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Climatic Changes in the East-European Forest-Steppe and Effects on Scots Pine Productivity

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Abstract—Climate change during the 20th and early 21st centuries in the transitional zone between forests and grasslands at the center of the East-European Plain (Voronezh oblast) was determined by examining climate trends and variability using tree ring radial increment data as representative of productivity. An increase in atmospheric moisture for the warm period of the year (May–September) since 1890s, and mean annual temperatures since the 1950s was identified. During the same time period, there was a marked increase in amplitude of the annual variations for temperature and precipitation. Study results revealed trends, variability in the climatic indices, and corresponding radial wood increment for the regional stands of *Pinus sylvestris* L. These fluctuations are consistent with 10–12-years Schwabe–Wolf, 22-years Hale, and the 32–36-years Bruckner Solar Cycles. There was an additional relationship found between high-frequency (short-period) climate fluctuations, lasting for about three years, and 70–90-years fluctuations of the moisture regime in the study region corresponding to longer cycles. The results of this study can help guide management decisions in the study region and elsewhere, especially where climate change induced alterations to the state and productivity of forest ecosystems and associated natural resource commodities are of growing concern.

Key words: Climate change, Voronezh oblast, cyclical fluctuations, dry years, hydrothermal coefficient, solar activity, Scots Pine (*Pinus sylvestris* L.), radial increment, dendroclimatic analysis.

1. *Introduction*

Significant changes in climatic conditions are resulting in similar changes in ecosystems (especially in forests), causing great concern among scientists and ecosystem managers about the long-term implications for the health of ecosystems, natural resources sustainability, and human health. However, there is more to understand regarding the interaction between variables in ecosystems, and this knowledge may help guide current and future management decisions. Much of the gap in understanding comes from the lack of information about past conditions. Trees can preserve records of collected information about the dynamics of climatic factors limiting their growth through variability in the tree rings width (Douglass 1919, Fritts 1976 and others). Annual tree rings have been widely used for the detection and analysis of climate change and are thus a well-accepted source of information for climate history (Briffa et al. 1999; Wilson et al. 2007; Agafonov and Kukharskikh 2008; Skomarkova et al. 2009; Hantemirov et al. 2011; Matskovskiy 2013; Lara et al. 2013; Gillner et al. 2014).

The dominant tree species in the forest-steppe zone of Eastern Europe are English or Summer oak (*Quercus robur*) and Scots Pine (*Pinus sylvestris* L.). When compared to oak, pine is a more sensitive tree to climate change in this region. Old-growth pine plantations are essential resources for studying the dynamics of radial increment of trees, including their exposure to climate variability, anthropogenic impacts, as well as characteristics of the ecological state and stand phytocenosis (Matveev 2003). In the Voronezh oblast, there are two large forest areas with a predominance of *Pinus sylvestris* L. Previous studies identified generalized chronologies for pine forests in the Voronezh Oblast, which is the region within the central part of the forest-steppe zone of the Russian Plain, and showed the existence of ring patterns in pine with moisture conditions and other external factors that limit the growth of pine (Matveev 1998, 2002, 2005, and others).

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Tree ring analysis in the literature is not limited to the East-European forest-steppe region. Other studies in adjacent regions have used *Pinus sylvestris* L. for dendrochronological studies in central Europe. For example, Pieper et al. (2014) studied the influence of volcanism over the last millennium in northeast Germany. Studies from central Europe including Poland, Germany, and the Czech Republic, however, are numerous and not limited to Scots Pine (e.g., Kolar and Rybnichek 2011). Studies in regions adjacent to the Voronezh Oblast (e.g., Dmitrieva 1987—in the southwest Urals) show strong climate-related variations at 11 and 29 years. A recent study (e.g., Matskovskiy 2013) demonstrates a strong relationship between tree ring growth and temperature north of 60°N, and better correlation with both temperature and precipitation in southern regions of European Russia.

These are the Umansky and Khrenovsky Forests. The goals of this study were to (1) identify the parameters representing the cyclic dynamics of solar activity and climatic factors in the East-European forest-steppe on the decadal time-scale, and separate those findings from long-term climate change (e.g., IPCC 2013), and (2) validate and quantitatively characterize climate factors of *Pinus sylvestris* L. radial growth. The results of this study can help guide management decisions in the study region and elsewhere, including places where climate change induced alterations to the state and productivity in forest ecosystems and associated natural resource commodities are of growing concern.

2. Materials, Facilities, and Research Methods

2.1. Study Sites

The Usmanskiy Forest (Fig. 1) is located within the forest-steppe zone of the northern (southern) part of the Voronezh (Lipetsk) oblasts of Russia. This area is part of the Voronezh and Usman river basins. The region is generally characterized by a cooler and more humid climate relative to the surrounding ecoregions (Milkov 1985; Khromov and Petrosyants 2006). The mean groundwater depth in Usmanskiy Forest is three meters. The natural pine forests currently make up less than half of the area, while the remaining territory is largely represented by artificial pine plantations of varying ages.

The Khrenovsky Forest (Fig. 1) is the southernmost of the pine forests in European Russia. It is located on the border between the steppe and forest-steppe natural environments, in the western part of the Bityug river valley (mostly on sandy soils within the first and second river terraces) as well as in the terrace depressions with intensive hydromorphism and large quantities of swamps and lakes. The depth of the groundwater in the first and second terraces is from three to five meters. The pine of natural origin in the Khrenovsky Forest accounts for no more than 20% of the total forest area (Matveev 2003).

The study pine stands are typical for the area of Umansky and Khrenovsky Forests (about 45% of the total area), with the geobotanical classification “grass pine forest with a mixture of oak species” (Sukachev 1961). These pine forests grow in relatively poor sandy soils (with low content of organic matter), and the soil surface under the canopy is covered by cereals, sedges, and other forest herbs (Matveev 2003). The site class of all study stands is II, state density of trees—0.6–0.7 ha (Matveev 2003).

The sub-areas used for dendrochronological research in the Usmanskiy Forest are situated within forest quarters 45 and 85 at the forestry experimental station of the Voronezh State Forestry University. Investigations were conducted during the fall of 2010 following the loss of the forest in quarter 85 by summer fires that occurred in association with the Russia drought of 2010 (e.g., Lupo et al. 2012a). In quarter 45, the pine plantation (average age of trees in the stand—120 years) was studied in three nearby test plots of 0.2–0.4 ha in which 15 tree cores were taken for dendrochronological analysis using a Pressler increment borer (Shestakova et al. 2016). In quarter 85, dendrochronological analysis in a test area of 0.4 ha was selected by examining stumps and trunks (cut using saws) of ten trees which had a typical age of 130–150 years. Trees in this area were cut for forest management purposes during September and October 2010.

