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Interrelation of the Radial Increment of Trees with Various Factors

Anzhella V. Rumyantseva [1], Sergei A. Chekrygin [2] and Elena O. Vidyagina [3,*]

1 Faculty of Biology and Health Education, Department of Biology, Cherepovets State University, Sovetsky Prospekt 8, 162600 Cherepovets, Russia
2 Faculty of Biology, Saint Petersburg State University, Universitetskay Embankment 7−9, 199034 Saint Petersburg, Russia
3 Branch of the Shemyakin-Ovchinnikov, Institute of Bioorganic Chemistry of the Russian Academy of Sciences, Prospekt Nauki 6, 142290 Pushchino, Russia
* Correspondence: vidjagina@mail.ru; Tel.: +7-9175559697

Abstract: Radial increment objectively reflects the quality of the assimilation apparatus of a woody plant. Its features indicate the influence of various anthropogenic, biotic and abiotic factors as well as the stability of the plant under stress. The aim of this study was to survey the long-term dynamics of the radial growth of six tree species: *Betula pendula*, *Ulmus glabra*, *Quercus robur*, *Tilia cordata*, *Picea abies* and *Pinus silvestris*, depending on the impact of creating a reservoir and the fluctuations of the water level in it. Additionally, another aim was to determine whether there is a dependence between the annual radial increment of these tree species and the change in the temperature factor during the growing season. We studied cores of trees growing in a park on the coast of the Sheksna river, the level of which is regulated by the water level in the Rybinsk Reservoir and changes along with it. This research presents the dynamics of the annual radial growth of *Betula pendula* over 59 years, *Ulmus glabra* over 50 years, *Quercus robur* over 59 years, *Tilia cordata* over 82 years, *Picea abies* over 128 years and *Pinus silvestris* over 125 years. The average annual radial growth decreases in the series *Ulmus glabra* > *Betula pendula*, *Quercus robur* > *Tilia cordata* > *Picea abies* > *Pinus silvestris*. The radial increase does not correlate with the annual water level in the Rybinsk Reservoir. However, years with extreme minimum and maximum reservoir filling affect the radial growth of *Quercus robur* (r = 0.56) and *Tilia cordata* (r = 0.52). It was found that after the creation of the reservoir, the radial increment of *Picea abies* was significantly reduced by 1.10 mm. The clearest dependence of ring width index was obtained for *Picea abies* on temperature in May (r = −0.30 at $p \leq 0.05$) and for *Pinus sylvestris* on temperature in July (r = −0.25 at $p \leq 0.05$). Similarly, a weak correlation of ring width index with temperature in some months was noted for deciduous trees. *Picea abies* is notable for its particular display of moderate inverse correlation to the radial growths of other trees.

Keywords: radial increment; radial growth; woody species; reservoir; ring width; ring width index (RWI); monthly mean temperature

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1. Introduction

People greatly influence the environment, sometimes completely changing the biocenosis. Living organisms are always sensitive to any changes in the environment. Plants are the most sensitive to changes in water and temperature conditions [1]. One of the local changes in the environment is the construction of hydroelectric power plants, reservoirs and changes in river beds. This change in water regime greatly affects coastal plants [2]. Additionally, one of the manifestations of human influence was the change in temperature indicators as a result of global climate change. Global and local climate change has a significant impact on weather-dependent forestry. In recent decades, human influence on the change in temperature and water indicators is especially intense. Woody plants are the most vulnerable to climate change and water regime changes because perennial forest plantations are forced to adapt to new conditions or die. This is especially important for Russia, where the air temperature is rising 2.5 times faster than the world average [3], and energy and shipping are closely related to changes in water bodies. Forests and the forest sector can play a significant role in the achievement and implementation of climate policy programs to reduce the concentration of carbon dioxide in the atmosphere, reduce the greenhouse effect, accelerate the decarbonization of the world economy, improve soil quality and water exchange in the biocenosis, improve the socioeconomic conditions of the rural population and protect the environment [4]. Thus, in addition to mitigating the impacts of climate change, there is a need to adapt to its consequences. Therefore, it is especially important to study the influence of the main factors on the productivity and radial increment of woody plants. This will allow for the quick acceptance of an eco-friendly model under changing climatic conditions [3].

The annual radial increment of trees is a complex biological process that depends on many exogenous and endogenous factors [5]. The patterns of variability of radial growth are due to the biological characteristics of natural rocks, environmental problems of the growth place and the variability of the conditions for the occurrence of climatic factors. Radial growth features of the of the trees of different species show the influence of various anthropogenic, biotic and abiotic factors. During seasonal growth, the genetic characteristics of the different species of woody plants and their age are manifested; the processes of production and differentiation of cells in the apical and secondary meristems are coordinated. The intensity of these processes is influenced by both a complex of permanent factors (geographical location, climate, soil) and variable factors (weather conditions, moisture content in the soil, mineral nutrition) [6]. The process of plant growth significantly depends on the state of the external environment, which is determined, among other things, by climatic conditions [7]. Seasonal and annual fluctuations in precipitation and temperature are the most common factors limiting the growth of sensitive trees [8]. Many researchers have found a dependence between changes in the radial growth of woody plants and climatic factors, in particular, temperature and soil moisture [9–12]. However, as noted by the researchers themselves, the correlation between the growth characteristics of woody plants and the values of meteorological and hydrodynamic variables are currently not well understood.

Tree species from the genus *Betula*, *Ulmus*, *Quercus*, *Tília*, *Picea* and *Pinus* are the main economically valuable species in the forestry of Russia [13]. The average forest cover of the territory of Russia in recent decades has been quite stable. It currently stands at 46.5%. Coniferous forests occupy up to 68% of the Russian Federation. Coniferous forests of great interest are *Picea abies* and *Pinus sylvestris*, which occupy 15% and 23% (respectively) of all coniferous forests in Russia. Birch in Russia is the main forest-forming species among deciduous trees and the third among all forest species (15% of all forests) after larch and pine; it is actively used in reforestation and is a promising species for plantation forestry [14]. Linden and elm are tree species not actively used in timber cutting. However, they are widely used in urban greening [15]. Oak occupies 1% of the area of all Russian forests, but at the same time, it is the main forest-forming species in the forest-steppe and steppe zones, and oak forests are among the most valuable forest communities with a high conservation significance. Oak forests are leaders in terms of the degree of influence on the water regime and soil structure, and the value of oak wood is generally known [14].

Effective forest management, which consists of using not only the economic, but also the ecological and social functions of forests, must take into account climate change. It is necessary to foresee various scenarios for the restructuring of forest biocenoses, which will be characteristic of different forest species. This is impossible without solving the fundamental and applied problem of forest biology, i.e., understanding the mechanisms of the adaptation of woody plants to abiotic stress factors. Therefore, the aim of this study was to survey the long-term dynamics of the radial increment of the plants *Betula pendula* Roth., *Ulmus glabra* Huds., *Quercus robur* L., *Tília cordata* Mill., *Picea abies* (L.) H.Karst., and *Pinus sylvestris* L., depending on fluctuations in the water level in the reservoir, as well as to determine how the creation of the reservoir affected the radial growth of trees. This study also aims to determine whether there is a regularity of the change in the temperature factor by the value of the annual radial increment of the different species of trees used in landscaping an industrial city. It should be noted that there are essentially no studies on the influence of the creation of artificial reservoirs on the radial growth of woody plants [12]. At the same time, thanks to such studies, it is possible to track the real physiological change in plants in response to such a coordinate in the environment.

2. Materials and Methods

2.1. Sampling Location

The studied trees grow in the park, which is located in the city of Cherepovets on the banks of the Sheksna river. The city is located in the southern part of the Vologda region, on the Russian platform, in the center of the East European Plain. This zone belongs to the southern taiga. The relief is hilly and the study site is located on the border of the Mologo-Sheksninskaya Lowland (59°07′05″ N; 37°55′32″ E). The Cherepovets is located in the temperate continental region of the temperate climate zone. The climate is characterized by long moderately cold winters and relatively short warm summers. The average January temperature is from −11 °C to −14 °C, the average July temperature is from +16 °C to +18 °C, respectively. There is quite a lot of precipitation, between 500 and 650 mm per year (maximum in the summer months), and the evaporation rate is much lower. Snow cover lies for 165–170 days. The growing season is about 130 days long. A characteristic feature is the frequent change of air masses due to the rapid passage of baric formations during the year. The seasonal change of prevailing wind directions is clearly expressed. Most of the year, south winds prevail, while east and north–west winds are less common [16,17]. The researched park is located on the banks of the Sheksna river. Up until the middle of the 20th century, the river had a length of about 395 km [16], but at present, it has been preserved as a river only in a small section since the upper reaches of the river are flooded by the Sheksninsky Reservoir and the lower reaches by the Rybinsk Reservoir. The Rybinsk Reservoir was created in 1941, and in 1947, it was finally filled [16] to the mark of the normal retaining level (101.81 m above sea level). Additionally, in the course of such a close location to the Rybinsk Reservoir, the level of the river is regulated by the water level in the reservoir and changes along with it. The shore where the park is located has a southern exposure and gently rises, so it does not flood when the water rises. Plants are well lit.

