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Moisture record of the Upper Volga catchment between AD 1430 and 1600 supported by a δ^{13}C tree-ring chronology of archaeological pine timbers

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ABSTRACT

Investigations of interactions between climate change and humans suffer from the lack of climate proxies directly linked to historical or archaeological datasets that describe past environmental conditions at a particular location and time. We present a new set of pine tree-ring records (*Pinus sylvestris* L.) developed from burial timbers excavated at the historical center of Yaroslavl city, Russia. A 171-year δ^{13}C tree-ring chronology from AD 1430 to AD 1600 evidences mostly wet summers during the 15th century but exceptionally dry conditions of the 16th century at the Upper Volga catchment. According to the tree-ring record there were four major droughts ($<-1.5\sigma$) lasting from 9 to 26 years: 1501–1517, 1524–1533, 1542–1555 and 1570–1596, and major pluvials ($>+1.5\sigma$) lasting from 70 to 5 years: 1430–1500, 1518–1523, 1534–1541, and 1556–1564. We discuss a plausible contribution of these droughts to crop failures and city fires documented with historical chronicles for the Upper Volga catchment. The devastating drought regime of the 16th century corresponds to the loss of independence of the Yaroslavl principality to the Grand Duchy of Moscow and the formation of the centralized Russian State during the reign of Ivan the Terrible (1533–1584) underpinning the emergence of the Russian Empire. This study substantiates the value of archaeological timbers from the oldest Russian cities and inclusion of stable carbon isotope analysis for understanding hydroclimatic regimes across the mid latitudes of East European Plain, and their relationship to the history of Russia.

1. Introduction

In world history, societal collapse and emergence of new states and empires often coincide with rapid environmental changes triggered by climate variability, and couple with significant change in socio-economic and political settings of pre-industrial societies (e.g., Weisse and Bradley, 2001; Büntgen et al., 2011). Droughts in particular strongly connect to decline of agricultural production, food insecurity and socio-political instability (e.g., deMenocal, 2001; Varien et al., 2007). Inadequate comparability of spatial-temporal scales for historical and/or archaeological data with climate proxies challenges current advances in modeling past coupled interactions between humans and environment. Spatial and temporal variability of thermal and hydrological regimes reconstructed from seasonally-resolved tree-ring records is particularly valuable for understanding a wide scope of environmental and human responses to climate variability. However, there are a few adverse factors preventing comprehensive application of tree rings to the human-environment modeling including spatial incoherence of climatic signals in tree rings and shortness of records.

This paper aims to explore tree-ring proxies for evaluation of climate variability impact on the emergence of the centralized Russian state (post AD 1547), which takes place during the cooling transition from the Medieval Warm Epoch to the Little Ice Age in the mid latitudes of the East European Plain. The 16th century is of particular interest for historians because this was the time of great reforms of Ivan the Terrible, who transformed a medieval disintegrated state to a centralized state, and the time of consolidating political power in the hands of a new ruling clan—the Tsarist family of Romanovs (Zimin, 1960, 1986). At that time, agricultural production in the Upper Volga and Don catchments was the backbone of people's income and state wealth, and variability of moisture regimes was the most important factor impacting the fluctuations of crop productivity in the region. What can tree rings tell us about variability of moisture regimes in the areas of main Russian political and economic centers across the Upper Volga and Don catchments?