In the Khrenovskiy Forest, dendrochronological research was executed during the same period as above in forest quarter 513 which is an experimental

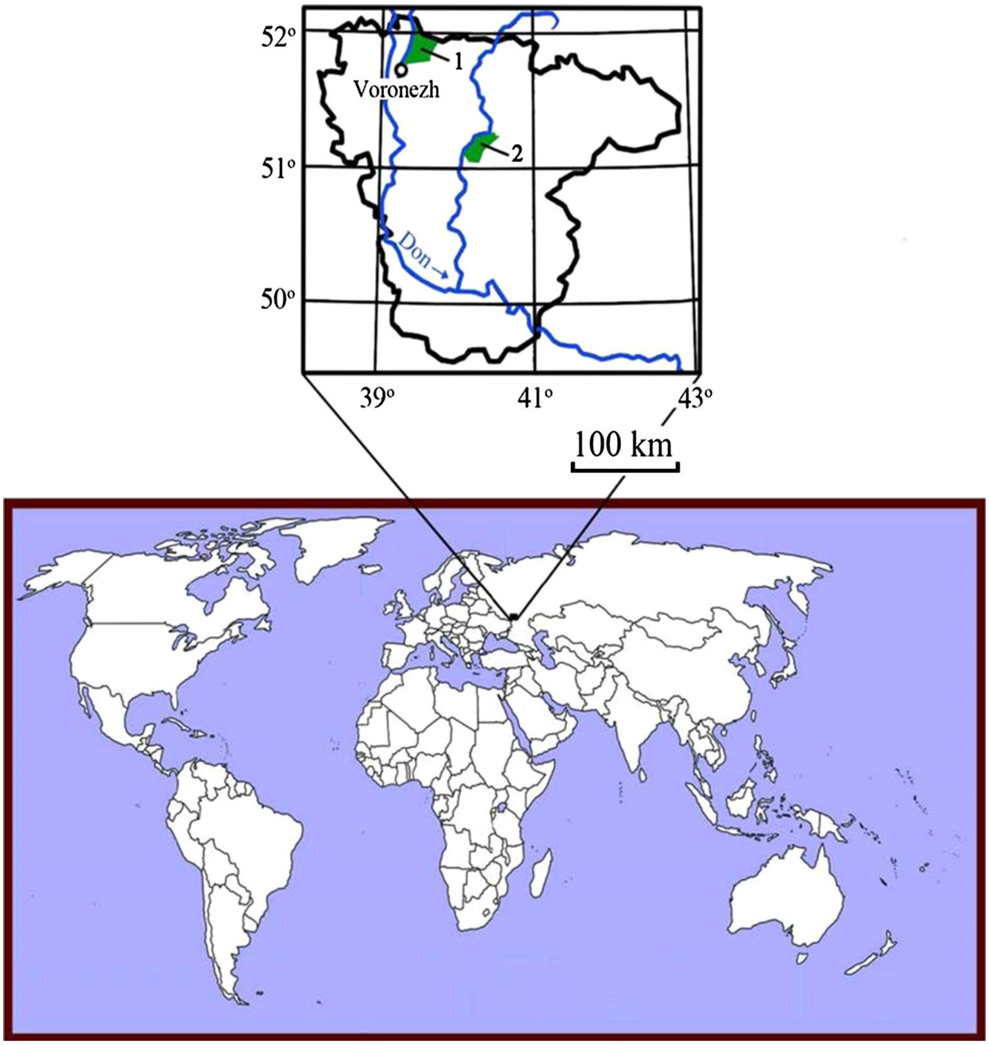


Figure 1
Scheme showing the location of the *1*—Usmanskiy Forest; *2*—Khrenovskiy Forest

forest owned by the Khrenovskiy Technical School of Forestry. Studies were carried out in one test area of 0.5 ha (50 × 100 m) on live trees in the forest by examining 12 *Pinus Sylvestris* L. trees with an average age of about 110 years.

2.2. Climatological Information

The period for meteorological observations recorded in Voronezh is 154 years. Meteorological observations started in 1861 for the study of precipitation, and in 1873 with combined measurements of surface temperature and precipitation. The current location for the meteorological station was designated in 1918 as "Voronezh" Station No. 34123 (located at 51° 40′N, 39° 13′E, and an altitude of 149 m), which is near the former location (see Weather and Climate 2015). The climatic indicators collected from the Voronezh Station were assumed to be representative of the conditions in the study areas (Usmanskiy and Khrenovskiy Forests).

The Continentality Index provides a simple indicator of the climatic character of the region, and a time series can then provide information about climate dynamics and change, and is calculated using the Zenker formulation (Borisov 1975; Matveev 2003):

$$K = [(1.2A_a/\varphi) \times 100\%] - 20, \quad (1)$$

where A_a is the annual amplitude of surface temperature (warmest minus coldest month °C), and φ is the latitude of a meteorological station (°). A higher continentality index is represented by greater amplitude in the annual cycle of temperature, and vice versa. This method provides an opportunity to compare the results of our research with those of an earlier study for the same area and using the same index (Kostin 1958).

An important characteristic in the study of climate during the warm period of the year is the hydrothermal coefficient (HTC—Gustokashina and Maksutova 2006; Strashnaya et al. 2011). This index demonstrates the connection between the surface temperature and precipitation, and plant productivity for the same period. The HTC was first proposed by climatologist Selyaninov (Selyaninov 1928; Tarankov 1991). The hydrothermal coefficient is calculated for the period of active plant vegetation, i.e., for months with average temperature greater than 10 °C, using the following formula:

$$\mathrm{HTC} = \sum P \Big/ \left(0.1 \sum T^*\right), \quad (2)$$

where P is the precipitation (mm) during the period with active plant vegetation, and T^* the mean daily temperature for this period (for months with daily temperature above 10 °C). In the city of Voronezh and the Voronezh oblast, the period with average monthly temperature above 10 °C extends from May to September, which was used for the HTC calculations here.

2.3. Solar Activity Data

Studies of solar activity and the interpretation of these results obtained in association with climatic and dendrochronological data have been performed using data from the Zurich time series for solar activity (WDC-SILSO 2014).

In the current work, sunspot data were used as a surrogate for solar activity and expressed as the Wolf Number (W). There are several solar cycles which were tested including the Schwabe–Wolf (11 years), Hale (22–24 years), Bruckner (33 years), and Gliessberg (70–90 years) cycles.

2.4. Dendrochronological Procedures

For the dating and measuring of tree ring width, the system used here was the LINTAB-6 with a binocular microscope and the TSAP-Win software professional programs. To eliminate the effect of age trend, as well as to determine the effect of climatic factors in the radial increment of trees, data were standardized. For this procedure, we used the methodology contained in the "Trend" program, which included the following techniques: (1) the age trend was modeled using 11-year sliding smoothing, and then (2) applied a polynomial smoothing function to the data (Mironenko and Matveev 2012). The relative index for the radial increment of trees (I) was calculated as the ratio between the average actual tree ring increment for the calendar year, and the growth rate depending on the age (Bitvinskas 1974).

The calculations of the basic statistical characteristics (mean, standard deviation, and standard error) of the dendrochronological series (Table 1) were performed using the program STATISTICA—6 (STATISTICA 2001). Using the program STATISTICA—6, this study executed a spectral and cross-spectral analysis (e.g., Wilks 2006) of time series (width of tree rings, the relative indices of annual radial increment, the hydrothermal coefficient, solar activity expressed as Wolf numbers) each in their turn, and using a Hamming window (smoothing periodograms by the weighed averaging). Cross-spectral analysis involves blending together any of the Fourier decomposed time series above, and then examining the resultant spectrum (see also Lupo et al. 2012b).