2.2. Plant Materials

This park plantation was created at the end of the 19th century. Currently, 8 species grow here as the tallest and most mature trees. In this study, 6 species of woody plants were analyzed: *Betula pendula* (80–120 years old), *Ulmus glabra* (55–70 years old), *Quercus robur* (68–75 years old), *Tilia cordata* (125–135 years old), *Picea abies* (137–140 years old) and *Pinus sylvestris* (128–130 years old). In the plantation, they are unevenly represented: *Ulmus glabra* (67%); *Tilia cordata* (19%), which has the largest share; and *Quercus robur*, *Picea abies* and *Pinus sylvestris* are represented by single individuals. The largest and oldest dominant trees were selected as model plants. The model trees selected for the study grow 20–120 m from the water's edge (102.5–104.5 m above sea level) and with a density of canopy of 0.5–0.7 in the stand. Shrubs and underwood were absent in the sampling sites. The cores were taken with a Pressler age borer. Drilling was carried out in the direction perpendicular to the longitudinal axis of the tree trunk, at a height of 130 cm from ground level. For reliability, it is necessary that the drill passes through the core of the tree. For an objective comparison, cores had to be taken from the southern side of the trunk, where the maximum values of radial increment can be recorded due to favorable conditions [18]. The width of growth rings was measured using an MBS-10 microscope (Russian Federation) with a measuring scale (an eyepiece micrometer with an accuracy of 0.05 mm). The cores were measured so that the measurement line was perpendicular to the boundary of the annual layer. To obtain clearer boundaries, the surface of the sample was wetted with an ethanol–glycerol mixture. It should be noted that many old-growth trees have rotten in the central part of the trunk, which made it difficult to obtain a large number of wood samples with the greatest possible time interval suitable for the purposes of the study. A total of 53 cores were taken (*Betula pendula*, *Ulmus glabra*—10 each, *Quercus robur*—5, *Picea abies*, *Pinus sylvestris*—4 each, *Tilia cordata*—20), while cores were taken from all oak, spruce and pine trees presented in this park plantation.

To analyze the dependence between the average annual radial increase and the average annual water level in the reservoir, data were used, starting from 1949 (after completion of reservoir filling). Information on the values of the water level in the Rybinsk Reservoir was obtained from a hydrometeorological station located on the territory of the Darwin State Natural Biosphere Reserve. They are published by Kuznetsov A.V. and Rybnikova I.A. during the period from 1946 to 2009 [19], and since 2009, have published in annual editions of the "Report on the state and protection of the environment of the Vologda region", which, in recent years, have also been published in electronic versions [20]. To answer the question of how the creation of the reservoir affected the radial growth of trees, the values of the average annual radial growth were compared for 10 years before the creation of the reservoir (1932–1941) and after the launch of the reservoir (1950–1959). To analyze the influence of the temperature factor on the value of the average annual radial increase, data were used starting from 1955. Temperature information was obtained from the nearest weather station in Cherepovets (59°16′52″ N; 38°01′56″ E altitude 117 m) [21].

2.3. Statistical Analysis

The data were processed using the standard program Microsoft Office Excel 2016 and Statistica 10.0.0.0 [22]. For statistical analysis, the distribution this factor/indicator was established. In the Statistica program, the distribution was analyzed by graphical and arithmetic methods (criterion: Kolmogorov–Smirnov). After determining the normality of the distribution, the correlation coefficient was calculated (Spearman's or Pearson's correlation) and the data were tested for significance using Student's *t*-test. To analyze the influence of the temperature factor, the value of the average annual radial growth was the standardization procedure from a ten-year calendar norm. This makes it possible to obtain growth indexes of annual rings (ring width index, RWI) without loss and/or distortion of the series members [23].

3. Results

3.1. Annual Fluctuations in Radial Increment

For analysis, we took six different species of woody plants, two of which belong to gymnosperms and four to angiosperms. The width of the average annual radial growth was measured in chronological order (Supplementary Materials: Tables S1–S6).

The dynamics of changes in the radial increment of *Betula pendula* showed that the average chronological series for the studied plants was 59 years (Supplementary Materials: Table S1; Figure 1). The minimum value of the radial growth was observed in 1957 (0.84 mm). The maximum value was observed in 1971 (5.52 mm). The average annual radial increment rate for this species was 3.50 mm. The figure shows that the radial growth of *Betula pendula* is rather unstable and has a large range of values. A significant dip is observed in 1957, then the rise begins until 1962, and finally a new decline in radial growth. The main peaks of maximum radial growth were seen in: 1962, 1969, 1971, 1979, 1981, 1986, 1989, 1999 and 2009. The minimum radial growth was typical for the years: 1957, 1964, 1996, 2000, 2004 and 2014.

The dynamics of changes in the radial increment of *Ulmus glabra* showed that the average chronological series was 50 years (Supplementary Materials: Table S2). This breed in the territory of the taiga is characterized by an average radial growth of 3.3 mm. The minimum value of radial growth was observed in 2015 (2.30 mm). The maximum value was observed in 1978 (6.21 mm). The average growth rate for this species is 4.07 mm (Figure 1). From the graph, we can see that from 1968, there was an increase in radial increment every year. After the decline of the radial stalk growth in 1970, a rather stable growth is observed, lying in the range from 3 to 5 mm. Peaks of maximum values were observed in: 1968, 1971, 1978, 1982, 1986, 1989, 1993, 2000, 2003 and 2005. Low peaks were seen in: 1966, 1970, 1977, 1980, 1988, 1991, 1995–1998, 2002, 2004, 2006, 2008, 2013 and 2015. Since the beginning of the 2000s, there has been a trend toward a decrease in radial growth due to the ages of the trees.

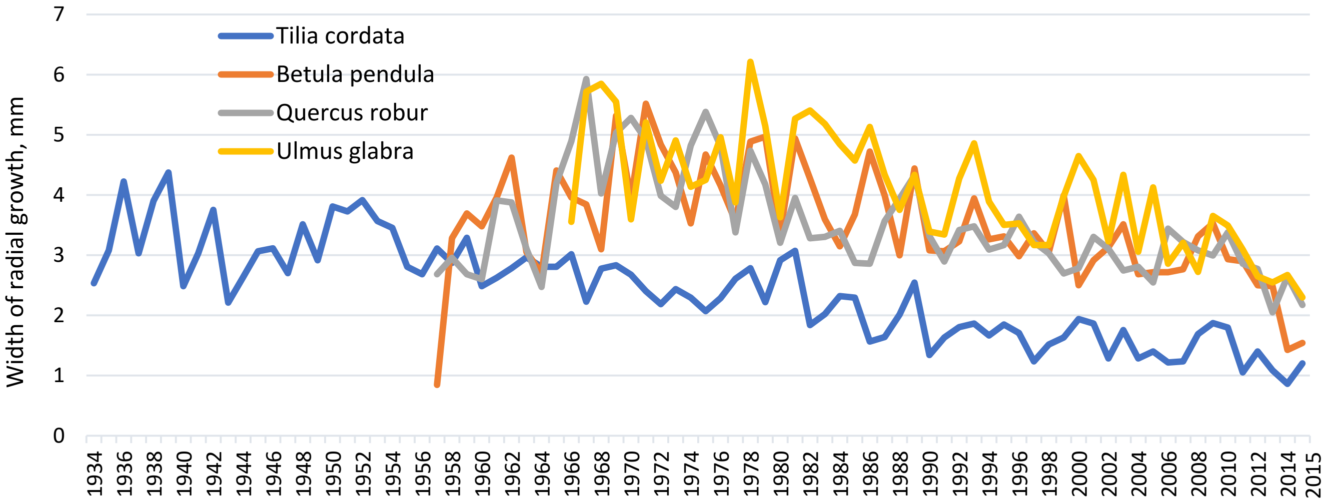


Figure 1. Average values of the radial increment of deciduous tree species in mm.