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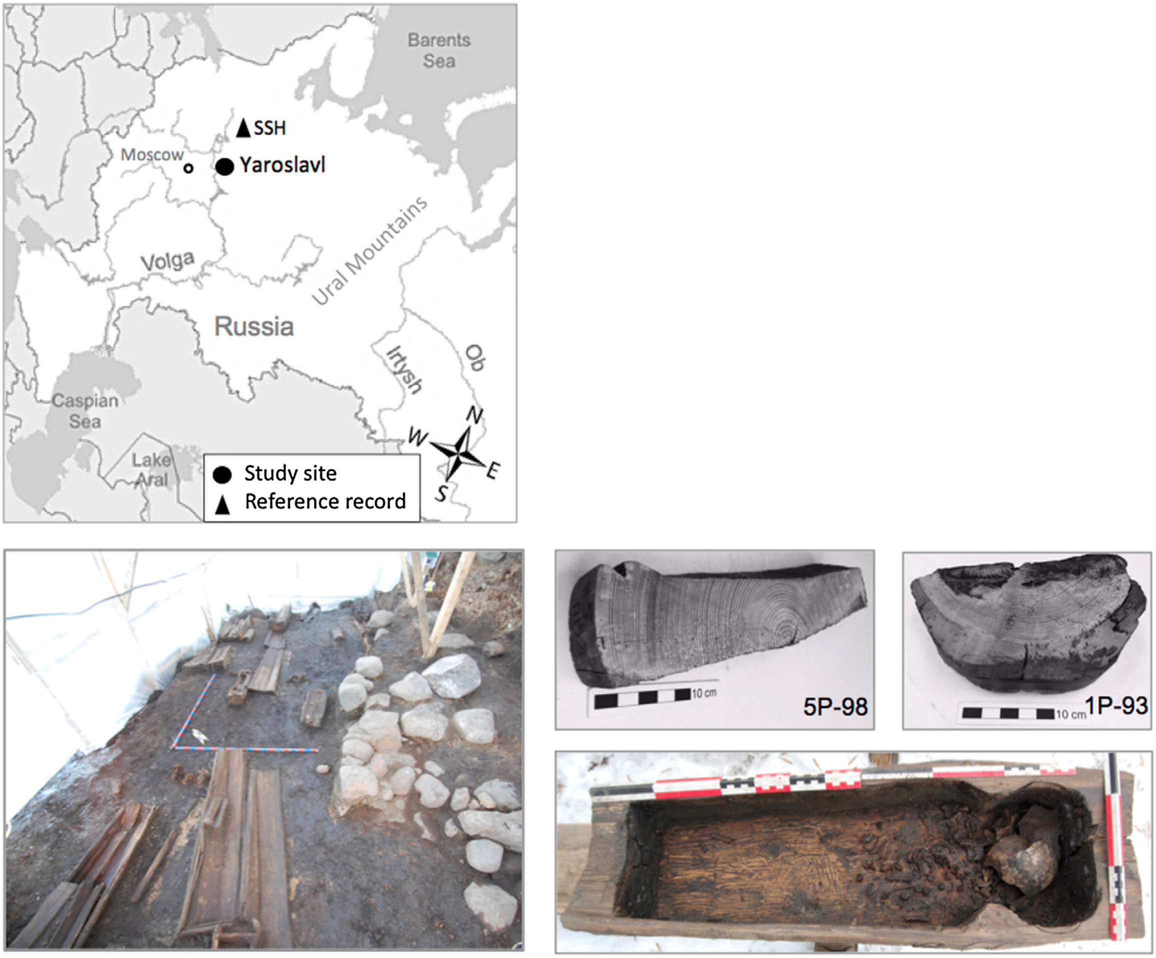

Fig. 1. Map of the European part of Russia with Yaroslavl city location. Photos show the general view of the excavated cemetery near the Church of St. John Chrysostom Nativity with coffins in situ (left) and wood specimens (right) sampled from coffins made of a pine plank (5P-98) and a pine tree-trunk (1P-93) with an example of 16th century child burial receptacle made of a single tree log.

Past climate of north and central Europe has been vigorously studied with tree-ring archives (e.g., Schweingruber and Briffa, 1996; Gagen et al., 2006; Treydte et al., 2007; Büntgen et al., 2011; McCarroll et al., 2013). On the East European Plain, tree-ring width variability of conifer trees is mostly attributed to summer temperature with stronger climatic signal in the boreal environments and weaker signal in the mid latitudes (Klimenko and Solomina, 2010; Solomina et al., 2011). Modeling precipitation signal in tree rings presents a much greater challenge, in part because of the greater spatial-temporal variability of moisture regimes involved (Pauling et al., 2006; Büntgen et al., 2010). Stable isotopes of tree rings are recognized for stronger sensitivity to moisture stress and seemingly better ability to predict moisture variability (Hartl-Meier et al., 2014). However, the climatic signature of tree-ring isotopes may be less uniform than tree-ring widths. This is illustrated in a recently-developed European network of tree-ring isotopic signals in space and time (Treydte et al., 2007), where the climatic signal of δ^{13}C and δ^{18}O tree-ring records corresponds positively to summer temperature in the north, but at mid-latitude the isotopic records correlate significantly with both summer temperature and precipitation. Spatially, the climatic signal of tree-ring δ^{13}C appears dependent on tree species/site-specific conditions. Trees alternate physiological strategies for water-use efficiency, which consequently yield a mix of climatic signals in δ^{13}C of tree rings through space (Gessler et al., 2014). Previous observations show a stronger response of δ^{13}C isotopes of pine trees to precipitation at drier sites of the mid latitudes (Gagen et al., 2004; Hartl-Meier et al., 2014). This is consistent with stable-carbon isotope fractionation models (e.g., Francey and Farquhar, 1982; Farquhar et al., 1989) that represent the ^{13}C/^{12}C ratio (δ^{13}C) of fixed carbon (and the tree rings to which it is transported) as influenced by rates of photosynthesis and leaf stomatal conductance. Consequently, low moisture conditions can induce lower stomatal conductance, reduced CO_2 concentrations in the leaves, and less discrimination by photosynthetic enzymes against ^{13}C, which resulting in higher ^{13}C/^{12}C ratios (higher δ^{13}C). This relationship is particularly strong in arid and semi-arid environments (Warren et al., 2001).