3. Results and Discussion

3.1. Climate Data Analysis

To analyze changes in climatic characteristics, the average temperature and precipitation were estimated

Table 1

Statistical characteristics of the studied dendrochronological series for the key plots, sub-area, number of trees, period and years of observation, width of tree rings for the mean, minimum and maximum values (mm), standard deviation (mm) (study forest), and deviation of error (mm) of the tree cores

Key plots	Sub-area (forest quarters)	Quantity of study tree cores	Period of observations	Number of years	Width of tree rings (mm)			Standard deviation of the mean width	Standard error of the mean width
					Mean	Min.	Max.		
Usmanskiy forest	45	15	1893–2009	117	1.72	0.38	4.63	0.985	0.090
	85	10	1864–2009	145	1.85	0.18	5.00	1.168	0.096
Khrenovskiy forest	513	12	1900–2009	110	1.71	0.31	3.99	1.081	0.102

for two 30-year intervals; 1961–1990, and 1985–2014. The latter corresponds to the most recent interval available for study. The annual mean (T_{mean}), minimum (T_{min}), and maximum (T_{max}) surface temperatures, and average annual precipitation from the meteorological station "Voronezh" during the 1961–1990 period (climatic norm, World Meteorological Organization (WMO) or Bulyugina et al. 2010) were as follows: $T_{mean} = +6.1$ °C; $T_{min} = +1.9$ °C; $T_{max} = +10.6$ °C; and average annual precipitation of 583 mm. The same variables for 1985–2014 are: $T_{mean} = +6.9$ °C; $T_{min} = +2.9$ °C; $T_{max} = +11.5$ °C; and average annual precipitation of 584 mm (Table 2).

The 1985–2014 climatic norms for Voronezh showed that the annual mean temperature increased by 0.8 °C, however, this increase was not seasonally consistent. An examination of the seasonal changes showed the summer temperatures increased to a lesser degree relative to winter temperatures (0.4 °C, significant at the 95% confidence level using the *F*-test, see Neter et al. 1988; Birk et al. 2010). Observed changes in temperature are consistent with changes in the global mean temperature during this period (see IPCC 2013). A comparison of annual temperatures from the instruments in Belgorod (Belgorod Oblast) shows a similar increase over the same period (0.8 °C). This area is located to the west and south of the study region (see also Lebedeva et al. 2016). Summer season temperatures increased by 0.8 °C as well, which is greater than that in the study region. The smaller temperature increase for the summer season at Voronezh is more consistent with similar studies in the United States (e.g., Birk et al. 2010).

The Continentality Index (Borisov 1975) for the period 1937–1966 was equal to 49.1%, and then for the next 30-year period, 1967–1996, was 44.2% (Matveev 2003). Using the data for the current period, 1985–2014, the continentality index of this region continued to decrease to 42.7%. Thus, the trend toward warmer conditions in the study region has been associated with decreasing continentality, and this decrease was noted for the Belgorod Region as well.

The average annual precipitation with comparison of the norm period had not changed when comparing the 1961–1990 and 1985–2014 periods (583–584 mm). In the Belgorod Region, the change in precipitation over the same time period showed a decline of 65 mm (from 603 to 538 mm). However, from 1860 to 1930 a gradual decline in precipitation was observed reaching a minimum annual total of 550 mm during that period, and then followed by a period of smooth growth to the present time (Fig. 2). An analysis of annual precipitation using long-term meteorological observations for Voronezh indicated that there is strong interannual variability, from a minimum of 263 mm (1891) to a maximum of 874 mm (2012). More than half of the wettest years occurred since 1980 (60%), while the majority of dry years (not always connected with high temperatures) occurred before 1980 (72%). Also, normally more than half of the annual precipitation falls during the May to September timeframe, but for some years this was not true.

Dry years (defined by a precipitation anomaly less than one standard deviation below the mean) in the central part of East-European forest-steppe were

Table 2

Average monthly temperatures (°C) and precipitation (mm) at meteorological station no. 34123 "Voronezh" from 1985 to 2014

Month	Mean minimum temperature (°C)	Mean temperature (°C)	Mean maximum temperature (°C)	Norm precipitation (mm)
January	−8.8	−6.1	−3.4	41
February	−9.3	−6.5	−3.0	37
March	−4.2	−1.0	2.9	33
April	3.6	8.3	13.9	38
May	9.3	14.8	21.1	46
June	13.2	18.5	24.5	74
July	15.2	20.5	26.6	62
August	13.7	19.2	25.6	52
September	8.7	13.3	18.9	61
October	3.6	6.9	10.9	50
November	−2.6	−0.4	−3.4	46
December	−7.6	−5.0	−3.0	44
Annual Mean	2.9	6.9	2.9	584

associated with spring droughts and/or high evaporation by dry winds (e.g., 1924, 1946, 1992, 2002), with summer droughts (e.g., 1908, 1921, 1975, 2005, 2007), or with a combination of spring and summer strong droughts (e.g., Lupo et al. 2014), which occurred as result of a long period of low rainfall, usually a two-year period involving the draining of soil and high temperatures during the warm season (e.g., 1891–1893, 1938–1939, 1971–1972, 2009–2010). These years were dry similarly for the Belgorod Region as well.

The average value of the HTC over the study period equaled 1.07, but the variance was very large ranging from 0.42 (1891) to 2.24 (1980). Notably, in years with HTC values of about 1.0, the region experienced weak drought. When the index was less than 0.8, however, this was associated with moderate to strong drought. The HTC values less than 0.6 were periods of severe drought (Tarankov 1991; Matveev 2003) corresponding to 1891–1893, 1897, 1924, 1938–1939, 1946, 1963, and 1971. The HTC ranged between 0.6 and 0.7 during 2009 and 2014.

According to our HTC index calculations for the period 1890–2014, which has been partitioned into 30-year intervals, there has been a trend toward a wetter climate in the study area (e.g., 1890–1920 = 1.00; 1921–1950 = 1.05; 1951–1980 = 1.09; 1981–2010 = 1.15). Coupled with an observed increase of the HTC index since the end of 19th century using 30-year intervals, there was also a clear cyclical fluctuation in HTC with a periodicity close to 70 years (Figs. 3, 4a). The high amplitude and frequency of the HTC modes superimposed on the background trends (Fig. 3) for the entire period of instrumental observations (1873–2014) demonstrates the strong climatic variability in the region. Similar variability is found for the Belgorod Region, but the HTC has shown a slight decrease in that area over the last 30 years.

A comparison of the HTC graphs and solar activity, expressed in Wolf numbers (Fig. 4b) showed that up to 1960 (from 1889 to 1958), fluctuations in the HTC and solar activity in the 60–80 year cycle were in opposition, and starting with 1960 (1958) to the present time these cycles have become synchronous.

To identify the modes of basic climatic variability or cyclic dynamics, limiting the growth of *Pinus sylvestris* L. in the Central forest-steppe zone of Eastern Europe, we performed spectral analyses (using a smoothing by Hamming weights) of time series for total precipitation in the April–October period, HTC, and Wolf numbers (*W*), characterizing solar activity (Fig. 4).

