

# The Resistance of European Beech (*Fagus sylvatica*) from the Eastern Natural Limit of Species to Climate Change

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## Abstract

In this study, different approaches were used to investigate the vulnerability of beech forests, located at the eastern limit of their natural range, to climate change. To accomplish this, six 2500 m<sup>2</sup> plots were sampled in four European beech forest genetic resources, located in Romania at different altitudinal levels, varying from 230 to 580 m in the Bacău hills and between 650 and 1300 m in the Curvature Carpathian (Braşov region). The analysis of trees phenotypic traits, their radial growth, and the regeneration, did not indicate a vulnerability of the sampled stands to the fluctuations of the environmental factors from the 1950-2014 period. The growth indices of all three populations of Bacău hills are negatively correlated with both June air temperature of current year and September of the previous year. The precipitation amount of September previous year positively influenced the growth indices. The radial growth of plots in Braşov region is slightly linked to the climate. The temperature during the growing season represents a limiting factor for stands that are located outside of the optimal altitudinal species distribution (600-1200 m, in Romania), especially at low altitudes. Our results indicated that a rise of the temperature accompanied by a possible reduction of the precipitations (as is predicted for the coming years) could increase the sensibility of beech forests at lower altitude.

**Keywords:** beech marginal populations, climatic parameters, quantitative traits, seedling characteristics, trees radial growth

## Introduction

The European beech (*Fagus sylvatica* L.) has in Romania an altitudinal amplitude between 200-1600 m, which makes this species the best one to assess the influence of temperature and precipitation at different altitudes on future tree growth. The high sensitivity of the species to drought increases the vulnerability of beech to climate change especially at the eastern limit of the species (Kramer *et al.*, 2010; Nahm *et al.*, 2006).

Numerous studies have assessed the distribution of beech forests (Bolte *et al.*, 2007; Czúcz *et al.*, 2011; Fotelli *et al.*, 2009; Kramer *et al.*, 2010; Stojanović *et al.*, 2013) at the lower limit of altitudinal distribution (i.e. xeric level) which is more difficult to determine than the upper limit, determined by temperature (Rasztovits, 2011). Special attention has been given to identifying some values that indicate beech resistance to drought in the context of climate change (Granier *et al.*, 2007; Jump *et al.*, 2007;

Silva *et al.*, 2012). Therefore, numerous temperature and precipitation indices have been established in order to project a lower altitudinal limit of beech distribution for the future. In previous researches, negative correlations were found between the temperature during the vegetation season and radial growth. The correlation between precipitation (especially during the vegetation season) and growth were positive (Dittmar *et al.*, 2003; Fotelli *et al.*, 2009; Scharnweber *et al.*, 2011).

Several studies showed coherent geographic patterns in the tree-ring growth response to climate, but these also depend upon local environmental gradients modulated by altitude or latitude (Di Filippo *et al.*, 2007; Piovesan *et al.*, 2005). For instance, analyses of *Fagus sylvatica* tree-ring width chronologies from south-western Europe have shown that May temperature and water availability in summer, together with the amount of winter precipitation, are the major drivers of radial growth (Lebourgeois *et al.*, 2005; Piovesan *et al.*, 2005).

In central Europe the predictions for the next 40 years indicate a temperature increase by approximately 2 degrees, while

the precipitations remain constant. In the vegetation season the soil water availability will diminish and the beech vitality will be affected (Geßler *et al.*, 2007). In Romania, in the period 1900-2005 an increase of mean temperature with 0.5 °C was recorded (compared to 0.74 °C the European average); this increase was doubled in the 1961-2007 period (Busuioc *et al.*, 2010). For the 2021-2050 interval an increase of temperature with approximately 1.4 °C compared to the 1961-1990 period is predicted for Romania. While in the 2071-2100 interval, the increase could be of up to 3.1 °C. In terms of precipitation, the 1900-2000 interval proved a decreasing trend of annual precipitation quantity (Busuioc *et al.*, 2010).

To investigate the vulnerability degree of genetically improved beech forests to climatic factors, we sampled our plots in forest genetic resources of European beech. The forest genetic resources / seeds sources are populations phenotypic superior to other populations of their regions. The genetic value of these populations was increased by removing of trees with inferior quality.

In this study we attempt to:

- analyse the main phenotypic characteristics of trees and seedlings from four beech forest genetic resources situated at different levels of altitude and at the eastern limit of beech area;
- analyse the growth dynamic of investigated forests;
- investigate the influence of climatic factors on radial growth, with the aim to identify potential stress factors for beech.

## Materials and Methods

Six plots were installed in four pure of European beech forest genetic resources in Romania (Table 1) and they were placed at different altitudinal levels (230 m, 430 m, 580 m, 650 m, 1050 m and 1300 m a.s.l.), with at least 200 m altitude difference between the plots located in the same stand or adjacent stands. The plots are situated at the eastern European limit of natural distribution of beech (Fig. 1), three in the Curvature Carpathians (Braşov region) and the other three are placed along the Bacău hills area.

