAS]2.0.CO;2

Gagen M., McCarroll D., Loader N.J., Robertson I., Jalkanen R., and Anchukaitis K.J. Exorcising the 'segment length curse': summer temperature reconstruction since AD 1640 using non-detrended stable carbon isotope ratios from pine trees in northern Finland. *Holocene*. 2007. Vol. 17. P. 435–446. https://doi.org/10.1177/0959683607077012

Gagen M., Zorita E., McCarroll D., Young H.F., Grudd H., Jalkanen R., Loader N.J., Robertson I., and Kirchhefer A. Cloud response to summer temperatures in Fennoscandia over the last thousand years. *Geophysical Research Letters*. 2011. Vol. 38(5). L05701. https://doi.org/10.1029/2010GL046216

Grissino-Mayer H. Evaluating Crossdating Accuracy: A Manual and Tutorial for the Computer Program COFECHA. *Tree-ring Res*. 2001. Vol. 57. No. 2. P. 205–221.

Hartl-Meier C., Zang C., Büntgen U., Esper J., Rothe A., Göttlein A., Dirnböck T., and Treydte K. Uniform climate sensitivity in tree-ring stable isotopes across species and sites in a mid-latitude temperate forest. *Tree Physiology*. 2014. Vol. 35. P. 4–15. https://doi.org/10.1093/treephys/tpu096

Helama S., Stoffel M., Hall R.J., Jones P.D., Arppe L., Matskovsky V.V., Timonen M., Nojd P., Mielikainen K., and Oinonen M. Recurrent transitions to Little Ice Age-like climatic regimes over the Holocene. *Climate dynamics*. 2021. Vol. 56. No. 11. P. 3817–3833. https://doi.org/10.1007/s00382-021-05669-0

Hughes M.K., Olchev A., Bunn A.G., Berner L.T., Losleben M., and Novenko E. Different climate responses of spruce and pine growth in Northern European Russia. *Dendrochronologia*. 2019. 56. 125601. https://doi.org/10.1016/j.dendro.2019.05.005

Jiang S., Zhang T., Yuan Y., Yu S., Shang H., and Zhang R. Drought reconstruction based on tree-ring earlywood of Picea obovata Ledeb. for the southern Altay Mountains. *Geografiska Annaler: Series A, Physical Geography*. 2020. 102(3). 267–286. https://doi.org/10.1080/04353676.2020.1773060

Kang S., Loader N. J., Wang J., Qin C., Liu J., and Song M. Tree-Ring Stable Carbon Isotope as a Proxy for Hydroclimate Variations in Semi-Arid Regions of North-Central China. *Forests*. 2022. Vol. 13(4). P. 492. https://doi.org/10.3390/f13040492

Karpukhin A.A. and Matskovsky V.V. *Absolyutnaya generalizirovannaya dendrokhronologicheskaya shkala basseinov rek Sheksna i Sukhona (1085–2009)*. (Absolute generalized dendrochronological scale of the Sheksna and Sukhona river basins (1085–2009)). *Russ. Archaeol*. 2014. Vol. 2. P. 76–87. (in Russ.)

Keeling C.D. The Suess effect: ^{13}Carbon-^{14}Carbon interrelations. *Environ. Int*. 1979. Vol. 2. P. 229–300. https://doi.org/10.1016/0160-4120(79)90005-9

Kress A., Saurer M., Siegwolf R.T.W., Frank, D.C., Esper J., and Bugmann H. A 350-year drought reconstruction from Alpine tree ring stable isotopes. *Global Biogeochemical Cycles*. 2010. 24, GB2011. https://doi.org/10.1029/2009GB003613

Kuznetsova V.V. and Solomina O.N. Contrasting climate signals across a Scots pine (Pinus sylvestris L.) tree-ring network in the Middle Volga (European Russia). *Dendrochronologia*. 2022. 125957. https://doi.org/10.1016/j.dendro.2022.125957

Larsson L-Å. CDendro & CooRecorder Program Package for Tree Ring Measurements and Crossdating of the Data, Version 8.1.1. 2016. http://www.cybis.se/forfun/dendro (access date: 23.04.2022)

Loader N.J., Young G.H.F., Grudd H., and McCarroll D. Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation. *Quaternary Science Review*. 2013. Vol. 62. P. 97–113. https://doi.org/10.1016/j.quascirev.2012.11.014

Liu Y., Ta W., Li Q., Song H., Sun C., Cai Q., and Li W. Tree-ring stable carbon isotope-based April–June relative humidity reconstruction since ad 1648 in Mt. Tianmu, China. *Climate dynamics*. 2018. Vol. 50(5). P. 1733–1745. https://doi.org/10.1007/s00382-017-3718-6

Lukač L., Mikac S., Urban O., Kolář T., Rybníček M., Ač A., and Marek M. V. Stable Isotopes in Tree Rings of Pinus heldreichii Can Indicate Climate Variability over the Eastern Mediterranean Region. *Forests*. 2021. 12(3). P. 350. https://doi.org/10.3390/f12030350

Matskovsky V.V. Climate signal in the width of annual rings of conifers in northern and central European Russia. Moscow: GEOS (Publ.), 2012. 148 p.

