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RADIAL INCREMENT OF BEECH (*FAGUS SYLVATICA* L.) IN THE UKRAINIAN CARPATHIANS

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Abstract

The objects of the study were pure and mixed middle-aged beech stands that grow on humid fertile hornbeam-beech forest type conditions on the southern and northern slopes at the altitude of 550–600 m a.s.l. We found a correlative relationship between beech radial increment and climate indices. Average radial increment of beech varies within the limits of 1.71 to 2.41 mm depending on tree composition with the maximum in the mixed stands. The share of early wood and late wood of the annual ring of beech fluctuates within the limits of 83–88 % and 12–17 %, respectively. In the mixed stands that grow on the northern slopes, annual radial increment of beech is maximal. In the mixed and pure forest stands average radial increment of beech on the northern side of the slope compared to the southern side is higher. It has been found that radial increment of the south-facing side of beech trees growing on the southern mountain slope and the north-facing side of them growing on the northern mountain slope is higher in comparison to the opposite side of the trees. Radial increment extremes in many cases are identical with climate indices extremes. In the years of the most intensive solar activity beech radial increment is minimal. Relationship between beech increment and climate indices is stronger in the pure beech stands than it is in the mixed stands. Relationship between beech increment and air temperature as well as precipitation becomes weak in the mixed stands and it is moderate in the pure stands. Beech increment correlates greatly with humidity deficiency, air temperature and precipitation, which is especially marked during the period from 2003 to 2013. Beech wood radial increment correlates closely with air humidity and humidity deficiency both in the pure and in the mixed stands.

Key words: climate indices, correlations, early wood, forest ecology, late wood, slope aspect.

Introduction

The beech (*Fagus sylvatica* L.) is a valuable and typical species of the Carpathian region and in other mountain ranges in Europe. This species demands air humidity, soil moisture, as well as the richness of the soil. In the Ukrainian Carpathians it grows within 250–1450 m a.s.l. Beech is the forest-forming species in the fertile and fairly fertile site type. It is one of the most shade-tolerant, soil-improving and wind-resistant tree species (Hensiruk 2002).

The beech forests of the Ukrainian Carpathians perform important protective, environmental and other ecological functions. The most of the beech forest types are characterized by the highest classes of water regulation (Polyakov 2003).

Beech is characterized by high productivity, and its wood is widely used in various industries. It regenerates in a natural way and that is why the majority of beech forests in the Carpathian conditions are natural and very often uneven-aged.

For the assessment of the forest ecosystems state, most researchers use dendrochronological and dendroclimatic methods based on the study of the radial increment of individual trees and forest stands (Schweingruber 1996, Hughes 2002, Matveev 2003, Speer 2009, Sheppard 2010). Radial increment is the most universal and comprehensive measure of forest growth throughout its life span, and therefore provides an opportunity to identify their reactions to the impact of external factors (Mölder and Leuschner 2014, Augustaitis et al. 2015, Remeš et al. 2015, Bosela et al. 2018, Šimůnek et al. 2019). The studying of radial increment dynamics of the mountain beech forests which grow in climate change conditions (Mazepa and Shyshkanynets 2013) is important to assess condition and productivity of stands and develop their predictive models.

Annual growth of beech is most significantly influenced by the climate and atmospheric air pollution. Correspondent to a significant warming trend from 1990–2010, average beech growth declined in the mixed beech-fir forest sites across Continental Europe, including Bosnia and Herzegovina, Germany, Italy, Romania and Slovakia (Bosela et al. 2018). The studies of Augustaitis et al. (2015) showed that frost in winter months and heat in June, along with drought in the vegetation period, limited beech tree growth outside its natural distribution range in northeast Europe (Poland, Lithuania and Latvia). Higher air concentration of surface ozone and sulphur deposition level reinforced the negative effect of the detected key meteorological variables on beech growth, while higher air concentrations and deposition of nitrate had a positive effect. These factors explained about 50 % of the total variation in increment indices of beech trees at sites on the north-eastern edge of their range. In the eastern Krkonoše Mountains, the Czech Republic the growth development of beech stands was significantly affected by air pollution load in 1977–1989, and increasingly frequent climate extremes in recent years (since 2010) (Šimůnek et al. 2019). The positive influence of temperatures on beech increments was recorded in winter, early spring, and especially in July and August of the current year. Conversely, precipitation in the previous year had higher impact on radial increment, with prevailing negative correlation. The plots were negatively affected by the decrease in sum of precipitation in February and March, but it was the temperature that influenced the beech increment most significantly.