An analysis of the periodogram derived from the time series of total precipitation in April–October for calendar years (Fig. 4a) showed the presence of cycles with different duration. Their durations rounded to whole years were on the order of 2–3, 8–9, 15–17, 20–24, 30, 40, 61, and 122-years, respectively. In order of significance, i.e., according to the spectral power in the periodogram in Fig. 4a, in

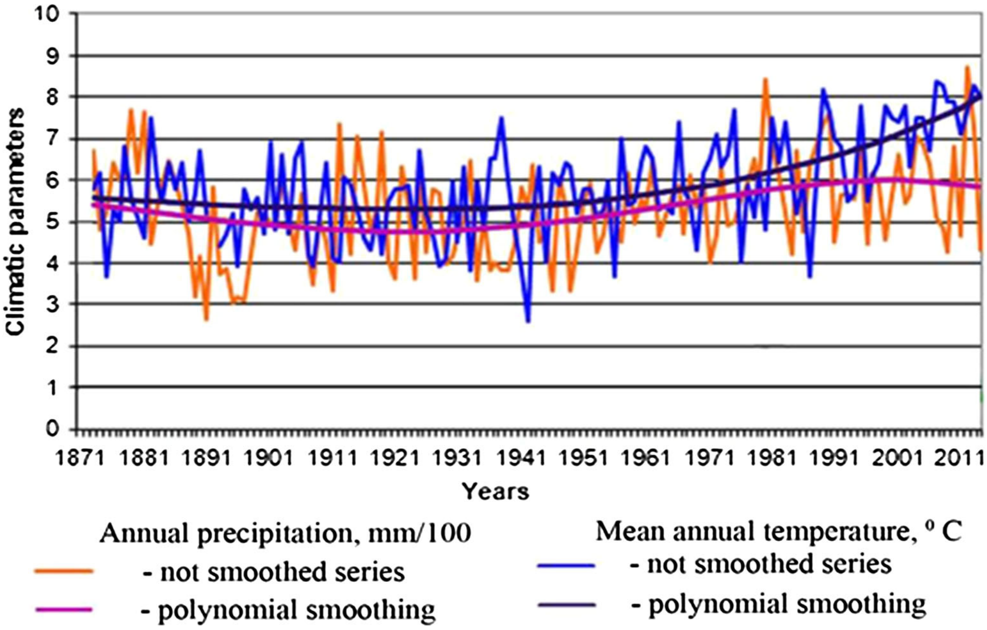


Figure 2
Change in annual precipitation and mean annual temperatures using long-term meteorological observations for Voronezh station

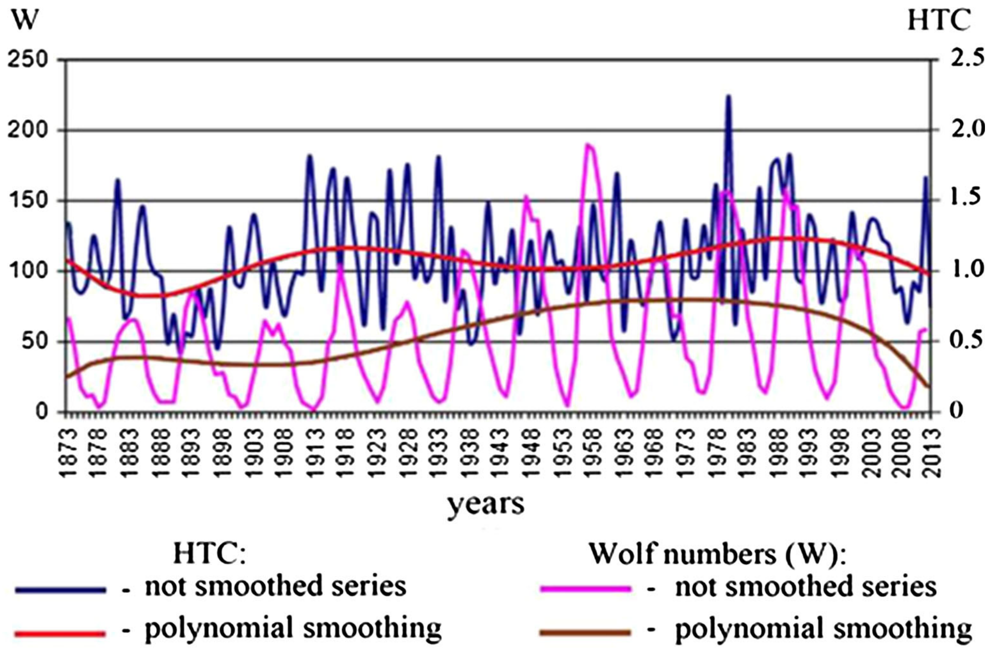
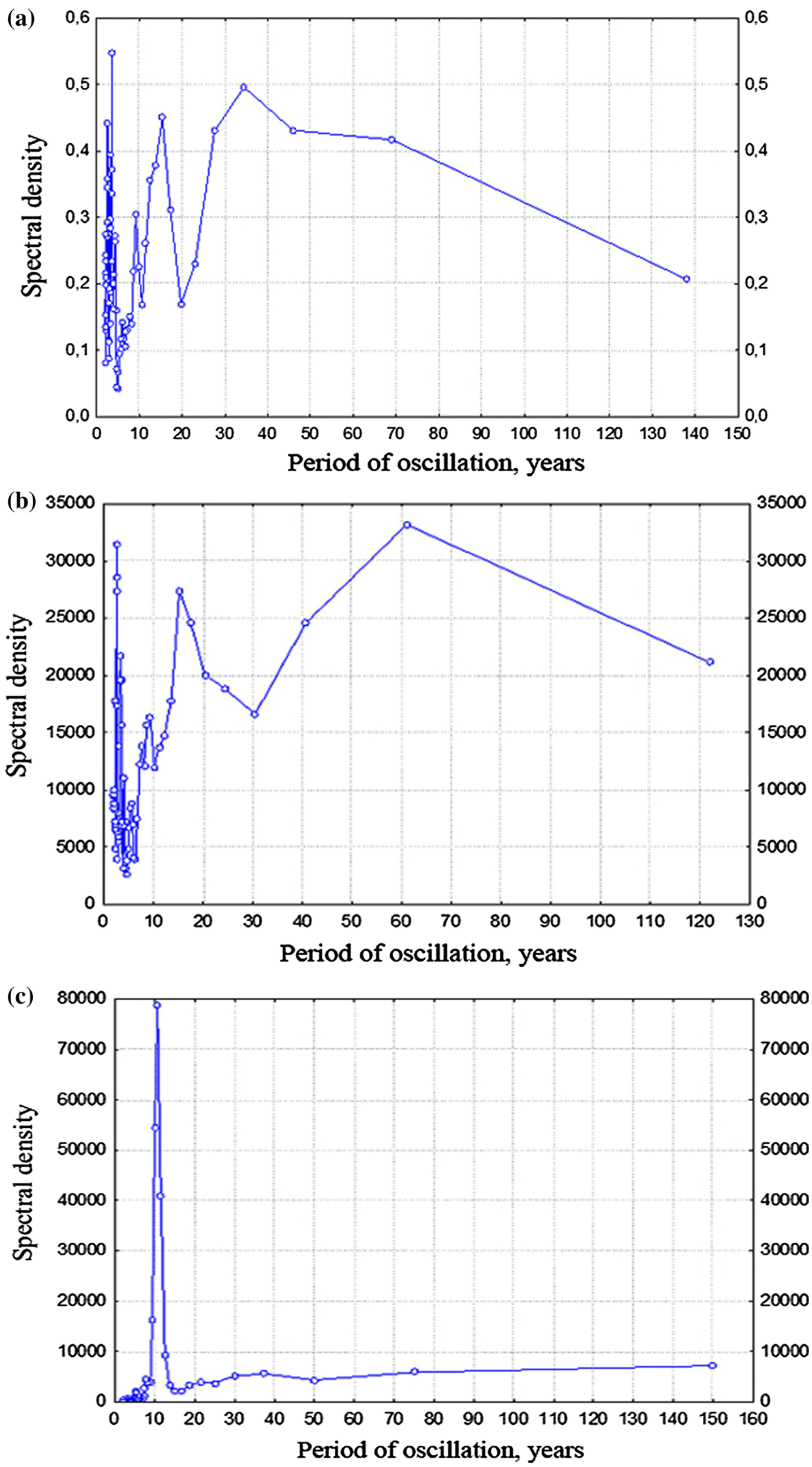