The radial increment dynamics of *Quercus robur* averages 59 years (Supplementary Materials: Table S3). The average growth rate for this species is 3.50 mm per year. The minimum value of radial growth was observed in 2013 (2.05 mm). The maximum value was observed in 1967 (5.93 mm) (Figure 1). The graph shows that until 1967, there was an upward trend in radial growth. From 1968 to 1981, it slightly decreased and reached a relatively flat plateau from 1982 to 2012. Then, a decrease in age-related growth processes began. Compared to other breeds, the peaks here are not sharp, but smoothed. Radial increment peaks were seen in: 1967, 1970, 1975, 1978, 1989, 1996, 2006 and 2010. Minimum peaks were observed in: 1960, 1964, 1968, 1973, 1977, 1980, 1986, 1991, 1999, 2005, 2013 and 2015. The fluctuations in the values are small and lie within 2 mm. Peaks and recessions are replaced on average in 1–3 years.

The dynamics of changes in the radial growth of *Tilia cordata* showed that the chronological series is 82 years (Supplementary Materials: Table S4). The average growth rate for this species is 2.40 mm. The minimum value of the radial increment was observed in 2014 (0.86 mm). The maximum value was observed in 1939 (4.37 mm). From the graph (Figure 1), we can see that the radial increment of *Tilia cordata* is quite variable from 1934 to 1943 and has a large range of values (4 mm differences). Further, the range of values becomes smaller and, on average, is 2 mm. Additionally, after 1952, a general trend toward a decrease in radial growth can be seen. Main maximum peaks were found in: 1936, 1939, 1942, 1950, 1952, 1959, 1966, 1969, 1981, 1989, 2000, 2009 and 2012. Minimum peaks were observed in: 1943, 1967, 1972, 1975, 1982, 1986, 1990, 1997, 2006, 2011 and 2014.

The dynamics of changes in the radial increment of *Picea abies* showed that the chronological series is 128 years (Supplementary Materials: Table S5). The average growth rate for this species is 1.52 mm. The minimum values of radial growth (0.22 mm) were observed in 1966, 1969 and 1970. The maximum value was observed in 1892 (6.14 mm). It can be seen from the graph that the radial increment of *Picea abies* at the beginning of plant ontogenesis is much higher, after which it decreases significantly. A similar schedule is typical for gymnosperms. There are two large groups of peaks on the graph (Figure 2). The first is from 1888 to 1901, and the second is from 1924 to 1940. The values of the peaks lie above the average value of the radial increase. The first group is rather narrow, but has a large range of values equal to 4.2 mm and contains three large peaks (1892, 1895 and 1897). The second group is wider, but the range of values is only 2.5 mm. It also has three major peaks (1924, 1934 and 1940). Between these two peaks, there is a group with small frequent peaks leading to a decrease in the values of radial increments.

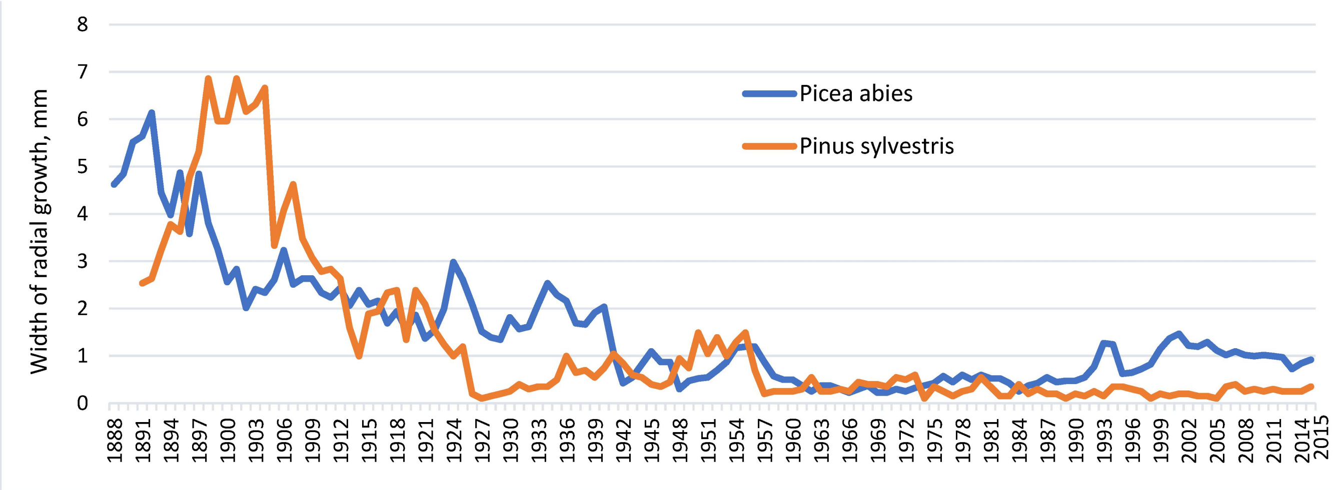


Figure 2. Average values of the radial increment of coniferous tree species in mm.

The dynamics of changes in the radial growth of *Pinus sylvestris* showed that the chronological series is 125 years (Supplementary Materials: Table S6). The average growth rate for this species is 1.13 mm. The minimum values of radial increment (0.09 mm) were observed in 1927, 1974, 1989, 1998 and 2005. The maximum value was observed in 1898 and 1901 (6.17 mm). It can be seen from the graph that the radial growth of *Pinus sylvestris* at the beginning of plant ontogenesis is much higher, after which it decreases significantly (Figure 2). These peaks lie above the average radial gain. The first group is the largest from 1891 to 1912; it has three high peaks (1898, 1901 and 1904) and one smaller one (1907). The second group can also be attributed to the first group from 1914 to 1925. Additionally, the third smallest group was observed from 1947 to 1958. The values of radial increment in subsequent years do not exceed 1 mm.

The largest average annual radial growth (Table 1) was noted in *Ulmus glabra* (4.1 mm), slightly less in *Betula pendula* (3.5 mm) and *Quercus robur* (3.5 mm). *Tilia cordata* has the smallest radial increment among the selected angiosperms (2.4 mm). In gymnosperms, it is approximately the same (*Picea abies*—1.5 mm, *Pinus sylvestris*—1.3 mm). *Pinus sylvestris* deviates the most from the average value of radial growth. The radial growth of *Betula pendula* has a higher amplitude among the angiosperms.

Table 1. Middle average annual radial increment data for different species of trees (mm).

Parameter	*Picea abies*	*Pinus sylvestris*	*Tilia cordata*	*Betula pendula*	*Quercus robur*	*Ulmus glabra*
Average annual growth	1.52	1.25	2.40	3.50	3.50	4.07
Standard deviation	1.28	1.51	0.81	0.92	0.85	0.96
Minimum growth	0.22	0.10	0.86	0.84	2.05	2.30
Maximum growth	6.14	6.86	4.37	5.52	5.93	6.21
Growth amplitude	5.92	6.76	3.51	4.68	3.88	3.91

3.2. Dependence of the Radial Increment of Trees on the Water Level in the Reservoir

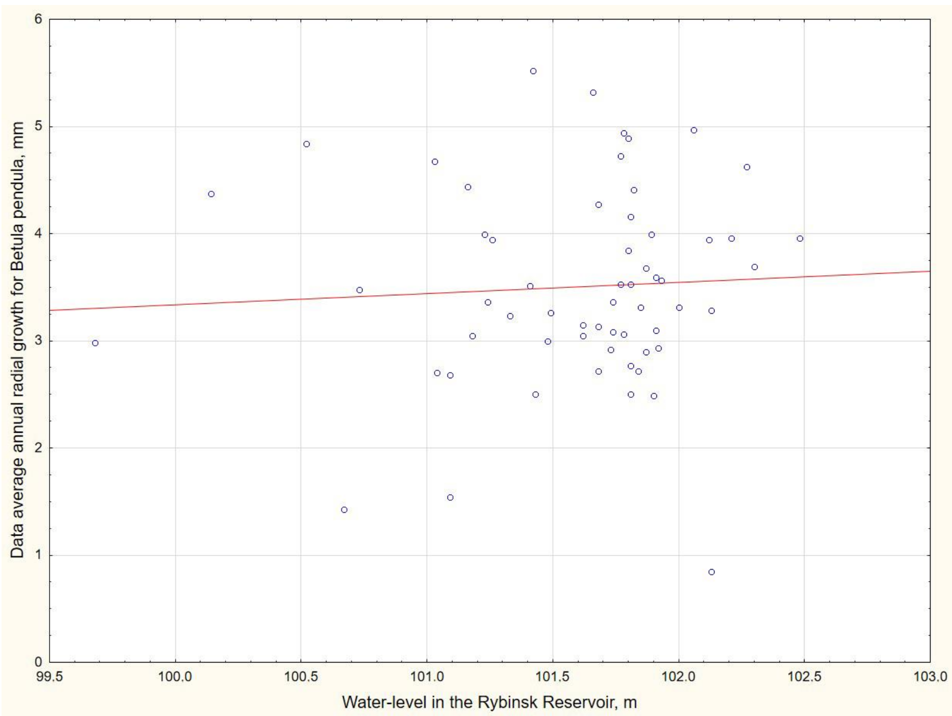
Sampling was carried out in the forest park, which borders on the coast of the Sheksna river, the level of which is regulated by the Rybinsk Reservoir. The water level is also dynamic throughout the year. It usually reaches its maximum marks at the end of