The aim of the research is studying the characteristics of the radial wood increment of beech stands depending on the main climate indices on the slopes of different aspects in the mountain forests of the Transcarpathian region of the Ukrainian Carpathians.

Material and Methods

We selected beech stands of the Nyzhni Vorota forest district in the Volovets State Forestry Enterprise in order to study the characteristics of beech stands radial increment and the influence of external environmental factors. On each sample area in the biogroups of 10 trees at the height of 1.3 m by means of Pressler drill core samples of wood were selected and 20 cores in the North-South directions were taken for each biogroup (Mazepa 2009). The width of early and late wood was measured by means of the microscope MBC-1 with an accuracy of 0.1 mm.

We compared absolute and relative growth values and carried out dendrochronological series analysis over the past 24 years depending on climate factors in order to evaluate radial increment of the forest stands.

Along with the amounts of precipitation and average temperature for the calendar year and the vegetation period a number of complex meteorological (climatic) indices (climate humidity, hydrothermal coefficient (0_1), complex hydrothermal index (0_3), complex hydrothermal coefficient (0_2), the coefficient characterizing the supply of moisture (*k*) were tested to establish correlations. Climate humidity was determined by the formula (1) of Vorobiov (1967).

$$W = \frac{R}{T} - 0.0286 \times T, \tag{1}$$

where: *R* is the amount of precipitation for the months with positive monthly average temperatures, *T* is a sum of positive monthly temperatures.

Hydrothermal coefficient O_1, O_2, O_3 were determined by means of formula of Bitvinskas (1974). Hydrothermal coefficient O_1 was determined by the formula (2).

$$O_1 = \frac{t_0 \times 100}{V_0}, \tag{2}$$

where: t_0 – average air temperature for the hydrological year (the period from the previous October to the current September); V_0 – precipitation (mm) for the hydrological year.

Complex hydrothermal coefficient of O_2 was determined by the formula (3).

$$O_2 = \frac{t_0}{V_0 \times k}, \tag{3}$$

where: t_0 and V_0 have the same meaning as in the formula (2), and *k* is a coefficient characterizing the supply of moisture and is determined by the ratio of the amount of precipitation during four hydrological years to average perennial rainfall for the same period – by formula (4).

$$k = \frac{V_3 + V_2 + V_1 + V_0}{4V_{avr}}, \tag{4}$$

where: V_0 – precipitation for the hydrological year, V_1 – precipitation in the previous hydrological year, etc.; V_{avr} – rainfall of the hydrological year (long run average).

Integrated hydrological indicator O_3 reflects the influence of climatic factors on the growth of stands in four years. It is determined by the formula (5).

$$O_3 = (V_3+2V_2+3V_1+4V_0)\cdot(t_3+2t_2+ +3t_1+4t_0)\cdot t_0 /10\times10\times100, \tag{5}$$

where: *V* is precipitation for a hydrological year, *t* – average annual temperature over the same period, indexes 0, 1, 2, 3 – years (current, previous, etc.).

Statistical processing of research results was conducted by methods of mathematical statistics (Dospekhov 1985) using MS Excell and Statistica 6.0 software.

For the analysis of meteorological parameters in the region of the mountain beech forests Nyzhni Vorota weather station data for 1992–2012 years were used. The meteorological station is located in the district of the upper reaches of the Latorytsya river, at altitude of 500 m a.s.l. and at a distance of 4.5 km from our sample plots.

The results of the analysis of climate indices (Table 1) show that in the study region magnitude of the major climate indices tends to increase.

Table 1. Dynamics of the main climate indices.