Tree-ring width reconstructions suggest with high degree of certainty that the thermal conditions of the Medieval Warm-Little Ice Age transition in the European part of Russia were cooling as in the most Europe (Klimenko and Sleptsov, 2003; McCarroll et al., 2013). Conversely, spatial and temporal variability of moisture in the East European Plain is unresolved, although it is relatively well defined for Europe (e.g., Treydte et al., 2007; Büntgen et al., 2010). This deficiency could be explained in part by the lack of a reliable network of tree-ring hydroclimatic proxies for the mid latitudes of Russia. The long-standing history of deforestation and natural vegetation change further restricts the length of tree-ring records from living trees. In this regard, stable isotopes of archaeological timbers offer an opportunity to increase coverage and temporal extent of moisture-sensitive proxies and compare with other climatic proxies. In this paper we compare historical indicators of moisture with a new δ^{13}C tree-ring record from Yaroslavl archaeological timbers originating from the southern taiga of the East

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Table 1
List of tree-ring specimens from the Yaroslavl archaeological collection. TT denotes tree-trunk type of coffin, and B indicates box coffin. Y = yes (for example in Column 4, pith center is present); *n* = no (for example in Column 4, pith center is absent); * = estimated number of rings to the pith from ring curvature when pith center is absent.

Sample ID & Burial No	Radii (cm)	Number of rings	Pith & outer rings	Coefficient of correlation with reference chronology	Cutting date	Calendar dates	Archaeo- logical date, century
9P-74 B	23	75	y/y	0.29	y	1553–1627	XVII
3P-92 TT	12	34	y/y	0.51	y	1438–1471	XVI
1P-93 TT	15	78	y/y	0.28	y	1421–1498	XVI
12P-98 B	16	112	+25*/y	0.32	n	1454–1565	XVII
13P-98 B	14	106	+9*/y	0.51	y	1473–1578	XVII
14P-98 B	14	89	+23*/y	0.43	n	1481–1569	XVII
4P-116 B	11	109	n/y	0.34	y	1512–1619	XVII
10P-118 TT	9	85	y/y	0.45	y	1404–1488	XVI
11P-124 TT	14	96	y/n	0.49	n	1399–1494	XVI
2P-131 TT	15	119	y/y	0.46	y	1378–1496	XVI
15P-145 TT	15	125	y/y	0.42	y	1371–1495	XVI
6P-148 B	11	139	n/n	0.39	n	1469–1607	XVII
7P-148 B	19	168	+20*/y	0.53	y	1426–1593	XVII
8P-148 B	19	148	+25/y	0.55	n	1430–1577	XVII

European Plain (57°N). Our goal was to establish $\delta^{13}C$ variance of pine tree rings and its relationship to other moisture proxies, and if successful, thereby provide a more highly-resolved supplemental record of the qualitative pattern of moisture variability between the 15th and 16th centuries in the Yaroslavl area from the tree rings.

2. Methods

2.1. Study area, archaeological context and tree-ring materials

The study area is located in the central part of the East European Plain drained by the Upper Volga River system, with average elevation of 200 m *asl*. The climate is temperate continental with 590 mm annual precipitation and annual temperature 3.6 °C, which is typical for Central and Eastern Europe. The growing season from April to October is relatively warm, with July average temperature around 18 °C (Yaroslavl weather station, download from www.meteorf.ru). The natural vegetation includes both southern taiga biomes dominated by *Picea* and *Pinus sylvestris* with widely distributed wetlands, and ecotones of mixed coniferous and broad leaves forests (*Tilia, Acer, Fraxinus, Quercus* and *Ulmus*).

The tree-ring material originating from archaeological timbers gathered at a rescue archaeological excavation during reconstruction of the historical center of Yaroslavl city (57°37′N and 39°5′E). Yaroslavl city was founded as early as AD 1010 on the banks of Volga River just 280 km northeast of Moscow (Fig. 1). During the medieval times, Yaroslavl was a relatively small principality that was absorbed into the Grand Duchy of Moscow by 1463. It rapidly become the major commercial and political center of the Rus, which played a key role in the consolidation of Russian State (Golovschikov, 1889 Zimin, 1986).

Between 2004 and 2013, the Moscow Institute of Archaeology, the Russian Academy of Sciences conducted excavations covering a 9000 km^2 area around the renovation project of the Cathedral of the Dormition (circa 1215) (Engovatova and Yaganov, 2011). The studied timbers derived from a medieval cemetery discovered in the surroundings of the Church of St. John Chrysostom Nativity at the south-eastern quarter of the renovation project (Section #19, Voljskaya Naberejnaya Street—1). The excavated part of the cemetery (200 m^2) contained a total of 224 burials. A limited number of burials (36) with preserved remnants of burial footwear dates to the 16th century (Mednikova et al., 2013a). The archaeological dating of materials from the majority of the burials, including burial receptacle design, burial goods, burial rites and cemetery stratigraphy, suggests that the cemetery was in use from the late 15th and the early 19th centuries (Panova, 2004; Mednikova et al., 2013b).

A total of 14 wood specimens from 10 funeral receptacles were sampled at the excavation site (Table 1, Fig. 1). Six samples of tree-trunk coffins from six child graves are dated archaeologically to the 16th century. A tree-trunk coffin is a hollowed tree log with dimensions of 1–1.3 m in length and ca. 30–40 cm in diameter used for burials of young children (Fig. 1). The other eight samples came from lidded box coffins made of thick wood planks, which were exhumed from four graves situated within the 17th century archaeological horizon. The box coffins were 2.2 m long and 0.5–1 m wide and used for a single adult or group inhumations. The tree-ring cross-sections sampled with a handsaw were shipped to the University of Arizona and analyzed at the Laboratory of Tree-Ring Research.