May and June; this is the time when plant growth processes are active. The maximum level can have an impact on improving the water supply of trees growing near the coast (Supplementary Materials: Table S7). Scatterplots are used to show the dependence between the maximum water level in the reservoir and the average annual radial growth of different tree species in the forest park of the Cherepovets city (Figure 3). The correlation coefficient (R) of Spearman was determined (Table 2). On the graphs, the values are located quite close to each other and move in a dense group. There are also significant outliers.

Since the water level in the Rybinsk Reservoir is regulated and the average annual values do not differ very much, we carried out the following analysis, for which the ring width values corresponding to years with extreme water level values in the reservoir during the growing season were left, and the values corresponding to the years with an average level (about 101.81 m a.s.l.) were excluded from the analysis. We compared the radial increment of trees with the water level only in those years when the minimum (≤100 m a.s.l.) and maximum (≥102 m a.s.l.) water levels in the reservoir were observed. Table 3 shows that a moderate direct dependence of radial increment on the water level in the reservoir in the case of extreme values is typical for *Quercus robur* (r = 0.56), *Tilia cordata* (r = 0.52) and *Betula pendula* (r = 0.26). Moderate feedback is observed in *Picea abies* and *Pinus sylvestris*. No correlation was found for *Ulmus glabra*.

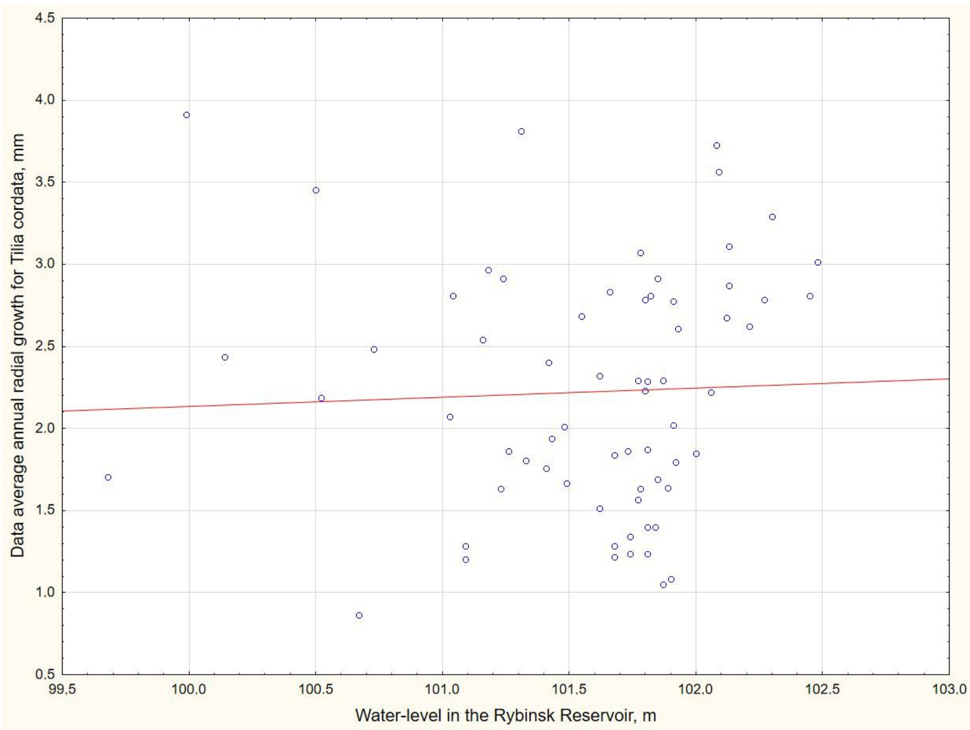
Table 2. Dependence of the average annual radial increment of various tree species on the maximum water level in the reservoir (Spearman's correlation coefficient).

Species	Spearman's Correlation Coefficient, R
Betula pendula	0.092
Ulmus glabra	0.011
Quercus robur	0.089
Tilia cordata	0.170
Picea abies	−0.136
Pinus sylvestris	−0.006



(**a**)

Figure 3. *Cont.*



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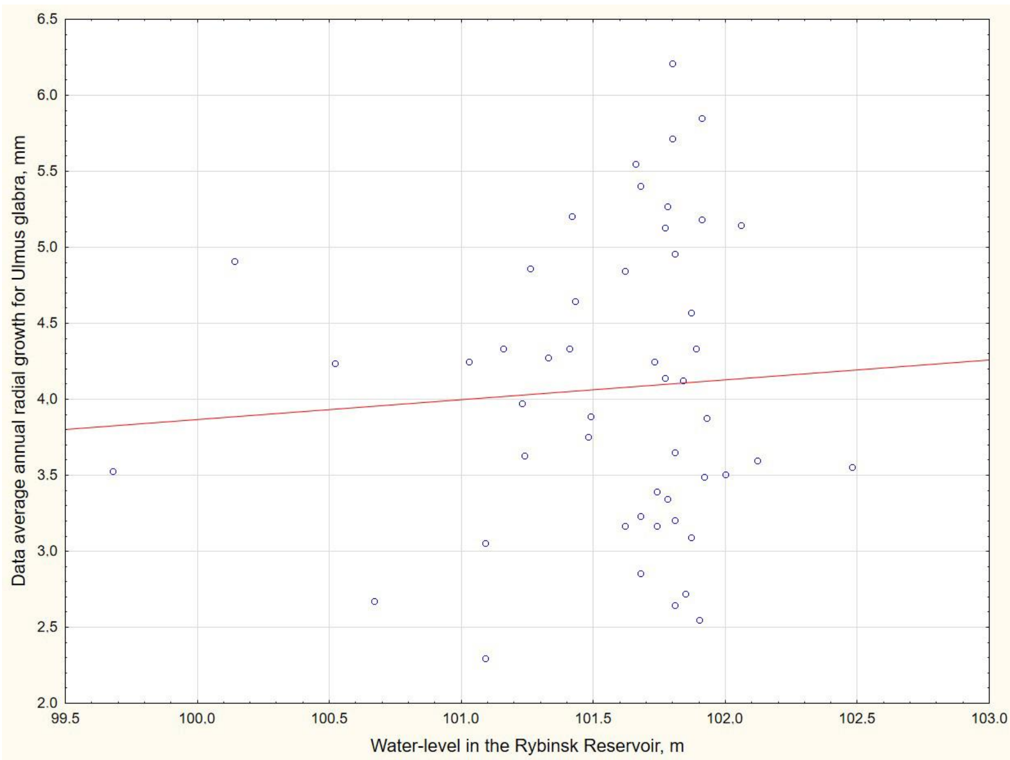