Climate indices	Period, years			Long-term average 1949–2000
	1992–2001	2002–2012	1992–2012	
Precipitation (annual average), mm	1128	1146	1138	1046
Precipitation during the vegetation period, mm	725	742	734	693
Average annual temperature, °C	7.1	7.6	7.3	6.6
Average temperature during the growing season, °C	12.8	13.3	13.0	12.2
Average humidity, %	78.5	79.6	79.1	-
Average humidity during the vegetation period, %	76.1	77.3	76.7	-
Average annual humidity deficit, mb	3.3	3.2	3.2	-
Average humidity deficit during the growing season, mb	4.7	4.6	4.6	-

Note: ‘-‘ means data is absent.

Climate indices changed most intensively in the period 2002–2012. Compared to the standard climate norm, average monthly air temperature during the growing season increased from 12.2 °C to 13.3 °C, and average annual temperature – from 6.6 °C to 7.6 °C. The annual rainfall increased from 1046 mm to 1146 mm. The dry years with the maximum annual average air temperature and the minimum rainfall during the growing season were: 2000, 2007, 2012.

To study the characteristics of radial increment of the beech stands and the impact of external environmental factors we selected forest stands of the Nyzhni Vorota forest district in the Volovets State Forestry Enterprise. Silvicultural description of the forest stands, where sample plots (SP) were laid is shown in Table 2. As can be seen from the stated in the table data, the middle-aged pure and mixed beech stands grow under conditions of humid hornbeam fertile beech forest type on the slopes of southern and northern aspect at the altitude of 550–600 m a.s.l.

Table 2. Silvicultural inventory indices of test sites.

No sample plot	Tree composition	Age, years	Site class	Aspect slope	Altitude, m
1	60B30Hb10Sp	44	II	SW-20□	600
2	50B48Hb1Br1As	49	II	NE-20□	600
3	98B2Hb	57	Ia	S-25□	550
4	98B2Hb	54	I	NE-20□	550

Note: B – beech, Hb – hornbeam, Sp – spruce, Br – birch, As – aspen.

Results and Discussion

The comparison of statistical indices of the dendrochronological series of radial increment in the fertile beech forest type on their composition and direction of trees according to the four cardinal points of the world made it possible to note similarity in the value of average annual increment for the same composition of the forest trees (Table 3). Depending on tree composition average increment changes in the range of 1.71–2.41 mm and reaches the highest value in the mixed stands (SP 1 and 2). Radial increment of the studied beech stands, depending on slope aspect also differs. Thus, average radial increment of the southern side of a beech tree which grows on the southern mountain slope and the northern side of a tree on the northern mountain slope is higher in comparison with the opposite side of it.

It should be noted that in the mixed and pure forest stands average increment on the northern side is higher compared to the southern side of the slope, but in the mixed stands, this difference is minimal. In the mixed stands the variability of the annual increment is higher, as it is evidenced by the standard deviation and variation coefficient (Table 3). Negative excess for series of the forest stands increment on the southern mountain slopes testifies to their smoothness in comparison with the ranks on the northern slopes.

Table 3. Statistical characteristics of radial increment series of the middle-aged beech forest stands (1989–2012).

No SP	Tree composition	Aspect slope	Tree side	Increment, mm			Standard deviation of selection	Excess	The coefficient of variation
				average	maximum	minimum			
1	60B30Hb10Sp	SW-20°	N	2.29	2.91	1.63	0.37	-0.89	16.4
			S	2.53	3.26	2.08	0.36	-0.61	14.2
			average	2.41	3.08	1.89	0.35	-0.87	14.7
2	50B48Hb1Br1As	NE-20°	N	2.50	3.62	1.59	0.46	0.19	18.4
			S	2.34	3.70	1.54	0.48	1.16	20.7
			average	2.42	3.66	1.56	0.47	0.65	19.3
3	98B2Hb	S-25°	N	1.69	2.29	1.28	0.26	0.33	15.1
			S	1.73	2.2	1.25	0.29	-1.06	16.7
			average	1.71	2.16	1.27	0.24	-0.53	14.3
4	98B2Hb	NE-20°	N	1.92	2.58	1.29	0.30	-0.26	15.6
			S	1.82	2.41	1.25	0.30	-0.15	16.5
			average	1.87	2.34	1.27	0.26	0.14	13.9