The European beech is a species adapted to moderate temperature values and in Romania the optimal altitudinal level is between 600 m and 1200 m (Şofletea and Curtu, 2007). The vegetation conditions are considered as unfavourable for beech both at higher elevation in the spruce-stand level (over 1300-1400 m), due to lower temperatures, and at lower elevation (under 500 m) due to its sensibility to drought and dryness

(Şofletea and Curtu, 2007). Therefore, we assume that environmental conditions in plots located at lower and higher elevation (230 m and 1300 m, respectively) are suboptimal-restrictive for the beech.

In all plots (the design in Fig. 2) the main phenotypic traits of the trees were analysed: diameter at breast height (dbh), total height, pruning height, forking height, stem shape, and stem straightness.

The dbhs were measured using the forest calliper (1 mm precision), while the total height, pruning height and the forking height were measured using a Vertex III instrument (Haglöf, Sweden) at a precision of 0.1 m. By using predefined indices, a visual assessment on qualitative traits of the trunk were made: the general form of the stem (1 = unitary, 2 = forked, 3 = many forked), the straightness of the trunk (1 = straight trunk, 2 = curvature in the upper third of the pruning height; 3 = curvature in the middle third of the pruning height; 4 = curvature in the lower third of the pruning height; 5 = sinuous stem). The volume of trees was calculated based on dbh, total height and species type, by using the regression equation of volume procedure (Giurgiu *et al.*, 2004).

The tree characteristics and the radial growth differences between plots were tested with the non-parametric Mann-Whitney U Test,  $p < 0.05$ , since the data did not comply with the requirements of parametric test methods.

Seedlings analysis was made starting from the idea advanced by Silva *et al.* (2012) that natural regeneration represents a vital condition for beech survival faced with climatic changes. The seedlings (with a height < 200 cm) from each plot were recorded and described in five circular areas of 2 m<sup>2</sup>, one located in the middle of the plot, and other four on the cardinal directions (Fig. 2). The following traits were determined: seedling height (cm), seedlings stem quality (1 = monopodial growth; 2 = sloping trunk; 3 = curved trunk; 4 = forking), seedlings stem viability (1 = unharmed lateral stems; 2 = below 10% stems harmed; 3 = 10-50% stems harmed; 4 = over 50% stems harmed). In addition to this detailed assessment, an overall description of beech seedling (visual assessment) was completed both on the surface of the plots and on the entire forest units in which the plots are located.

The cores from a total of 30 trees were collected from each plot, respecting the diameter class distribution of trees, using the Pressler drill. The cores were extracted from a height of 1.30 m by sequentially changing the cardinal direction (North, East, South, and West) of extraction (Badea, 2008). Measurements of the annual growth were recorded using the CooRecorder software

Table 1. The location of the tested populations

Populations	Administrative location	Latitude N Longitude E Altitude (m)	Surface (ha)	Exposition Slope	Number of plots / altitude a.s.l.
Braşov 1	F.D. Pădurile Şincii UB Şinca Veche u.a. 103	45°42' 25°11' 590 - 750	31.4	NE 15 <sup>G</sup>	1 at 650 m
Braşov 2	F.D. Pietra Craiului UB Zărneşti u.a. 179B	45°39' 25°11' 1000 - 1380	25.3	SE 24 <sup>G</sup>	2 at 1050 and 1300 m
Bacău 1	F.D. Fântânele UP II Fântânele u.a. 66, 82D	46°37' 26°48' 230 - 430	48.8	NE 12 <sup>G</sup>	2 at 230 and 430 m
Bacău 2	F.D. Livezi UP III Coman u.a. 19A	46°28' 26°49' 400 - 580	22.9	N 25 <sup>G</sup>	1 at 580 m

F.D. = Forest district, UB= Base unit, UP= Production unit, u.a.= parcel.