2.2. Laboratory and analytic procedures

For crossdating, tree-ring widths were measured on polished cross-sections using a Lintab measuring system with 0.01-mm precision. Tree-ring-width series within and between burials were crossdated visually using TSAP software (Rinn, 2003) and combined in floating crossdated tree-ring width series. Quality control of ring-crossdated positions was assured by correlation significance (inter-serial correlation) calculated in COFECHA (Holmes, 1983). To establish absolute calendar years, the floating tree-ring series were crossdated against a reference tree-ring record of pine averaging well-matched tree-rings from the Sukhona and Sheksna watersheds of the Vologda region (Solomina et al., 2011; Karpukhin and Matskovsky, 2014). The reference record spanning from AD 1085 to 2009 combines tree-ring series from living trees, historical buildings and archaeological timbers collected across the south and middle taiga of the East European Plain, which is about 300 km north of Yaroslavl city.

For isotopic measurements, individual rings from five wood specimens (7P-148, 8P-148, 6P-148, 12P-98 and 4P-116) were separated, and combined for pooled isotopic measurements, except every tenth year the rings of each tree were analyzed separately. The specimens overlap 171 years from AD 1430 to 1600. The innermost twenty-five juvenile rings of each sample were excluded from the analysis. After grinding to 20-mesh in a Wiley Mill, the subsampled tree rings were converted to hollocellulose using the Jayme–Wise oxidation method adapted by Leavitt and Danzer (1993). The samples were sequentially extracted with toluene/ethanol and then ethanol organic solvents in a soxhlet extraction apparatus, and later boiled in deionized water. Samples were delignified in an acetic acid-acidified, sodium chlorite aqueous solution at 70 °C, rinsed thoroughly in deionized water, and then dried at 70 °C. These holocellulose samples were treated with 17% NaOH to isolate α-cellulose (Sternberg, 1989).

The tree-ring α-cellulose was analyzed on a Finnigan Delta PlusXLmass-spectrometer in flow-through mode at the Laboratory of Isotope Geochemistry, University of Arizona. One split of α-cellulose was combusted to CO_2 at 1030 °C in an elemental analyzer with combustion products carried by a helium carrier gas and separated in a gas chromatograph after which the gas stream was introduced into the mass-spectrometer for δ^{13}C analysis. The isotopic measurements are reported with the PDB standard for δ^{13}C. Working standards of known isotopic composition were run ca. every 10 samples to monitor mass spectrometer reproducibility (analytical precision) and to adjust sample results for any offset in absolute value of the standard. Recent analysis of an acetylnide working standard indicates a precision of 0.08‰ (1 sigma).

3. Results

3.1. Calendar age of the archaeological timbers

The collected timbers belong to one tree species identified as Scots pine (*P. sylvestris*). The tree-ring width series crossdating within a burial receptacle and between graves of the same archaeological horizon are combined into two floating tree-ring records: a 128-year record from 6 series and a 202-year record from 8 series associated with the 16th century and 17th century burials, respectively. Absolute dating of the floating archaeological records was done through correlation with two regional chronologies of pine tree rings from the northern taiga (Solovky) and middle-southern taiga (Vologda) of the Russian Plains (Solomina et al., 2011; Karpukhin and Marskovsky, 2014). The overlaps were only found with the Vologda chronology about 300 km north of Yaroslavl city, which dates the records to AD 1371–1498 and 1426–1627 intervals (Table 2, Fig. 1). Correlation coefficients with the reference chronologies are significant and above 0.4 ($p < 0.01$).

It was reported that pine tree rings from the middle and southern taiga, whose growth is limited by summer temperature, correlate across distances over 300 km (Solomina et al., 2011; Matskovskiy and Solomina, 2011). Our crossdating result is consistent with those observations. Likewise, we assume the variability of pine tree-ring widths in the archaeological records are driven by summer temperature to the same degree. Nine out of 14 specimens contain cutting dates that imply a range of wood harvesting for 15th century burials between AD 1471 and 1498, and 17th century burials between 1607 and 1627 (Fig. 2). Thus, the collected timbers and burials are dated by late 15th century and early 17th century. There is a discrepancy between the archaeological (16th century) and crossdated ages (late 15th century) of the first group of burials composed by tree-trunk coffins.