Growth curves in the pure and mixed stands vary synchronously (Fig. 1). In the pure stands natural reduction of radial increment of beech can be traced (SP 3 and 4). We observed reduction of radial increment in the mixed stands prior to 2000 year (SP 1 and 2), and then a sharp increase of it, in our opinion, due to the intensive thinning. Years with peak growth of beech in most cases, coincide with the years of climatic extremes. Thus, the minimum increment of beech was observed in 2000 and 2007, and the maximum in 1998, 2004, 2005 and 2010 years. Accordingly, in 2000 and 2007 it was recorded maximum solar activity (119 units in Wolf number) and the maximum average air temperature (8.4 °C). In 1998 the maximum amount of precipitation (1521 mm) and minimal humidity deficit (2.6 mb) were registered. The humidity deficit describes the conditions of heat transfer through the evaporation of moisture from any surface.

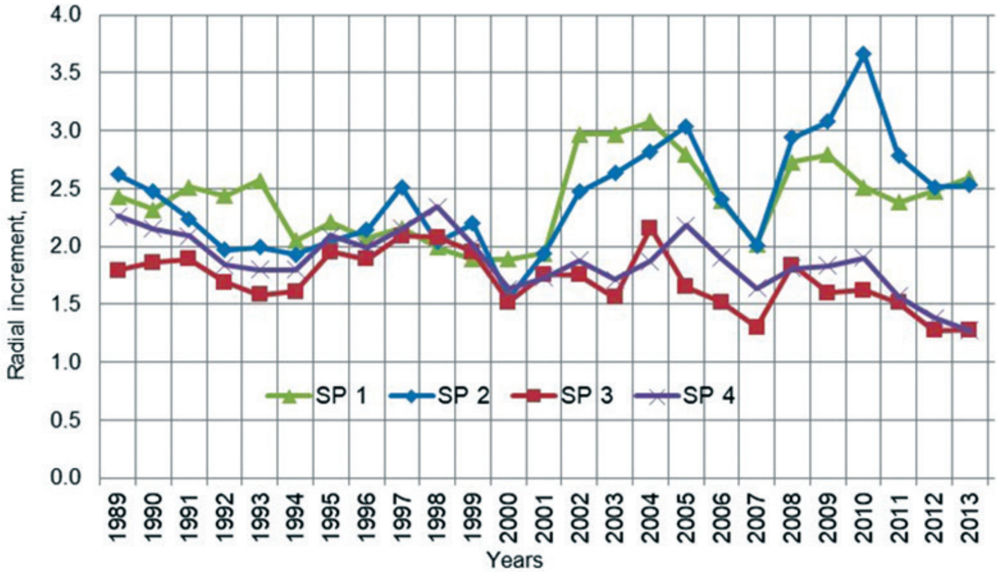

Fig. 1. Dynamics of radial increment of beech on the slopes of different aspect.

As it was shown by our studies (Shyshkanynets and Mazepa 2014), the percentage of early and late wood in the beech annual rings varies in the range of 83–88 % and 12–17 %, respectively.

The formation of early and late wood of beech is affected by climate, the influence of which on the northern slopes is more effective than on the southern slopes (Table 4).

Table 4. The correlation coefficients of early and late wood of beech, climate indices and Wolf numbers.

Indices	Aspect			
	SW-20°		NE-20°	
	Early wood	Late wood	Early wood	Late wood
The amount of precipitation (mm) for: - calendar year	-0.09	-0.05	0.28	0.15
- the vegetation period	0.05	-0.02	**0.34**	0.16
- hydrological year	0.005	0.12	**0.41**	0.27
- May	-0.09	0.1	**0.51**	**0.39**
-June	-0.05	0.16	0.11	0.16
- July	-0.01	-0.26	0.24	0.02
Temperature (°C): - calendar year	0.02	0.12	-0.13	0.32
- the vegetation period	0.03	0.36	-0.19	0.32
- hydrological year	-0.16	0.08	-0.16	0.07
- May	0.25	0.15	0.05	0.07
- June	-0.02	0.04	-0.02	0.24
- July	0.09	**0.48**	0.0	0.4
Air humidity (%) for: - calendar year	-0.11	0.23	0.23	**0.44**