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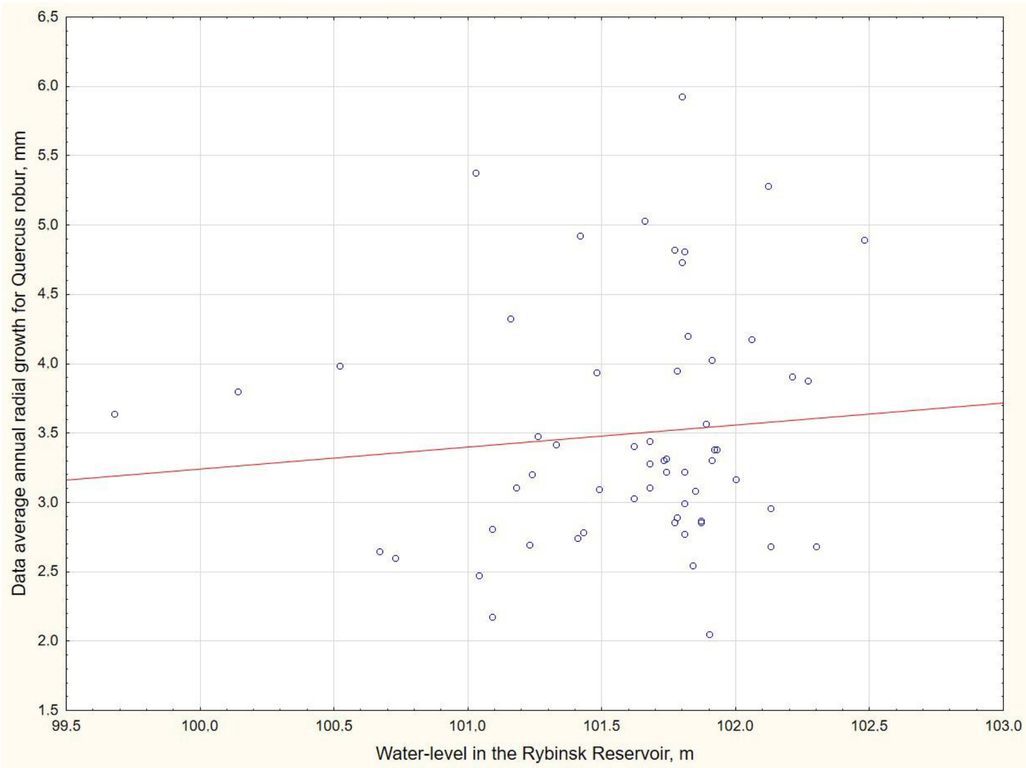

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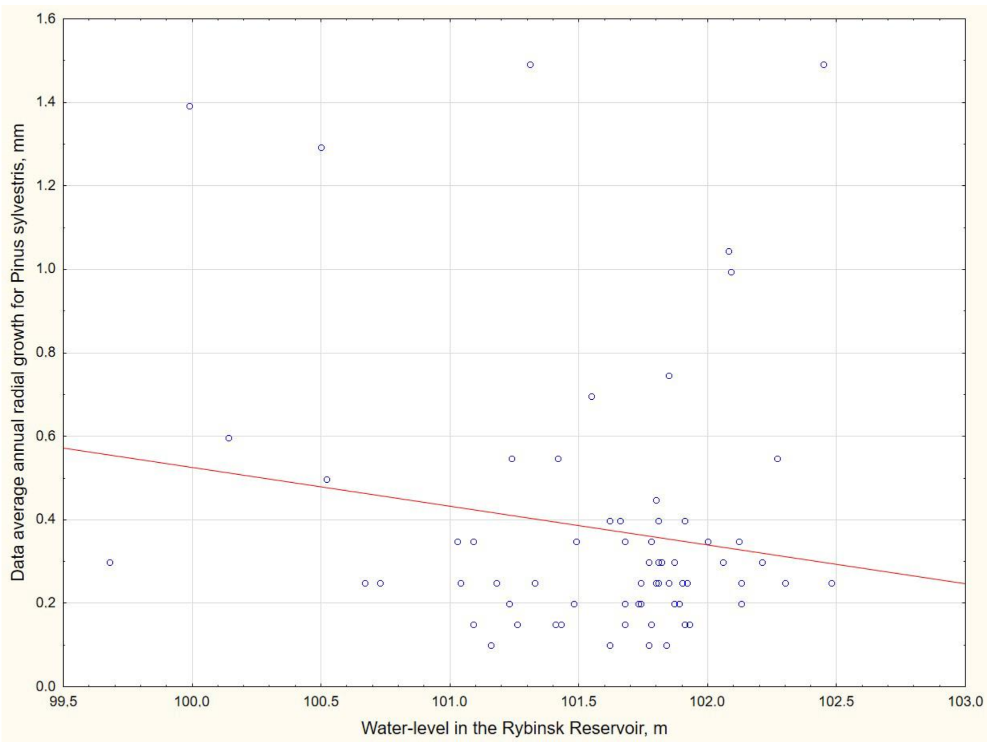

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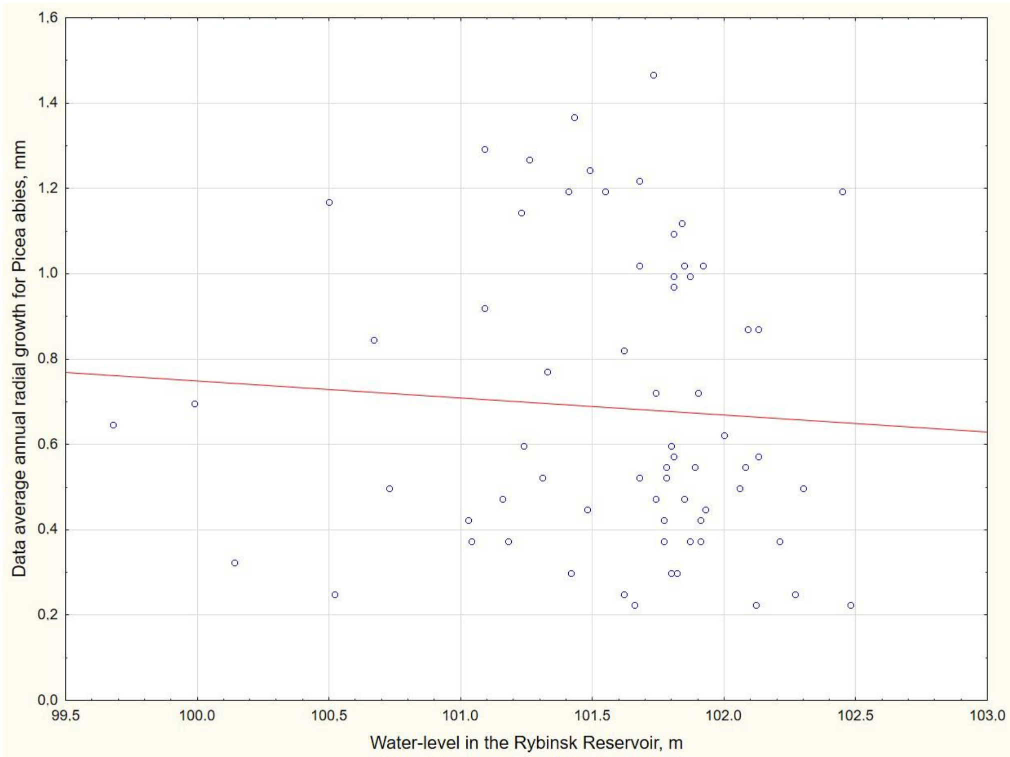


(**f**)

Figure 3. Graphs of the dependence of the average annual radial increment for different species of woody plants on the water level in the Rybinsk Reservoir: (**a**) *Betula pendula*; (**b**) *Tilia cordata*; (**c**) *Ulmus glabra*; (**d**) *Quercus robur*; (**e**) *Pinus sylvestris*; (**f**) *Picea abies*.

Table 3. Dependence of the average annual radial increment of different tree species in years with low and high water levels in the reservoir.

Species	Pearson's Correlation Coefficient, r	Student's *t*-Test
Betula pendula	0.26	0.77
Ulmus glabra	−0.06	0.99
Quercus robur	0.56	0.28
Tilia cordata	0.52	0.13
Picea abies	−0.40	0.34
Pinus sylvestris	−0.23	0.75

The established differences in the average annual ring widths in years with minimum and maximum water levels in tree species are not significant. To find out the impact of the reservoir creation, we analyzed the annual rings before and after filling the reservoir area. The filling of the reservoir area began in 1941 and was completed in 1947 [16]; therefore, for the analysis, the values of radial increments for 10 years before 1941 (1932–1941) and 10 years (1950–1959) after the filling of the reservoir were used (Table 4). Not all the model trees are of suitable age for such an analysis. Therefore, only old-growth tree cores were used: *Picea abies*, *Pinus sylvestris* and *Tilia cordata*. The radial increment of *Pinus sylvestris* after flooding increased by 0.29 mm, while the radial increment of *Picea abies* decreased significantly by 1.10 mm. It is possible that the rising water level did not have a significant effect on *Tilia cordata*.