3.2. δ^{13}C record of pine tree rings

The isotope record from AD 1430 to 1600 combines isotopic series from pooled tree samples and decadal individual tree samples (Fig. 3). Average δ^{13}C value of the cellulose measurements is −22.5‰ and standard deviation is 0.66. The overall trend of tree-ring δ^{13}C is increasing. Variance of isotopic series appears lower during the interval 1430–1520, after which it shifts to higher variance, especially true for decadal tree series (up to 4‰ range). Around the time of shift to higher variability, the δ^{13}C values of Trees 4 P and 12 P sharply shift downward, whereas δ^{13}C of 6 P shifts upward. Re-analysis of some of the very low δ^{13}C values, however, confirmed the accuracy original values plotted in Fig. 3. Additionally, the shift in the variance appearing in the second half of the record should not be associated with the isotope "juvenile effect" reported for some δ^{13}C tree-ring records (Gagen et al., 2007; Leavitt, 2010), because the juvenile tree rings (ca. first 25 rings from the tree pith in each of the samples) were excluded from analysis. Likewise there is no evidence of sample size effect on the isotopic variance toward either end of the record. Thus, the isotopic measurements seem to be capturing the individual and mean values of the trees, and demonstrate high inter-tree isotope variability during this time period. We have no reason to believe that the annual and decadal patterns in the mean δ^{13}C record cannot be used to infer environmental change in this period. Perhaps variable provenience of the archaeological timbers from the studied burials is contributing to the inter-tree isotope variability, but this would also mean the isotope record is representing a larger area and range of growth environments.

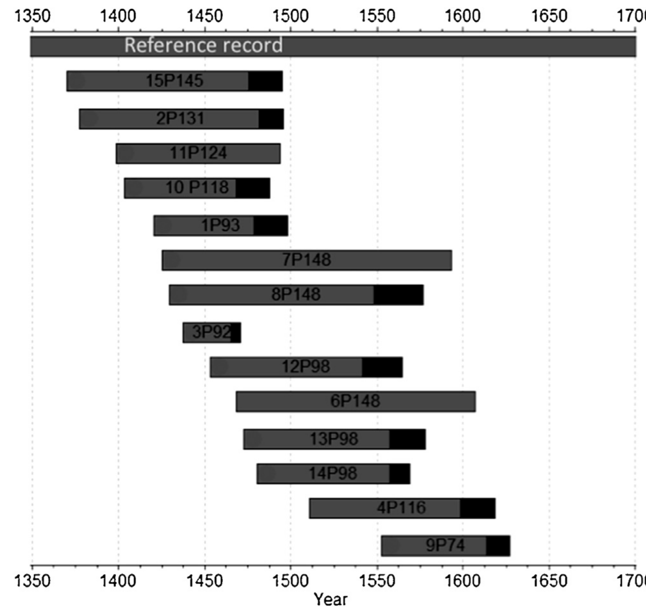

Fig. 2. Positions of archaeological tree-ring series against reference chronology of pine tree rings from the Sukhona and Sheksna River basins called the Vologda record (Karpukhin and Matskovskiy, 2014). Pith is marked with black circles and outer rings with squares.

4. Discussion

4.1. Climatic signal of δ^{13}C tree-ring record

At regional scale, the δ^{13}C isotopic signature of mid latitude conifers from the European tree-ring isotope network indicates a negative relationship with summer precipitation and positive with summer temperature (Treydte et al., 2007; Hartl-Meier et al., 2014). Both parameters relate to hydroclimatic conditions. Generally, dry/warm summer weather results in high δ^{13}C values due to low stomatal conductance and subsequent reduction in δ^{13}C discrimination (Saurer et al., 2004; Farquhar et al., 1989). This applies to carbon isotopes of pine tree rings as well. The Suwalki forest chronology of *P. sylvestris* δ^{13}C cellulose from Poland (southern taiga, 54°N, 23°E) demonstrates a positive relationship with summer temperature and much stronger but negative correlation with summer precipitation (Pawelczyk et al., 2004). δ^{13}C of *P. sylvestris* tree rings from the European high latitudes responds positively to summer temperature (McCarroll and Pawellek, 2001; Boettger et al., 2005). Its variations from dry alpine environments (southern slope exposure) contain a strong moisture stress signal (Gagen et al., 2004).

In this study, the floating but absolutely-dated isotopic record could not be directly calibrated with instrumental weather data. Potentially, the Yaroslavl south taiga δ^{13}C record of pine tree rings may represent both positive response to summer temperature

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Table 2
Crossdating results of tree-ring width series from the Yaroslavl archaeological collection.

Chronology span	Length	Number of series	Correlation with reference chronology	St. dev.	Sample IDs of overlapped series
1371–1498	128	6	0.43	0.56	3P-92, 1P-93, 10P-118, 11P-124, 2P-131, 15P-145
1426–1627	202	8	0.4	0.47	9P-74, 12P-98, 13P-98, 14P-98, 4P-116, 6P-148, 7P-148, 8P-148

and negative to summer precipitations, and thus be suitable for approximation of summer moisture conditions. Weak correlation of the Yaroslavl tree-ring δ^{13}C record with both the mean tree-ring width series of Yaroslavl and the master tree-ring width chronology from Solovky (sensitive to summer temperature) suggests that the climatic response of the δ^{13}C tree-ring variations may be much stronger for moisture stress than thermal conditions. Based on the tree species, geographical location and climatic signature of δ^{13}C in cellulose for the European mid latitudes, it is highly likely that the high δ^{13}C values of the Yaroslavl record translate into hot and dry summer, and low values correspond to wet and cool conditions.