Indices	Aspect			
	SW-20°		NE-20°	
	Early wood	Late wood	Early wood	Late wood
- the vegetation period	-0.05	0.26	**0.41**	**0.43**
- hydrological year	-0.12	0.23	0.22	**0.47**
- May	0.1	0.31	**0.47**	**0.44**
- June	-0.22	0.15	0.2	0.29
- July	0.07	0.04	**0.39**	0.24
Humidity deficit (mb): - calendar year	0.09	-0.07	**-0.40**	-0.27
- the vegetation period	0.06	-0.06	**-0.43**	-0.26
- hydrological year	-0.01	-0.11	**-0.46**	**-0.36**
- May	0.09	-0.1	-0.30	-0.27
- June	0.1	-0.19	-0.24	-0.17
- July	-0.07	0.11	**-0.35**	-0.07
Integrated climate indices: - *W*	-0.08	-0.22	0.12	-0.09
-*k*	0.09	0.28	0.09	0.31
-O_1	-0.08	-0.02	**-0.42**	-0.15
-O_2	-0.06	-0.06	**-0.40**	-0.30
Wolf numbers	-0.04	0.06	-0.13	-0.30

Note: the numbers in bold indicate a reliable correlation at a 95% level of significance.

Correlation analysis of the main climate indices and beech increment showed that the largest number of moderate and significant correlation is formed in the pure beech stands on the southern and north-eastern slopes (Table 5). Relationship between beech increment and climate indices in the mixed beech stands on the north-eastern slope is somewhat lower compared to the pure beech stands, but on the south-western slope such dependence is not visible.

Table 5. The correlation coefficients of the average radial increment of beech, climate indices and the Wolf numbers (1992–2013 years).

Indices	Aspect (No SP)			
	SW (1)	S (3)	NE (2)	NE (4)
The amount of precipitation (mm) for: - calendar year	-0.09	**0.45**	0.27	**0.39**
- the vegetation period	0.0004	**0.53**	0.28	**0.50**
- hydrological year	0.009	**0.40**	**0.38**	**0.37**
- May	-0.04	0.28	**0.50**	0.29
- June	-0.002	0.16	0.19	0.19
- July	-0.06	**0.44**	0.12	0.18
Temperature (°C): - calendar year	0.007	**-0.58**	0.09	**-0.63**
- the vegetation period	-0.06	-0.33	-0.008	-0.17
- hydrological year	-0.18	**-0.49**	-0.01	**-0.44**
- May	0.2	**-0.50**	0.015	**-0.41**

Indices	Aspect (No SP)			
	SW (1)	S (3)	NE (2)	NE (4)
- June	-0.03	**-0.34**	0.11	**-0.39**
- July	0.13	-0.29	0.22	-0.19
Air humidity (%) for: - calendar year	-0.04	0.17	**0.43**	**0.33**
- the vegetation period	-0.04	**0.50**	0.28	**0.64**
- hydrological year	-0.02	0.06	**0.44**	0.24
- May	0.18	0.24	**0.54**	0.29
- June	-0.12	0.11	0.33	0.21
-July	0.07	0.25	0.32	0.14
Humidity deficit (mb): - calendar year	0.01	**-0.61**	**-0.38**	**-0.64**
- the vegetation period	-0.06	**-0.52**	**-0.41**	**-0.46**
- hydrological year	-0.11	**-0.64**	**-0.46**	**-0.67**
- May	-0.0002	**-0.45**	**-0.36**	**-0.44**
- June	-0.002	-0.28	-0.29	**-0.35**
- July	-0.08	**-0.37**	-0.23	-0.23
Integrated climate indices: - *W*	-0.15	**0.50**	0.07	**0.43**
- *k*	0.04	**-0.40**	0.18	**-0.50**
- O_1	-0.11	**-0.62**	-0.28	**-0.57**
- O_2	0.06	**-0.44**	-0.34	**-0.35**
Wolf number	-0.11	0.13	-0.32	0.18

Note: the numbers in bold indicate a reliable correlation at a 95% level of significance.