Figure 3
The dynamics of hydrothermal coefficient (HTC) and solar activity (using the observations from Voronezh meteorological station)


(a)
Spectral density
0,0 0,1 0,2 0,3 0,4 0,5 0,6
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Period of oscillation, years
(b)
Spectral density
0 5000 10000 15000 20000 25000 30000 35000
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Period of oscillation, years
(c)
Spectral density
0 10000 20000 30000 40000 50000 60000 70000 80000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
Period of oscillation, years

◀Figure 4
Periodograms smoothed using Hamming weights, for spectral density of the **a** April to October precipitation, **b** the HTC and **c** solar activity (Wolf numbers) time series

decreasing order of spectral density were the following: 61, 2–3, 15–17, 40, 122, 20–24, and 30-years. Using the HTC time series for calendar years (Fig. 4b), we found the following cycles: 2–3, 9–11, 12–18, 20–23, 28–46, 69, 138-years. In order of importance, the cycles were as follows: 2–3, 28–46, 12–18, 69, 9–11, 20–23, 138-years. The most clearly identifiable cycles that prevailed were high-frequency oscillations (2–3 years—El Niño and Southern Oscillation—see Birk et al. 2010), then about 33–34 years (Bruckner cycle), and about 15 years. At last, the dynamics in the time series of Wolf numbers characterizing solar activity (Fig. 4c) showed the following periodicities; 7–8, 9, 10–11, 15–17, 19–24, 30–38, 50, 74, and 150 years. In order of importance these are: 10–11, 9, 150, 74, 30–38, 50, 19–24, 15–17, and 7–8 years. Note that the 10–11-year periodicity (Schwabe–Wolf cycle) completely dominated over the other cycles in this data set. Thus, this analysis indicates periodicities in the HTC that are consistent with the time-scale of the Bruckner Cycle (Figs. 3, 4). The phase for increases in HTC is characterized by increased humidity for warm season of the year with average temperatures above 10 °C; and vice versa (increased aridity).

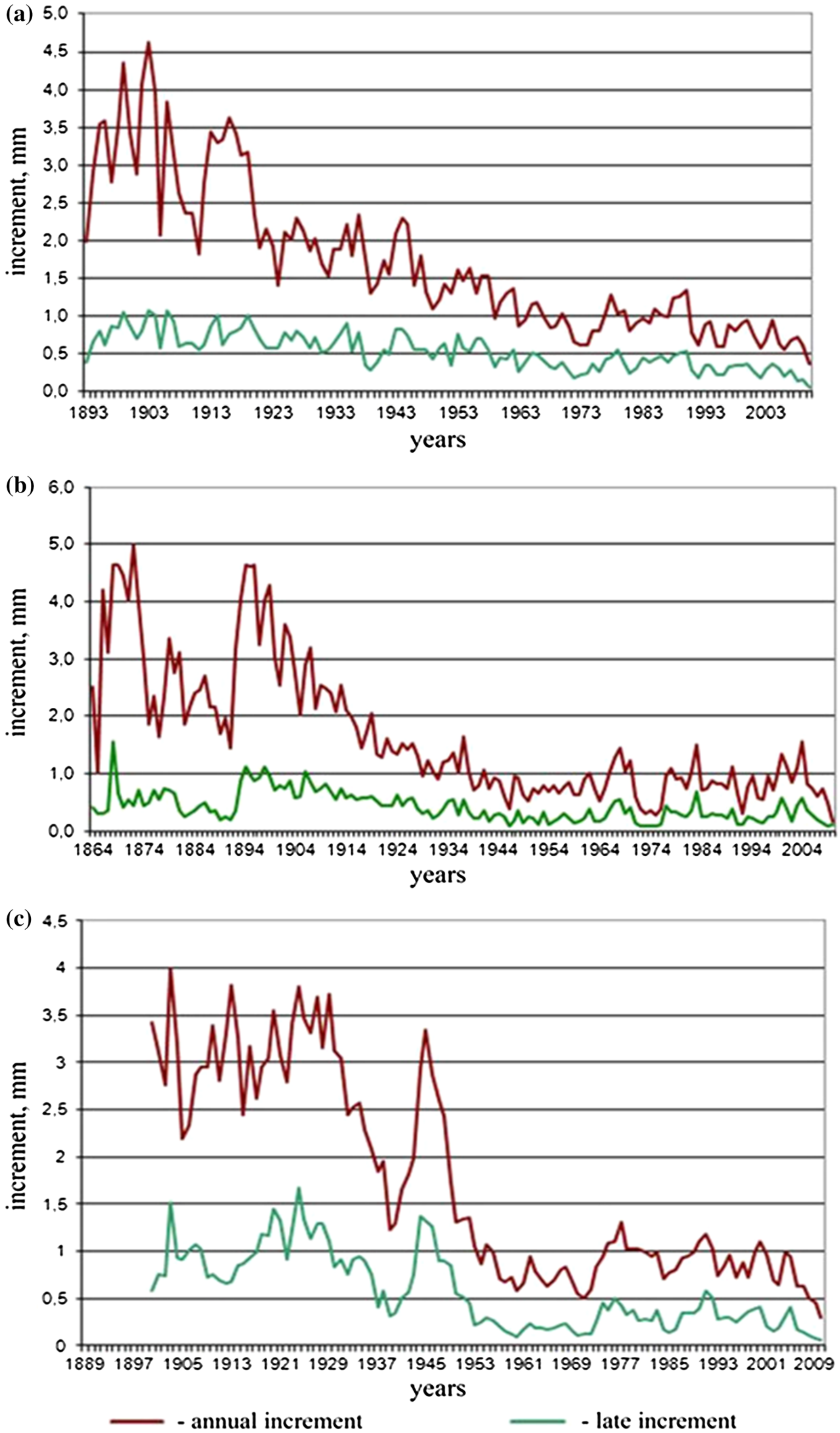
Similar spectral analyses were not done for the Belgorod Region since interannual temperature and precipitation variability can be quite different in locations as distant as the Belgorod Region and Voronezh (see Birk et al. 2010 and references therein). However, initial analyses show significant interannual variability related to El Niño and Southern Oscillation and interdecadal variability for the region qualitatively similar to other regions in Asia (e.g., Mokhov et al. 2014).

According to Shnitnikov (1969), the duration of intra-secular Bruckner cycles ranges from 20–30 to 45–47 years, as the background for which short-term climate cycles appear lasting for about 7–11 years. Longer secular cycles (or those possibly associated with a multi-decadal signal in the North Atlantic Oscillation or NAO—see Moore et al. 2013 and references therein) are recognized to be about double the time-scale of the Bruckner cycles; these having duration of 60–80 years, but approaching in the northern regions of Eurasia to 90 years (Shnitnikov 1969).

The intra-secular dynamics of droughts within the East-European forest-steppe is well traced not only to Bruckner cycles, but also the 11-year Schwabe–Wolf cycles, and Hale (magnetic cycles) 20–24-year cycles in solar activity. Thus, these cycles have important long-term prognostic value (decades) for models of future regional climate. Variations with smaller frequencies (3–4 or 5–6 years) likely related to ENSO are also clearly identified (e.g., Birk et al. 2010), but application to long-term (decadal) forecasting purposes is not yet effective (Matveev 2003). Synoptic patterns showing the atmospheric conditions associated with wet and dry years in the region and their connection to ENSO are shown in Lupo et al. (2014).