4.2. Climate variability of the 15–16th centuries in the Upper Volga

The developed isotope tree-ring record (AD 1425–1600) falls into the transition from the Medieval Warm Epoch to the Little Ice Age dated in Northern Europe between 1350 and 1550 and characterized by highly variable weather regimes (Boettger et al., 2005; Grudd, 2008; Büntgen et al., 2011). In the central part of the East European Plain, the regional thermal regime of this period was consistently cold including the coldest century of the last millennium, the 15th century (Lyakhov, 1984; Klige et al., 1993). A brief warm anomaly interrupts the cooling trend in the mid-late 16th century (Klimanov et al., 1995; Klimenko and Sleptsov, 2003). Interestingly, various historical reconstructions show different contributions of summer and winter temperature to the coldest regime of the 15th century (Klimenko and Solomina, 2010). Our tree-ring width record suggests mild summer temperature in the 15th century in the Upper Volga basin. As for moisture regime, historical and pollen proxy reconstructions for the Upper Volga-Don River watersheds show decline of precipitation amount in the central part of the East European Plain during the transition (Lyakhov, 1984, 1987; Borisenkov and Pasetskiy, 1983, 1988; Klige et al., 1993; Klimanov et al., 1995; Krenke and Chernavskaya, 1998; Klimenko and Sleptsov, 2003; Klimenko and Solomina, 2010). Analysis of extreme weather from historical chronicles compiled by Borisenkov and Pasetskiy (1983, 1988) directly links the description of droughts or wet summers to crop failure, famine, city fires and diseases.

Fig. 4 shows the developed isotope tree-ring record that we use as an evidence of annual and decadal variability of summer moisture regime from AD 1430 to 1600 in the Yaroslavl area. For convenience, we reversed *y*-axis of the record because δ^{13}C values are negative, so hot and dry summers now appear at the bottom of the plot rather than at the top (Fig. 4). It is striking that positive moisture regimes prevail in the 15th century whereas frequent and prolonged negative anomalies punctuate the 16th century. The regime of wet summers ends at ca. AD 1500, after which a period of highly variable and extremely hot/dry summers and pronounced droughts emerges (Table 3). Historical records suggest the mid 16th century as a threshold in amplification of climatic variability (Borisenkov and Pasetskiy, 1983) while the Yaroslavl record places the shift between the lower and higher climatic variance a decade earlier –at the beginning of the 16th century (Figs. 3 and 4). Overall, climatic conditions of the 16th century were

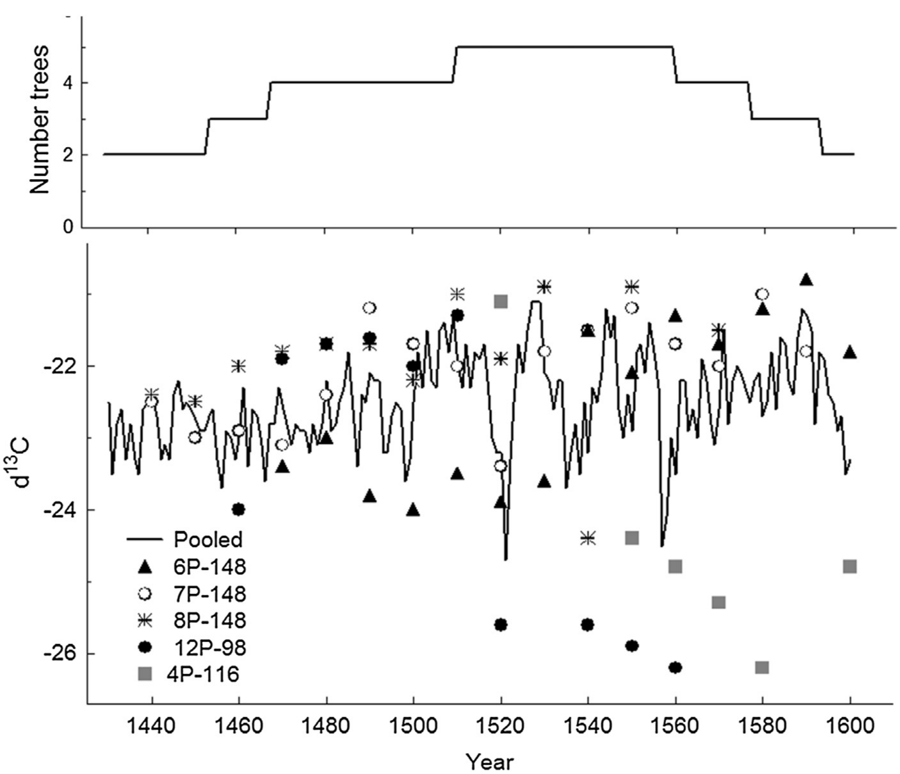

Fig. 3. Isotopic measurements of cellulose from Yaroslavl archaeological timbers. δ^{13}C values measured on pooled subsamples are shown with line, and symbols are δ^{13}C values measured on subsamples from individual trees (low plot). The top pot shows the number of trees used in this study.