Matskovsky V. Climatic signal in tree-ring width chronologies of conifers in European Russia. *International journal of climatology*. 2016. Vol. 36(9). P. 3398–3406. https://doi.org/10.1002/joc.4563

McCarroll D., Gagen M.H., Loader N.J., Robertson I., Anchukaitis K.J., Los S., Young G.H.F., Jalkanen R., Kirchhefer A.J., and Waterhouse J.S. Correction of tree ring stable carbon isotope chronologies for changes in the carbon dioxide content of the atmosphere. *Geochim. Cosmochim. Acta*. 2009. Vol. 73. P. 1539–1547. https://doi.org/10.1016/j.gca.2008.11.041

McCarroll D. and Pawellek F. Stable carbon isotope ratios of Pinus sylvestris from northern Finland and the potential for extracting a climate signal from long Fennoscandian chronologies. *The Holocene*. 2001. Vol. 11. No. 5. P. 517–526. https://doi.org/10.1191/095968301680223477

Nikolov N.T., Massman W.J., and Schoettle A.W. Coupling bio-chemical and biophysical processes at the leaf level: an equilibrium photosynthesis model for leaves of C-3 plants. *Ecological Modelling*. 1995. Vol. 80. P. 205–235.

Panyushkina I.P., Karpukhin A.A., and Engovatova A.V. Moisture record of the Upper Volga catchment between AD 1430 and 1600 supported by a $\delta^{13}C$ tree-ring chronology of archaeological pine timbers. *Dendrochronologia*. 2016. Vol. 39. P. 24–31. https://doi.org/10.1016/j.dendro.2016.02.002

Pogoda i klimat [Electronic data] http://www.pogodaiklimat.ru/history/27330.htm (access date: 09.02.2022)

R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2021. URL https://www.R-project.org/ (access date: 23.04.2022)

Robertson I. and Woodborne S.W. Carbon Isotopes Confirm the Competitive advantages of Prosopis over Acacia Erioloba. In Study of Environmental Change Using Isotope Techniques, IAEA-CSP-13/P. *International Atomic Energy Agency*. Vienna. 2002. P. 433–434.

Sidorova O.V., Siegwolf R.T.W., Myglan V.S., Ovchinnikov D.V., Shishov V.V., Helle G., Loader N.J., and Saurer M. The application of tree-rings and stable isotopes for reconstructions of climate conditions in the Russian Altai. *Climatic Change*. 2013. Vol. 120 (1). P. 153–167. https://doi.org/10.1007/s10584-013-0805-5

Solomina O.N., Bushueva I.S., Dolgova E.A., Zolotokrylin A.N., Kuznettsova V.V., Kuznetsova T.O., and Tchernokulsky A.V. *Zasukhi Vostochno-Evropeiskoi ravniny po gidrometeorologicheskim i dendrokhronologicheskim dannym* (Droughts of the East European Plain according to hydrometeorological and tree-ring data). St. Petersburg: Nestor Istoriya (Publ.), 2017. 360 p. (In Russ.)

Stokes M.A. and Smiley T.L. An Introduction to Tree-Ring Dating Chicago: University of Chicago Press (Publ.), 1968. 95 p.

Voelker S.L., Merschel A.G., Meinzer F.C., Ulrich D.E., Spies T.A., and Still C.J. Fire deficits have increased drought sensitivity in dry conifer forests: Fire frequency and tree-ring carbon isotope evidence from Central Oregon. *Global Change Biology*. 2019. Vol. 25(4). P.1247–1262. https://doi.org/10.1111/gcb.14543

Waterhouse J.S., Barker A.C., Carter A.H.C., Agafonov L.I., and Loader N.J. Stable carbon isotopes in Scots pine tree rings preserve a record of flow of the river Ob. *Geophysical Research Letters*. 2000. Vol. 27. P. 3529–3532. https://doi.org/10.1029/2000GL006106

Warren C.R., McGrath J.F., and Adams M.A. Water availability and carbon isotope discrimination in conifers. *Oecologia*. 2001. 127. P. 476–486. https://doi.org/10.1007/s004420000609

Wigley T.M., Briffa K.R., and Jones P.D. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Applied Meteorology and Climatology*. 1984. Vol. 23. No. 2. P. 201–213.