The graphs of temperature and precipitation with time in Voronezh (Fig. 2) show that since mid-1970s there has been an increase in the variability of climatic conditions reflected by an increase in mean annual temperature combined with an increase in the variability of annual precipitation (Fig. 2). This may be partly connected with a more active solar cycle (Fig. 3). Also solar activity is likely reflected to the occurrence of abnormal climatic conditions (severe drought) in the East-European forest-steppe and a number of other regions of Russia in 2010 (Mokhov 2011; Matveev and Chebotarev 2012; Lupo et al. 2012a, 2014) via the combined influence of minima (2008–2009) in the 11-year cycle, the Bruckner Cycle, and secular solar activity cycle.

The question of Bruckner Cycle influence on different components of the environment is consistent with the importance of this information as applied to the studies of anthropogenic impacts and natural resources management. The data from this research and the research of other scientists using the wood radial increment, as well as data on content and stocks of soil organic matter dynamics (Bashkakova et al. 1984), shifts in time for the areas of wet soils (Ovechkin and Isaev 1985) and swamp ecosystems (Chendev and Petin 2009), different kinds of soils areas (Chendev et al. 2013), all show the visible impacts of these cycles, as reflected in the intra-secular dynamics of many natural processes.


(a)
increment, mm
years
(b)
increment, mm
years
(c)
increment, mm
years
- annual increment
- late increment

◀Figure 5
Mean annual and late radial increment for pine stands in **a** quarter 45, Usmanskiy Forest, **b** quarter 85, Usmanskiy Forest, and **c** quarter 513, Khrenovskiy Forest

3.2. Tree Ring Analysis

The study of the radial increment (annual tree ring width) for *Pinus sylvestris* L. in key areas of the Usmanskiy and Khrenovskiy Forests in conjunction with climate factors limiting wood growth provided important results. For example, fluctuations in the average annual ring width of *Pinus sylvestris* L. in quarter 45 Usman Forest (Fig. 5a) showed that growth rings correlate well with the cyclic occurrence of dry periods. However, depending on the distribution of monthly rainfall, temperature, and the influence of internal factors, in some cases there has been a displacement of the minimum increments by one or even 2 years after dry event. Such patterns have also been found by other researchers (Breshears et al. 2009; Allen et al. 2010).

By examining fluctuations in the radial growth for *Pinus Sylvestris* L. stands in the quarter 45 of Usman Forest the narrowest annual rings observed were found during the following year(s): 1897, 1905, 1909, 1911, 1921, 1924, 1939–1940, 1946, 1949–1950, 1959, 1963–1964, 1972–1974, 1981, 1992, 1995–1996, 2002, 2006, and 2009. Particularly deep minima in annual wood data were observed in 1939–1940, 1949, 1972–1973, and 1995–1996 (Fig. 5a). These deep minima for the late wood increment were characterized by a clear cyclic recurrence and they were observed in the following years: 1911, 1922, 1931, 1939–1940, 1952, 1963, 1972, 1981, 1992, 2002, and 2010. These repeating 9–12-year minima illustrate the connection between unfavorable months (dry seasons) of late wood increment in the second half of the HTC periods, and the Schwabe–Wolf 11-year solar cycle, as well as the Hale 20–24-year cycle of solar activity.

In quarter 85 of the Usmanskiy Forest (Fig. 5b), the deep minima in annual and late wood increments were observed during the following years: 1889, 1905, 1946, 1964, 1972–1976, 1992, 1996, 2002, and 2009–2010. A conjugated analysis for quarters 45 and 85 from the Usmanskiy Forest of the minima in the annual wood increment for pine stands shows the following matches for years: 1905, 1946, 1964, 1972–1974, 1992, 1996, 2002, and 2009–2010.

The annual radial wood increment data from the Khrenovsky Forest, quarter 513 (Fig. 5c), are well correlated to the Bruckner Cycle at 32–36 years. In particular, there are deep minima in this data set observed at intervals of 34 years (between 1905–1906 and 1939–1940), 32 years (between 1939–1940 and 1971–1972), and 36 years (between 1971–1972 and 2006–2009).

For identifying cycles of different magnitudes, using a relative index of wood radial increment (Fig. 6) is a better approach. The minima for the pine radial growth in all three study stands (quarters 45, 85 in Usmanskiy Forest, and quarter 513—in Khrenovskiy Forest) were observed for the years: 1920–1921, 1931, 1939–1940, 1948–1950, 1959–1960, 1962–1963, 1971–1972, 1983, 1992–1993, 1995, 2002, and 2005. Deep radial increment minima took place in the years 1939–1940, 1971–1972, and 2009–2010. Thus, the minimum increment occurred at intervals corresponding approximately to the 11-year Schwabe–Wolf cycle, with the index deepest minima showing a frequency closer to the period of the Bruckner cycle. Exact correspondence should not be expected in the presence of shorter term variability in the climate record such as that associated with ENSO since these shorter term maxima and minima would constructively or destructively interfere with the longer cycle (e.g., Gershunov and Barnett 1998; Tsonis et al. 2007; Mokhov et al. 2014; Thieblemont et al. 2015).

Spectral analysis of the time series variability for the pine radial increment, as well as analysis of the smoothed periodograms provided compelling results. In the time series for annual ring width (Fig. 5), the periods corresponding to the banded frequencies with increasing spectral density were not the same. Decadal periods were found within quarter 45 (Usmanskiy Forest) at 14.8, 10.7, and 3.9 years, quarter 85 at 12.2 years, and quarter 513 for the Khrenovskiy Forest at 18.3 and 11.0 years, respectively. In the time series of the relative indexes for annual radial increment (Fig. 6), the maximum spectral density was observed in the 10.5–10.9 year period, while the index of the late wood increment was observed in the 9.8–10.5 year

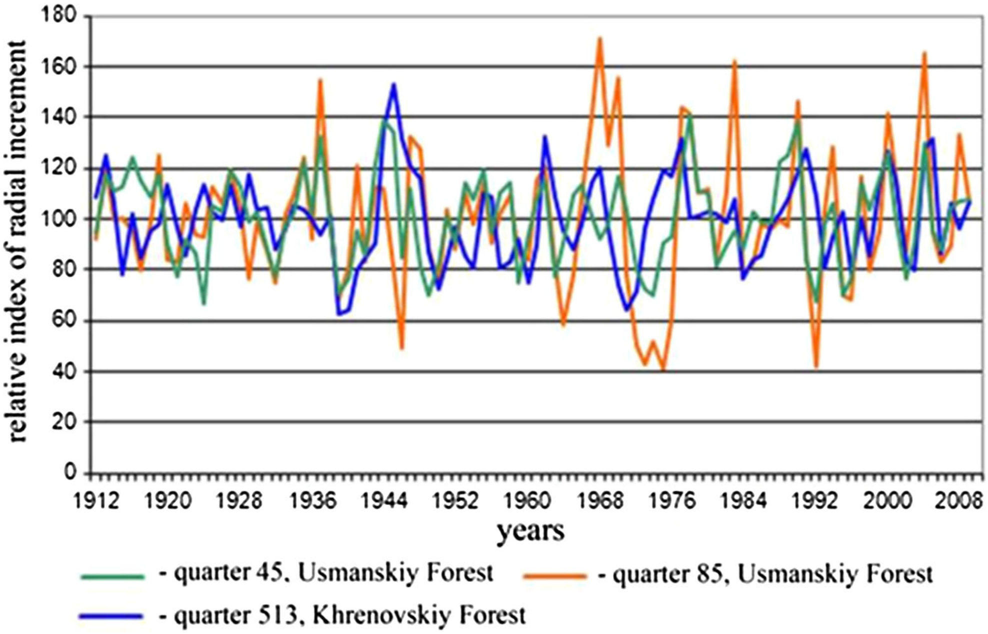


Figure 6
Relative indexes of annual radial increment for Scotch pine within the three study sub-areas of the Usmanskiy and Khrenovskiy Forests

period. Thus, it is shown here that there is a close match between the maximum for the spectral density of wood radial increment with the 11-year cycle of solar activity in the Voronezh Oblast and surrounding regions.