Together with humidity deficit, air humidity, air temperature and precipitation radial increment of beech wood forms the greatest number of significant correlations. Integrated climate indices and beech increment form a significant and moderate correlation in the pure beech stands (SP 3 and 4). In the mixed stands (SP 1 and 2) relation closeness is absent or weak. The absence of correlation between radial increment and complex climate indices of the mixed beech stands testifies to their higher resistance to climate change compared to the pure beech stands.

Analyzing the correlation of the main climate indices and beech increment for the ten-year period, we found that in the last period (2003–2013) the closeness of relation was higher compared to the previous period (1992–2002) (Table 6). Radial

Table 6. The correlation coefficients of average radial increment of beech and climate indices for ten-year periods.

Indices	Aspect (No SP)			
	SW (1)	S (3)	NE (2)	NE (4)
1992–2002				
The amount of precipitation (mm) for: - calendar year	-0.30	**0.47**	-0.003	**0.39**
- the vegetation period	-0.12	**0.60**	0.27	**0.62**
Temperature (°C): - calendar year	-0.002	**-0.55**	-0.33	**-0.55**
- the vegetation period	-0.08	**-0.52**	**-0.45**	**-0.48**

Indices	Aspect (No SP)			
	SW (1)	S (3)	NE (2)	NE (4)
Air humidity (%) for: - calendar year	**-0.52**	**0.60**	0.06	**0.56**
- the vegetation period	**-0.36**	**0.70**	0.28	**0.65**
Humidity deficit (mb): - calendar year	**0.39**	**-0.73**	-0.32	**-0.66**
- the vegetation period	0.29	**-0.74**	**-0.41**	**-0.66**
Humidity of climate (*W*)	-0.16	**0.43**	0.09	**0.38**
2003–2013				
The amount of precipitation (mm) for: - calendar year	0.07	**0.59**	**0.63**	**0.49**
- the vegetation period	0.18	**0.58**	**0.56**	**0.46**
Temperature (°C): - calendar year	**-0.58**	**-0.47**	-0.27	**-0.60**
- the vegetation period	-0.32	-0.12	-0.08	0.15
Air humidity (%) for: - calendar year	-0.1	0.32	**0.40**	**0.69**
- the vegetation period	0.13	**0.51**	**0.41**	**0.75**
Humidity deficit (mb): - calendar year	**-0.39**	**-0.77**	**-0.63**	**-0.87**
- the vegetation period	**-0.43**	**-0.66**	**-0.59**	**-0.53**
Humidity of climate (*W*)	-0.04	**0.55**	0.33	**0.44**

Note: the numbers in bold indicate a reliable correlation at a 95% level of significance.

increment of beech wood together with humidity deficit forms particularly high inverse correlation. In our opinion this is due to more intensive increase of average air temperature in comparison to average annual humidity, especially during the last decade (Mazepa and Shyshkanynets 2013).

Conclusions

In the Ukrainian Carpathians the average radial increment of beech, depending on the composition of trees varies in the range of 1.71–2.41 mm and is the largest in the mixed stands. The proportion of early and late beech wood in the annual ring is 12–17 % and 83–88 %, respectively.

Average increment and characteristics variability of the mixed stands is higher compared to the pure stands. Radial increment of beech on the southern slopes of the south side of a tree and on the northern slopes on the north side of a tree is larger in comparison with the opposite side of a tree. On the northern slopes the annual increment is larger compared to the southern slopes. Extreme values of radial increment, in most cases, coincide with the critical values of climate indices. In the years of the most intensive solar activity radial increment of beech is minimal.

In the pure beech stands relationship between beech increment and climate indices is more substantial in comparison with the mixed forest stands. The beech increment correlates greatly with humidity deficit, air humidity, temperature and rainfall, which is especially observed in the last decade (2003–2013). Significant correlation between annual beech wood increment and air humidity as well as humidity deficit was found in the pure and mixed stands. The correlation of radial increment, temperature and precipitation in the mixed stands is weak and in the pure stands it is moderate. No significant correlation is obtained between Wolf numbers and beech radial increment neither for the annual growth, nor for the early and late wood.

The mixed beech stands compared to the pure beech stands are more resistant to climate change.

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