Table 4. Average annual radial increment of park trees before and after flooding of the Rybinsk Reservoir.

Species	Average Radial Increment, mm		Student's *t*-Test
	Before the Flooding of the Reservoir	After the Reservoir Flooded	
Tilia cordata	3.33 ± 0.74	3.32 ± 0.42	0.723
Picea abies	1.91 ± 0.41	0.81 ± 0.29	0.000 *
Pinus sylvestris	0.62 ± 0.26	0.91 ± 0.53	0.207

* Statistically significant correlation.

According to the data presented in Table 5, the growth rates of different tree species are significantly correlated with each other. The highest similarity (at $p \leq 0.05$) is observed in increments of hardwoods with each other. *Pinus sylvestris* has a low similarity on the value of radial increment with deciduous trees, while *Picea abies* differs, having a moderate inverse correlation with respect to radial increments of other trees.

Table 5. Pair correlations (Spearman's correlation coefficient, R) between the average annual radial increments of various tree species.

Species	*Tilia cordata*	*Quercus robur*	*Ulmus glabra*	*Pinus sylvestris*	*Picea abies*
Betula pendula	0.48 *	0.64 *	0.72 *	0.27 *	−0.56 *
Tilia cordata	x	0.41 *	0.69 *	0.26 *	−0.53 *
Quercus robur		x	0.54 *	0.34 *	−0.56 *
Ulmus glabra			x	0.11	−0.45 *
Pinus sylvestris				x	−0.28 *

* Statistically significant correlation.

3.3. Dependence of the Radial Increment of Trees on Temperature

Unfortunately, reliable data on temperature changes during the year have been available only since 1955 (Supplementary Materials: Table S8). When analyzing the temperature data, it was revealed that the average temperature in May is 10.52 °C, and the range of fluctuations between monthly mean temperature values over the years does not exceed 9 °C. The average June temperature is 15.05 °C, and the range of average temperature fluctuations does not exceed 8 °C. The average July temperature is 17.38 °C. This month is the warmest, characterized by the highest average temperatures, sometimes above 23 degrees. The average temperature in August is 15.01 °C, which is similar to June.

To determine the effect of temperatures on the average annual radial increment of plants, the calculated growth indices of tree rings (ring width index, RWI) were used, comparing them in pairs with the temperatures of different months of the growing season of the corresponding year. We used simple (Pearson's) correlation (Table 6) and linear regression (Figure 4).

Table 6. Intercommunication between mean monthly temperature (period 1955–2015) and ring width index of woody plants (Pearson's correlation coefficient, r).

Month	*Picea abies*	*Pinus sylvestris*	*Tilia cordata*	*Betula pendula*	*Quercus robur*	*Ulmus glabra*
May, t °C	−0.30 *	−0.21	0.07	−0.18	−0.04	0.06
June, t °C	−0.15	0.01	0.12	0.04	−0.11	−0.26
July, t °C	−0.08	−0.25 *	0.18	0.01	−0.07	0.04
August, t °C	−0.09	−0.01	0.01	−0.12	−0.14	−0.06

* Statistically significant correlation.

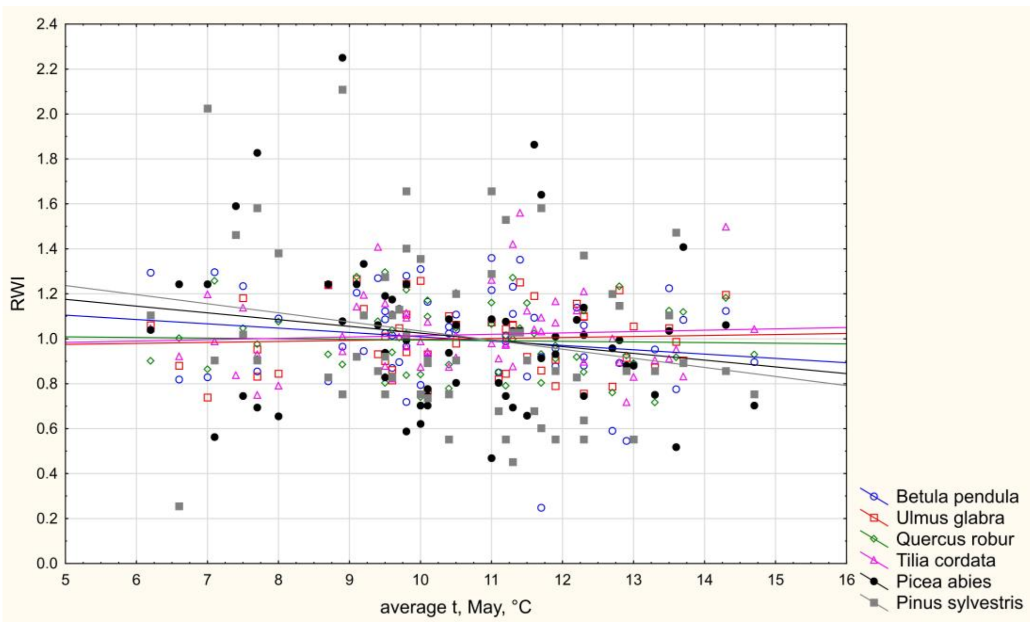
According to Table 6 and the graphs below (Figure 4a), the gymnosperms are the most sensitive to May temperatures: *Picea abies* (r = −0.30 at $p \leq 0.05$), *Pinus sylvestris* (r = −0.21) as well as *Betula pendula* (r = −0.18). The revealed dependence between the ring widths and the monthly mean temperature in May is inverse, that is, the higher the temperature, the lower the radial growth. It is moderate and statistically significant only for spruce. The inverse relationship between the radial increment and June temperature (Figure 4b, Table 6) is typical for *Ulmus glabra* (r = −0.26) and, to a lesser extent, for *Picea abies* (r = −0.15). *Pinus sylvestris* most significantly reacts to the July temperature (Figure 4c, Table 6), where a moderate feedback was revealed (r = −0.25 at $p \leq 0.05$). Only *Tilia cordata* has higher ring width indices at elevated summer temperatures in June and July (Figure 4b,c). The graph (Figure 4d) shows that the ring width index of various tree species reacts weakly to the August temperature.

In addition to the temperature influence on the individual months of the growing season on the average annual radial increment of model trees, the influence of the average temperature of the entire growing season was analyzed (Figure 5, Table 7). A weak dependence of the value of ring width index of *Picea abies* (r = −0.27, at $p \leq 0.05$) and *Pinus sylvestris* (r = −0.21) on the average temperature of the growing season was revealed. For other species (*Tília cordáta*, *Quercus robur*, *Betula pendula*, *Ulmus glabra*), no dependence was found.

Table 7. The dependence between the average temperature during the growing season of different years (period 1955–2015) and the ring width index.

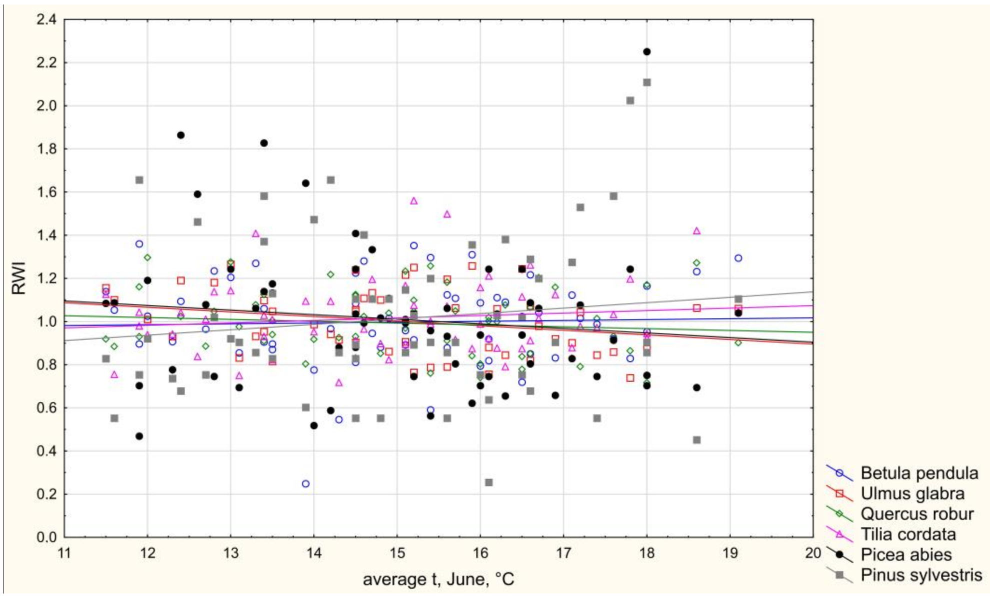
Species	Pearson's Correlation Coefficient, r
Betula pendula	−0.10
Ulmus glabra	−0.06
Quercus robur	−0.14
Tilia cordata	0.17
Picea abies	−0.27 *
Pinus sylvestris	−0.21

* Statistically significant correlation.