To identify the connection between cyclical dynamics in the radial increment of tree stands and limiting factors of tree rings growth, dual graphical analysis of cyclical indices for tree ring increment was conducted in the HTC, and Wolf numbers (Fig. 7), as well as cross-spectral analysis of *Pinus sylvestris* L. radial increment with the above factors (HTC, *W*, and the amount of precipitation for the period April–September) (Fig. 8). The analysis was performed using quarter 45 of the Usmanskiy Forest as an example.

According to Fig. 7, the period 1914–2009 can be divided into three phases, each of which showed similar trends from correspondence between minima and maxima in *W*, *I*, and HTC. From 1913 to 1938 during years when maxima and minima for solar activity was observed, an out-of-phase relationship of 180 degrees between HTC and I occurred. From 1944 to 1969, there was a dissonant relationship between the three parameters with a diverse mix of minima and maxima combinations. Then, from 1975 to 2009, there was a direct correspondence between the three considered parameters. In years of solar activity minima, there was also a minimum in the HTC and wood redial increment (*I*), as well as increasing variability in each. The identified cyclical phenomena as studied during three distinct eras corresponded to the above-detected climatic phase changes, or the alternation of backward and forward linkages between the HTC minima–maxima and minima–maxima in the Wolf number time series over the period 1913–2009 (Fig. 3).

Cross-spectral analysis of combined series for the pine radial increment and the warm period precipitation totals (Fig. 8a) revealed the following periodicities; 2–3, 4–5, 6–7, 8–10, 11–12, 13–15, 18, 22, 27, 35, 53, and 108 years. It should be noted here that these periodicities from cross-spectral analysis are not derived from the analysis of the raw time series. In order of importance, these periodicities ranked from greatest spectral density to least were; 22, 11–12, 27, 18, 13–15, 2–3, 35, 8–10, 6–7, 53, 108, and 4–5 years. Among these, the 22-year (magnetic or Hale) and 11–12 years (solar or Schwabe–Wolf) cycles (Fig. 8a). Joint analysis of series for pine radial increment and HTC (Fig. 8b)

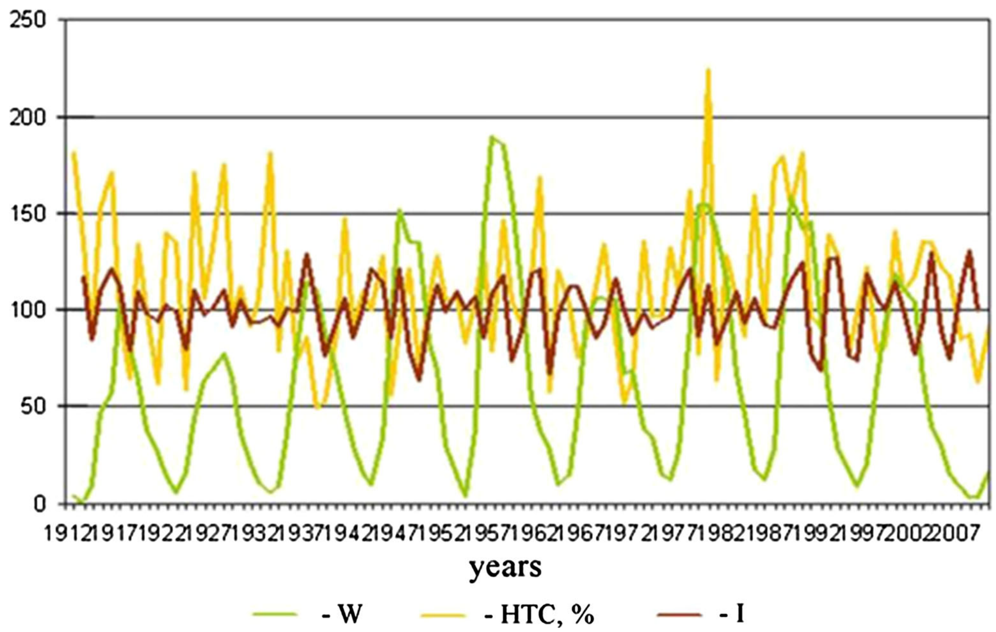


Figure 7
Variations of solar activity (Wolf number, *W*), hydrothermal coefficient (HTC), and radial increment of Scotch pine relative index (*I*) in quarter 45, Usmanskiy Forest