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Table 3
Chronology of hydroclimatic events during the 15th and 16th centuries in Yaroslavl area (the Upper Volga River watershed) documented in the δ^{13}C tree-ring record (Fig. 4).

Hydro-climatic event	Time span	Number of years	Minimum or maximum year, mean −/± 1.5 σ	Extreme year, mean −/± 2σ
Pluvial	1430–1500	70	1431, 1434, 1436, 1437, 1442, 1444, 1455, 1456, 1459, 1462, 1466, 1476, 1487, 1493, 1494, 1498, 1499	
Drought	1501–1517	16	1503, 1506, 1507, 1508, 1509, 1512, 1514, 1516	
Pluvial	1518–1523	5	1521, 1522	1521
Drought	1524–1533	9	1524, 1526, 1527, 1528, 1529	1527,1528,1529
Pluvial	1534–1541	7	1535, 1538	
Drought	1542–1555	13	1544, 1545, 1546, 1551, 1552, 1554, 1555	1544
Pluvial	1556–1564	8	1557, 1558, 1560	1557
Drought	1570–1596	26	1571, 1582, 1584, 1585, 1588, 1589, 1590, 1591, 1593	1589
Pluvial	1597–1600	–	1599, 1600	

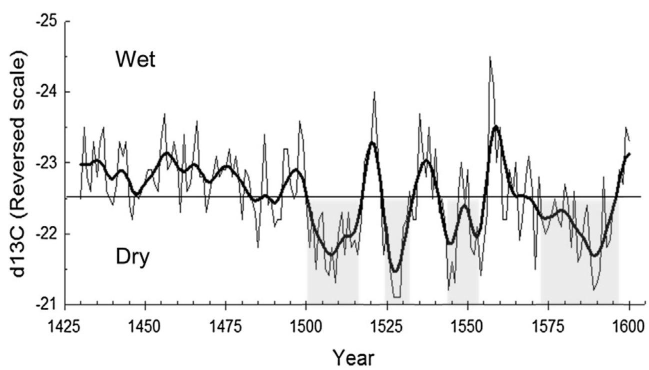

Fig. 4. δ^{13}C tree-ring chronology of Yaroslavl area plotted with reverse *Y*-axis showing annual (thin line) and decadal (thick curve of a 10-year Turkey–Hamming filter) variability of summer moisture conditions from 1430 to 1600. Less negative δ^{13}C values below the mean line (−22.5 per mil) are tracers of hot and dry summers, and more negative values related to cool and wet summers. Light gray shades four episodes of pronounced droughts during the 16th century.

highly variable. There were four major droughts in the 16th century ranging from 9 to 26 years: 1501–1517, 1524–1533, 1542–1555, and 1570–1596. The drought of 1524–1533 has the largest amplitude, whereas the longest one occurred between 1570 and 1596. Short but extreme- amplitude wet episodes subsequently return between the droughts. There is no well-fitted correlation between our record and regional hydroclimatic reconstructions for the East European Plain, which could be the result of both the variability of local precipitation patterns and differences in accuracy and scale of the climatic proxies being compared.

We compared our independent tree-ring evidence of droughts during the 16th century in Yaroslavl with historical data of regional-scale droughts, wet summers, and failed crops existing for the upper Volga River basin (Borisenkov and Pasetskiy, 1983). This comprehensive historical dataset of extreme weather phenomena includes the Laurentian and Trinitarian Codices describing economical life of the Rostov Velikiy, an old Russian city just 50 km away from the Yaroslavl city. The historical data largely corroborate the extreme summer conditions captured by the local tree-ring record (Fig. 5). This is especially true for the detected number of dry summers and number of failed crops due to the dry weather (Fig. 5B). There is only one discrepancy for the interval 1430–1490 when the Yaroslavl tree-ring record accounts no dry conditions at all, which may be the result of inconsistency of historical accounts or non-drought reason of the crop failure. At regional scale, there is a positive trend of failed crops due to droughts over the last millennium across the East European Plain (Borisenkov and Pasetskiy, 1983, 1988; Lyakhov, 1984), and our record strongly agrees with this pattern for the interval of the 15–16th centuries.

The described changes of the moisture regime had profound impact on the urban development of Yaroslavl city. The series of identified droughts correspond to documented frequent and severe city fires whose number was unprecedented in comparison with the previous centuries (Borisenkov and Pasetskiy, 1983). During the 16th century, city fires ravaged Yaroslavl and a very significant number of the city blocks, city walls and the majority of city churches were burned down. The city area was reduced twice but the churches and monasteries were rebuilt in stone and bricks at that time, and some of them survive to this day (e.g., the St. Savior Cathedral). The largest known fires of the 16th century chronicled in historical documents occurred in the summers of 1501, 1536 and 1547 (Jitiya, 1895; PSRL, 1926–1928), which fall in the drought intervals derived from the tree-ring isotopes.