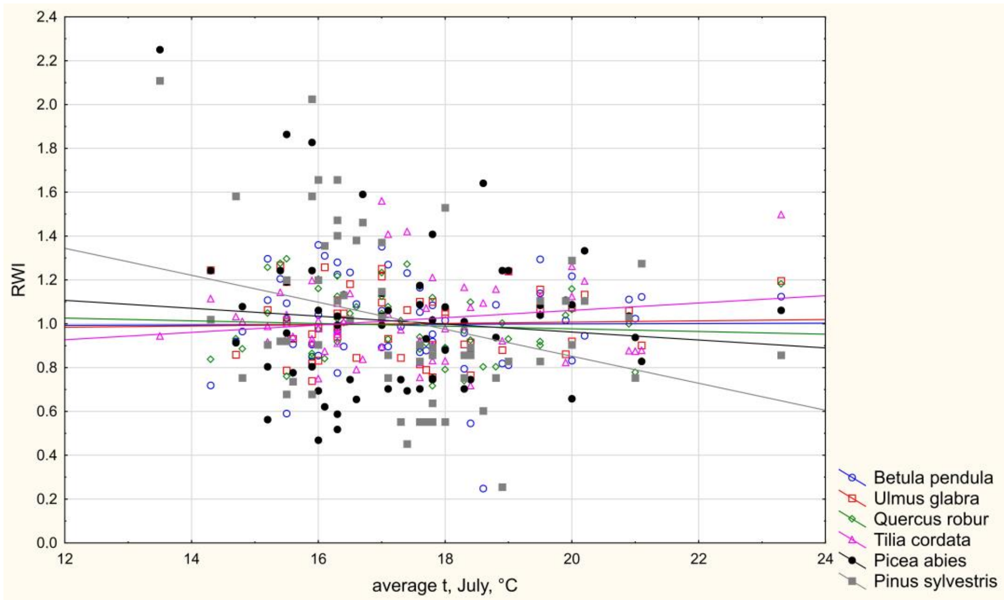


(**a**)

Figure 4. *Cont.*

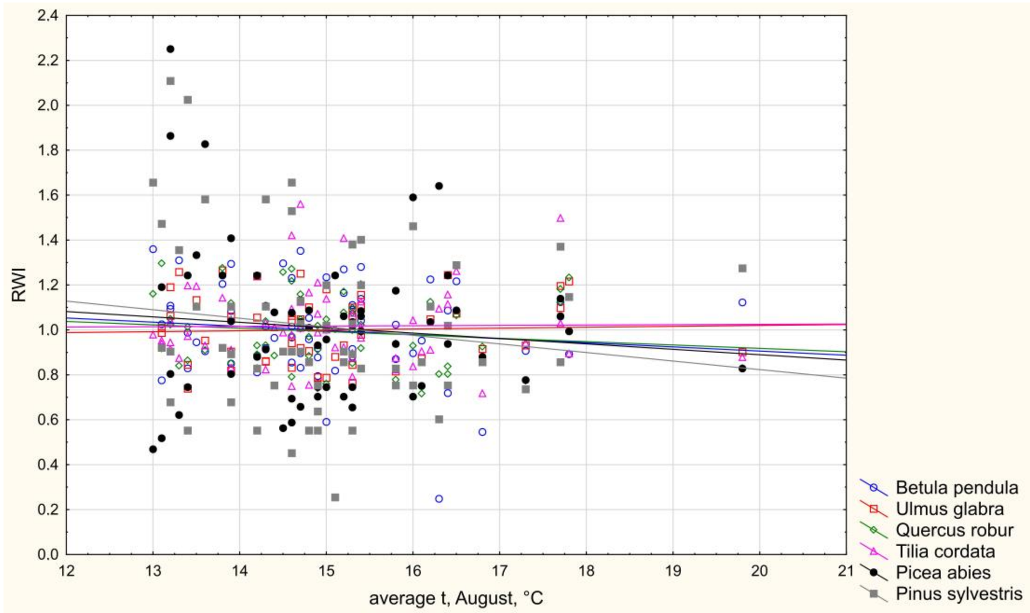


(**b**)



(**c**)

Figure 4. *Cont*.



(**d**)

Figure 4. Graphs of the dependence of ring width index (RWI) on monthly mean temperature, s: (**a**) May temperatures; (**b**) June temperatures; (**c**) July temperatures; (**d**) August temperatures.

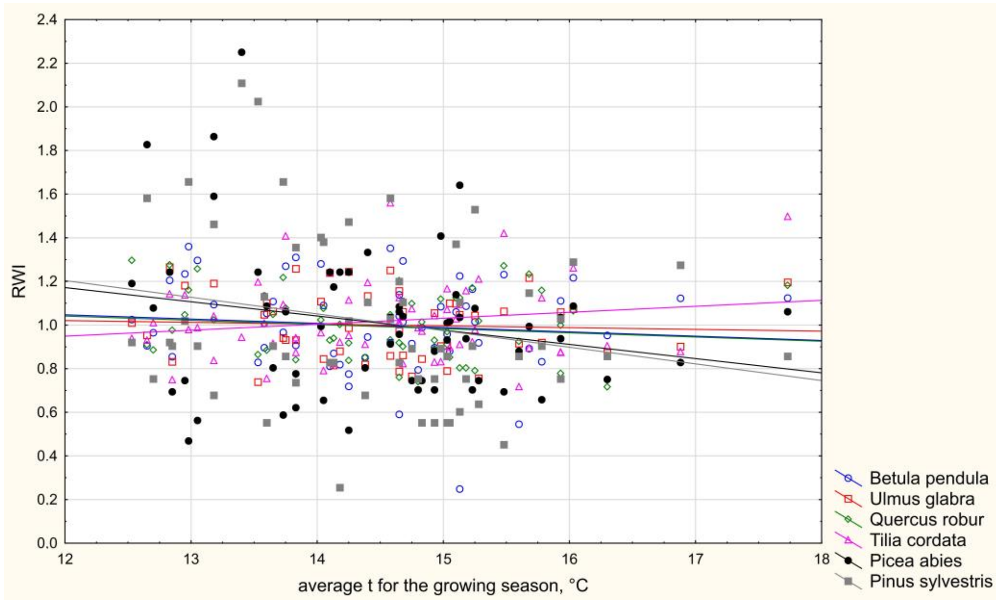


Figure 5. The value of the ring width index (RWI) of trees depending on the temperature during the growing season.

4. Discussion

The main donor of constructive metabolism necessary for the processes of growth and development are photosynthetic leaves. The tree has several acceptor—or attracting—zones: the apical shoot meristem, the cambium meristem and the tips of the roots. These zones constitute the main centers between which the bulk of mobile assimilates are distributed [24]. A decrease in the photosynthetic surface under the influence of natural and anthropogenic factors causes a decrease in the growth of a tree in height and diameter, which can be characterized as a stressful state. Stress causes a metabolic restructuring. The specificity of woody plants is that protective biochemical reactions are formed under the influence of repeated stresses for a long time. Primary morphological signs of weakening can be detected by studying the development of the growth ring of wood [25]. Thus, the radial increment objectively reflects the quality of the assimilation apparatus of a woody plant. A similar dependence between crown biomass and trunk diameter was found for 64 woody plant species growing in China [26]. Radial growth depends on many factors (temperature, precipitation, wind, air composition, etc.), which manifest themselves in different combinations. The influence of climate factors on the growth rate depends on the tree species, origin, age, soil typological conditions, geographical location, and features of the structure of plantations. Erteld W. et al. indicate that in Central Europe, the annual fluctuations of the current increase depend mainly on the amount of precipitation, while in Scandinavia, it depends on the temperature regimen [27]. Zanedris A. established that in the territory of Latvia, the width of the annual rings depends on the geographical distribution of forest stands. It has been established in Denmark that the amount of precipitation in May–July of the current year has a decisive influence on the annual growth of beech and spruce, while summer air temperatures have a decisive influence on the annual growth of beech and winter temperatures have a decisive influence on the growth of alder and pine. The influence of various factors on the magnitude of the radial increase is so diverse that opinions on this issue differ greatly. Molchanov A.A. believes that the influence of solar activity is of paramount importance, and Fiedler F., Wenk G. express the same for air temperature and precipitation [28].