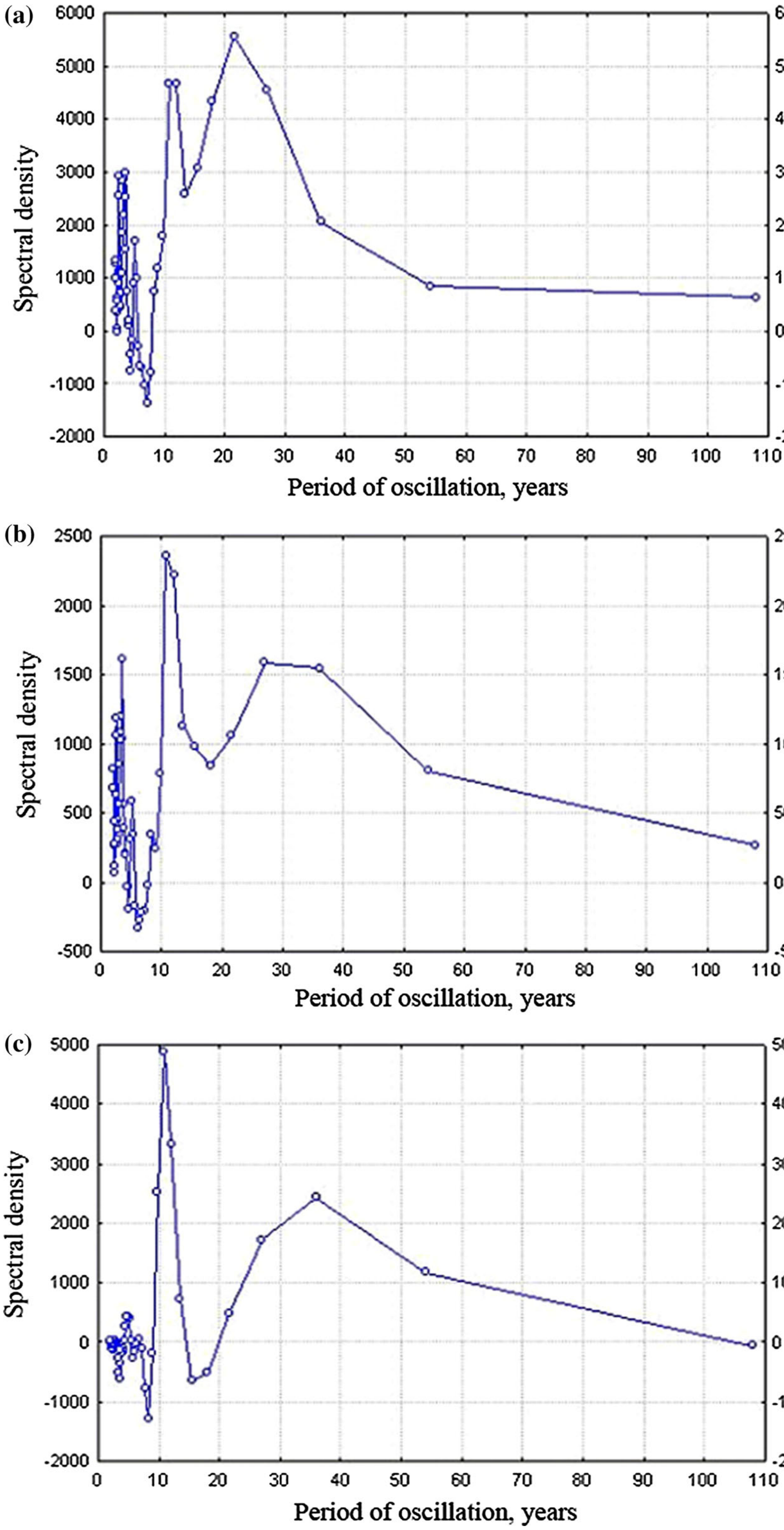
revealed the following cycles; 2, 3, 4–5, 6–9, 11–12, 13–18, 22, 26–36, 53, and 108-years. In order of importance, they are: 11–12, 3, 26–36, 2, 13–18, 22, 53, 4–5, 108, and 6–9 years. The most significant was 11–12-years cycle (solar or Schwabe–Wolf) showed the maximum power. But significant cross-spectral density also showed a high-frequency (2 and 3-year) fluctuations as well as fluctuations in the duration of 26–36 years, i.e., close to that of the Bruckner cycle (Fig. 8b). Note, that HTC involves the combined effect of temperature and precipitation.

Finally, in the cross-spectral density analysis for the radial increment relative index and Wolf numbers (Fig. 8c) revealed the following cycles: 2–7, 8–9, 10–12, 13, 15–18, 22, 28, 36, 53, and 108-years, respectively. In order of importance they were: 10–12, 36, 28, 53, 13, 22, 4–5, 108, 2–7, 15–18, and 8–9 years. In this series, the 10–12 year cycle (solar or Schwabe–Wolf) was dominant, however, there was also a high peak in spectral power with a cyclical duration of about 36 years (Bruckner cycle). Cross-spectral analysis allowed for the detection of resonance in the combined time series (increment—limiting factors) and finding the following wavelengths dominant across all three combinations; 10–12 years (solar or Schwabe–Wolf), 22 years (magnetic or Hale)—especially with precipitation, 33–36 years (Bruckner cycle), and also high-frequency oscillations lasting about three years (ENSO). These results are consistent with previous research whether near our region or elsewhere (e.g., Douglass 1919; Dmitrieva 1987; Tarankov 1991).

Combining the dominant cycles and building a dynamic model for the management of natural ecosystems, such as managing fish productivity have been suggested in the published literature (e.g., Klyshtorin and Lybushkin 2007; Lupo et al. 2012b). Therefore, the results of this study could be used in a similar way to guide management decisions quantitatively in the study region and elsewhere, or at least qualitatively providing guidance for managers. This would be especially true where climate change induced alterations to the state and productivity of forest ecosystems and associated natural resource commodities are of growing concern.

4. Summary and Conclusions

This work examined the Voronezh Region climatological record in the Eastern European forest-steppe, and correlated this information to the radial


(a)
Spectral density
6000
5000
4000
3000
2000
1000
0
-1000
-2000
0 10 20 30 40 50 60 70 80 90 100 110
Period of oscillation, years
(b)
Spectral density
2500
2000
1500
1000
500
0
-500
0 10 20 30 40 50 60 70 80 90 100 110
Period of oscillation, years
(c)
Spectral density
5000
4000
3000
2000
1000
0
-1000
-2000
0 10 20 30 40 50 60 70 80 90 100 110
Period of oscillation, years

◀Figure 8
Periodogram smoothed using Hamming weights, for the; **a** cross-spectral density of the annual radial increment relative index (*I*) and the April to October precipitation (mm), **b** annual radial increment relative index (*I*) and HTC, and **c** the annual radial increment relative index (*I*) and Wolf numbers (*W*)

increment (annual tree ring width) of Scots Pine (*Pinus sylvestris* L.) stands in the Usmanskiy and the Khrenovskiy Forests for a longer period than previously published. The following information was learned through this investigation.

1. Within the central part of the East-European forest-steppe meteorological observations for a period greater than 100 years revealed trends and variability that corresponded to the recent changes in surface temperature (here increasing from about the 1950s to 2014). The variability in the Hydrothermal Coefficient (HTC), which combines temperature and precipitation, increased over successive 30-year averaged periods from 1890 to 2014. This trend reflects an increase of climatic humidity during the warm period of the year in the region, defined as the period with monthly temperatures greater than or equal to +10 °C (May–September), as well as an increase in the variability of annual precipitation and mean annual surface temperature. Another trend evident during the second half of the 20th century was the decline in continentality.
2. Comparatively, the Belgorod Region, to the south and west, showed temperature increases, but a decrease in precipitation. The continentality and HTC indexes showed the opposite trends for the Belgorod Region which is adjacent to the study region. Initial analyses show interannual and interdecadal variability in the Belgorod Region surface temperature and precipitation was also present, but may not be comparable to that of the Voronezh Region (e.g., Birk et al. 2010).
3. In the regional stands of *Pinus sylvestris* L., cyclical periods of minima and deep minima for annual and late wood radial increment were identified. Minima in the increments occurred with a frequency close to the 11-year solar cycle (Schwabe–Wolf). This was confirmed by a close match between the maximum spectral density of wood radial increment and the 11-year cycle of solar activity. Deep minima in the tree ring productivity are detected with a frequency close to that of the Bruckner cycle (32–38 years): 1905–1906, 1939–1940, 1971–1972, and 2009–2010.
4. This work revealed that there was a correlation between climatic variables and solar activity maxima and minima (*W*). The hydrothermal coefficient (HTC) has a phase relationship with *W*, and then both of these variables with the radial increment relative index maxima and minima in *Pinus sylvestris* L. (*I*) during the last 100–140 years. The length of each phase with similar combinations of the index maxima and minima were approximately 34 years, corresponding to the duration of the Bruckner cycle.
5. The combination of time series for oscillations (radial increment of *Pinus sylvestris* L. and limiting factors) revealed the fields of resonance at the following wavelengths: 10–12 years (solar or Schwabe–Wolf), 22 years (magnetic or Hale)—especially with precipitation, 33–36 years (Bruckner cycle), and also high-frequency oscillations lasting about three years (ENSO).

Further studies in other forests of Eastern Europe and elsewhere will be important to confirm and clarify the results found here, and to contribute to resolving the interdecadal variability of natural processes in response to climate change.

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