Despite the devastating impact of failed crops and city fires, the city of Yaroslavl experienced a revival during the 16th century. The economic growth of Yaroslavl, situated on the banks of the Volga River was driven by the soaring trade between Moscow and Europe via Volga and Arkhangelsk during the reign of the Ivan the Terrible (Grand Prince of Moscow in 1533–1547 and Tsar of All of Russia in 1547–1584). Under his reign the Yaroslavl become not only a hub of international trade with large shipping yards and warehouses but also an important political and government node (Golovschikov, 1889). Practically, the transfer of political power to Ivan the Terrible and the emergence of the centralized Russian state engendered by him occur during the most stressful drought episodes of 1524–1533 and 1542–1555 in the Yaroslavl. These pronounced dry conditions were unfavorable to arable agriculture and undeniably contributed to the degradation of the local governance and people's living conditions. The politics of Ivan the Terrible responded well to the need for new leadership during these challenging times, and he gained tremendous popularity and support among the commoners by investing income from trade into food security and construction of city infrastructure and churches when people were overwhelmed by famines and city fire destruction (Zimin, 1960). Our results suggest that the change of political power from the old ruling family of Ruriks to the Romanov family initiated by Ivan the Terrible occurred in the period of great food insecurity and poverty was triggered by the moisture-stressed regime of hydroclimatic conditions. The droughts of the 16th century in the context of the previous century were unprecedented in the Yaroslavl.

In conclusion, this study demonstrates the potential of cellulose δ^{13}C measurements from archaeological pine timbers. Based on isotope theory and empirical comparison with historical climate-related records, the δ^{13}C record we generated appears sensitive to summer moisture stress, and suitable for evidence of local hydroclimatic patterns. Our findings therefore offer great potential in expanding environmental proxies from this region in space and time. The developed tree-ring isotopic record contributes to understanding changes of summer moisture regimes during the

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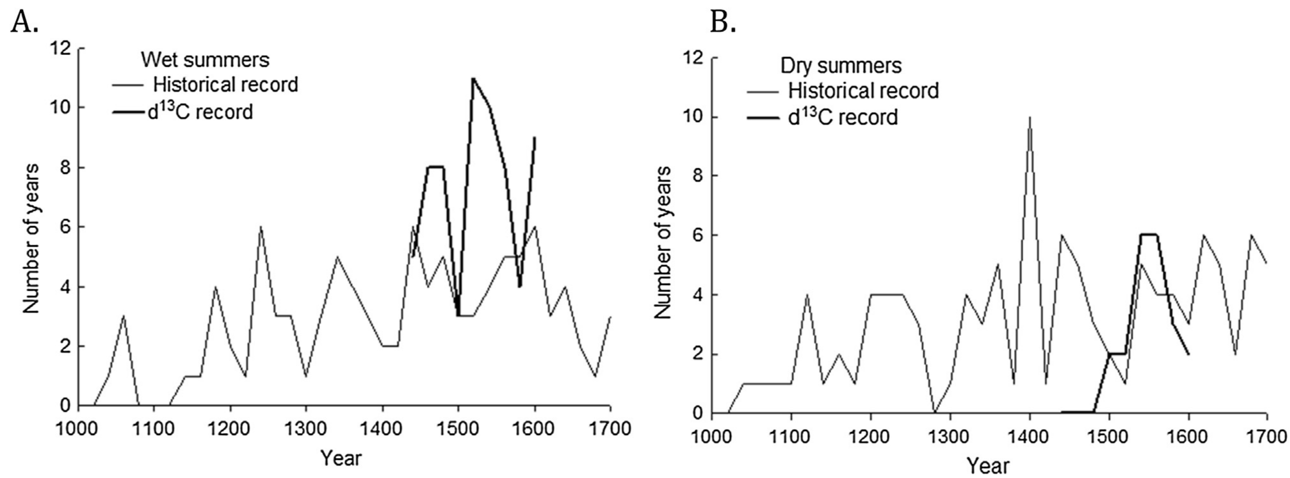

Fig. 5. Comparison of regional historical record of failed crops related to wet (A) and dry summers (B) derived from our δ^{13}C record of moisture regime in Yaroslavl area. The curves indicate the total number of years with dry or wet summers occurring within a 20-year interval calculated from the extreme weather events described in historical chronicles (thin line) from the central part of European Russia (modified after Borisenkov and Pasetskiy, 1983), and from the Yaroslavl δ^{13}C tree-ring record (thick line). In the δ^{13}C record, the number of years per 20-year interval is calculated as $>+2\sigma$ or $<-2\sigma$.

transition from the Medieval Epoch to Little Ice Age at the local scale. There was an abrupt shift in the hydroclimatic regime of the Yaroslavl area from wetting to drying, and higher climatic variability dated at ca. AD 1500.

Our data provide independent evidence for timing, amplitude and duration of severe droughts in the upper Volga River basin in the 16th century, confirmed with historical data of failed crops and city fires. Overall, the exceptional climatic variability of the 16th century traces deteriorating conditions for agricultural production and frequent large city fires prompted partially by extremely dry weather. This coincided with the emergence of the centralized Russian state and concentration of political power by Ivan the Terrible. This study highlights the potential of seasonally-resolved tree-ring proxies of climate in the mid latitudes of temperate Russia for evaluation of the relationship between the emergence of the centralized Russian state and the environmental change.

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