Based on the foregoing, the creation of an artificial large reservoir and an assessment of the impact of the changes that have occurred can answer the question of the influence of such a factor as humidity on the radial increment of trees and on the general condition of plants. Data on the water level in the Rybinsk Reservoir were obtained after the moment of flooding (1949) until now. During its existence, the minimum and maximum values of the high water level were recorded. In 1966, the water level reached 102.48 m (a.s.l.), which is above the normal limit (101.81 m). High values were also observed in 1951, 1953, 1955, 1957, 1958, 1959, 1961, 1962, 1970, 1979 and 1995. The minimum value of the water level during the growing season was recorded in 1996, and it dropped to 99.68m above the Baltic Sea level. Additionally, low values of the maximum level (less than 101 m) were observed in 1952, 1954, 1960, 1972, 1973, 1996, 2003 and 2014 [19,29]. For the most part, the changes are not very significant, but even these can be enough to affect the water availability for trees growing on the shore. The analysis of the radial increment of the studied plants is, on average, typical for the studied species [30–34]; therefore, in the study area, they are in optimal conditions. When studying the dependence of the radial increment of trees in the park under study on the water level in the Rybinsk Reservoir, it was found that the average annual radial increment depends on the value of the maximum (or high) water level in the reservoir, with a positive correlation for deciduous trees, and a negative one for conifers. After 2011, a decline in radial increment begins, which may be associated with the age-related dynamics (attenuation) of growth processes [35,36]. A similar trend in growth processes was also noted by us for *Ulmus glabra* and *Tilia cordata*. These tree species are also characterized by a decrease in radial increment upon reaching a certain age [32,33]. For *Tilia cordata*, it was also shown that the filling of the reservoir area did not correlate in any way with its growth characteristics. For the species *Quercus robur*, in contrast to other analyzed deciduous species, slight fluctuations in values of the ring width were noted. Fluctuations are noted, but they are not associated with changes in the water level in the reservoir. Peaks and recessions are replaced on average in 1–3 years. A similar trend was noted by other researchers. In studies related to the growth of oak on substrates with high humidity in the north–east of Germany, it was shown that neither the change in humidity nor age significantly affects the radial increment [34].

The gymnosperms studied by us were characterized by changes in the reaction of radial growth (decreased significantly), which was clearly manifested only in *Picea abies*, on the change in hydrological conditions in connection with the creation of the Rybinsk Reservoir. The absence of significant changes for *Pinus sylvestris* indicates that other factors determine the magnitude of the radial increment. The lower average growth rate of pine compared to spruce can be explained by the fact that pine is a light-loving breed and when shaded, the productivity of the photosynthetic apparatus decreases, which increases with the development of neighboring trees and is reflected in radial growth decrease [37].

The process of plant growth essentially depends on the state of the external environment determined by climatic conditions, including temperature. The temperature during the growing season has both a direct and indirect effect on the growth processes of plants. To determine the effect of temperature on the annual ring width of woody plants, we used average temperature data taken throughout several months during the active vegetation of plants (from May to August) along with the average temperature for the specified period as a whole. In general, the average annual radial growth of trees is not always distinct, but, nevertheless, decreases under the influence of higher temperatures [38]. With regard to the dependence between radial increment and temperature, it is worth explaining why the higher the temperature, the smaller the radial growth. This is due to an increase in plant transpiration, as the temperature rises, the evaporation of water from the surface of the leaves occurs faster. At the same time, the efficiency of photosynthesis begins to fall, since water is the source of electrons in the photosynthesis of green plants, then non-cyclic photophosphorylation, during which reduced ferredoxin, ATP and O_2 is generated, slows down and is not very efficient. Additionally, due to the decrease in the efficiency of photosynthesis, the radial increment of the plant also slows down [39]. The plants studied by us show an inverse dependence of ring width index on temperature in some months. The gymnosperms *Picea abies* (r = –0.30 at $p \leq 0.05$) and *Pinus sylvestris* (r = -0.21) especially react to the May temperature, while *Pinus sylvestris* reacts to the July temperature (r = -0.25 at $p \leq 0.05$). An inverse dependence of ring width index on temperature was also noted for hardwoods: *Ulmus glabra* on June temperature (r = -0.26) and *Betula pendula* on May temperature (r = -0.18). An inverse dependence was noted for the birches of the Baltic region. However, even the authors point out that this phenomenon is not typical [36]. The weak dependence we found is statistically significant only for coniferous trees. This can be explained by the fact that the conditions of the summer period are the least favorable for the productivity of photosynthesis in coniferous species: plants do not tolerate high temperatures, soil and atmospheric drought [40]. Therefore, in pine and spruce, the sensitivity to higher temperatures is higher than in other species studied. They are recommended for use in dendrochronological studies to identify climatic cycles [41]. For example, for Siberia, phases of increased radial increment of Scotch pine were identified: during the '50s to the '80s of the 19th century and from the end of the 19th century to the '40s of the 20th century. Decline phases were observed from the 1800s to the 1850s, from the 1880s to the end of the 19th century, and from the 1940s to the 1970s. The sharp increase in the growth of *Pinus sylvestris* from the 1890s to the 1930s coincides with the "warming" period of the Arctic. According to instrumental observations, although the onset of warming is attributed to the years 1918 to the 1920s, the response of trees to warming and a general improvement in forest conditions was observed almost three decades earlier [42]. When studying the spruce forests of the southern taiga, it was found that the radial increment is essentially independent of climatic and environmental factors [43]. This is also confirmed by our data. The spruce in the study area is distinguished by the peculiarities of the dynamics of radial growth, demonstrating a moderate inverse correlation with respect to the radial increment of other trees.

5. Conclusions

As a result of the study, the largest average annual radial increment was found in *Ulmus glabra* (4.07 mm) and slightly less in *Betula pendula* (3.50 mm) and *Quercus robur* (3.50 mm). *Tilia cordata* has the smallest radial growth among the selected angiosperms (2.40 mm). In gymnosperms, it is approximately the same (*Picea abies*—1.52 mm, *Pinus sylvestris*—1.25 mm). The average annual radial increase does not correlate with factor annual water level in the Rybinsk Reservoir. Years with minimum and maximum reservoir filling significantly affect the radial increment of *Quercus robur* (r = 0.56) and *Tilia cordata* (r = 0.52). An analysis of the effect of filling the reservoir area showed that the radial increment was significantly reduced for *Picea abies* by 1.10 mm (p = 0.00). An inverse dependence of ring width index on temperature in some months was revealed. This is especially true for the gymnosperms *Picea abies* (r = −0.30 at $p \leq 0.05$), *Pinus sylvestris* (r = −0.21) for May temperature and *Pinus sylvestris* for July temperature (r = −0.25 at $p \leq 0.05$). An inverse dependence of ring width index on temperature was also noted for hardwoods: *Ulmus glabra* on June temperature (r = −0.26) and *Betula pendula* on May temperature (r = −0.18). The dependence of the ring width index for the other studied species on the temperature of different months of the growing season has not been established. The annual radial increment of deciduous trees growing in the same area shows great similarity, weakly correlating with individual factors. At the same time, the data for *Picea abies* are unusual, demonstrating a moderate inverse correlation with respect to the radial increments of other trees. The results are not conclusive and more research will be performed to find a significant dependence between the ring widths and of the water level and/or the temperature at this site. Additionally, we are planning a more detailed study of the impact of the creation of the Rybinsk Reservoir for other species of woody plants in the protected area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/physiologia3020024/s1, Table S1: Year-long dynamics of the radial increment of *Betula pendula*; Table S2: Year-long dynamics of the radial increment of *Ulmus glabra*; Table S3: Year-long dynamics of the radial increment of *Quercus robur;* Table S4: Year-long dynamics of the radial increment of *Tilia cordata*; Table S5: Year-long dynamics of the radial increment of *Picea abies*; Table S6: Year-long dynamics of the radial increment of *Pinus sylvestris*; Table S7: Year-long dynamics of the maximum water level in the Rybinsk Reservoir; Table S8: Indicators of the monthly mean temperature by months.

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