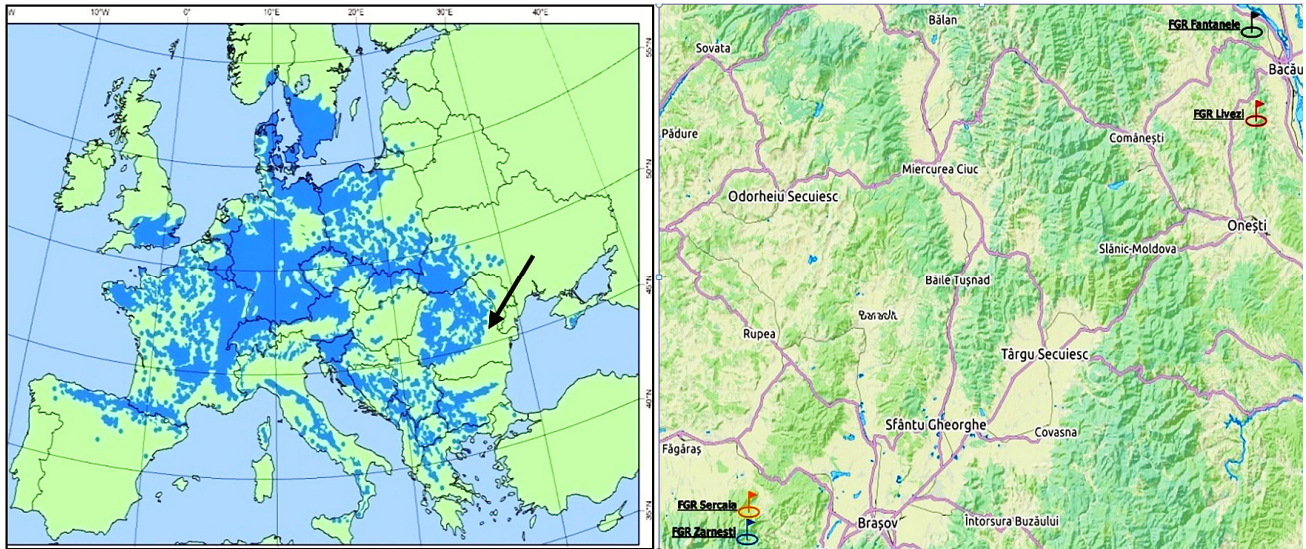


Fig. 1. Geographic distribution of *Fagus sylvatica* in Europe ([www.euforgen.org](http://www.euforgen.org)), with outline (arrow) of the study area (left) and the location of plots (right, <http://www.openstreetmap.org>)

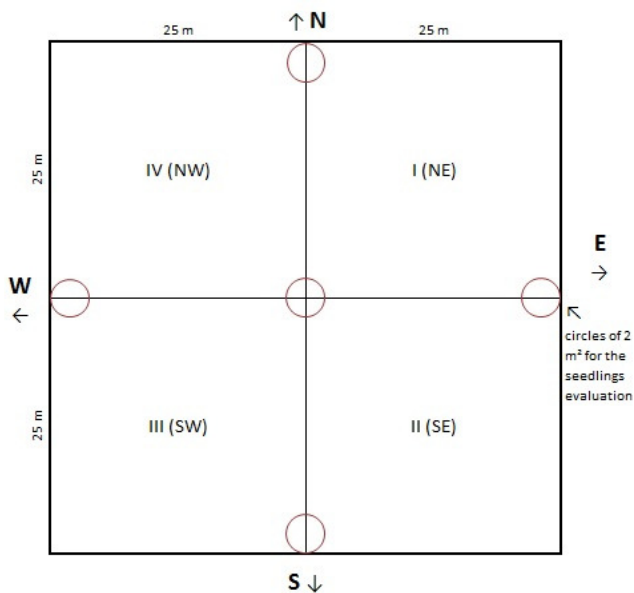


Fig. 2. The plot design

(Cybis Elektronik & Data AB, 2015; [www.cybis.se](http://www.cybis.se)). The primary analysis of data and saving of the results in a format that allows other subsequent analysis were performed using the CDendro program ([www.cybis.se](http://www.cybis.se)). The chronology of the annual rings was checked visually and statistically using the COFECHA program (Holmes, 1983). In order to eliminate the influence of age on achieving growth as well as obtaining the standardized growth indices, the ARSTAN program (Cook and Kruse, 2006) was used.

For the standardized indices of radial growth, only cores from dominant trees were used, which have been well crossdated (correlations higher than 0.5). In order to highlight the climate information, all series of individual growth were standardized therefore achieving a transformation of a series of nonstationary growth in a number of stationary indices with an average of 1 and

a relatively constant variance (Popa, 2004). To eliminate the influence of age we applied a cubic spline function with a frequency equal to 67% of the length of the series (Cook and Kairiukstis, 1990; Leca, 2014). The transformation in the Excel format was performed using TRiCYCLE software (Brewer *et al.*, 2011).

The climatic data from 1950-2014 was collected from the following websites: CRU (<http://www.cru.uea.ac.uk>; Hulme *et al.*, 1998; Ceda catalogue, 2014; Osborn and Jones, 2014; CRU Dataset, 2015), Worldclim (<http://www.worldclim.org>) and ECA&D (<http://www.ecad.eu>, Klein Tank *et al.*, 2002; ECA&D, 2015). This data is centralized from weather stations Făgăraș and Bacău, located closest to the plots.

For a better expression of climate favourability range, a number of climatic indices were calculated and the values were compared with the thresholds considered as limiting for the beech.

- *De Martonne aridity index:*

$I_A = \frac{P}{T+10}$ , where P = the amount of the annual precipitation, T = average annual temperature.  $I_A < 30$  = silvosteppe,  $30 < I_A < 45$  = climate favourable for the forest, with an optimal for beech in the range 35 - 40 (Satmari, 2010).

- *Ellenberg Quotient:*

$EQ = \frac{T_w}{P} \times 1000$ , where  $T_w$  represents the temperature of the warmest month of the year, P = annual precipitations (Stojanović *et al.*, 2013). Ellenberg (1988) has set a threshold of beech favourability for EQ values lower than 30, and at EQ values that are higher than 40, the beech disappearance occurs.

- *Forestry Aridity Index:*

$FAI = 100 \times \frac{T_{VII-VIII}}{P_{V-VII} + P_{VII-VIII}}$ , where  $T_{VII-VIII}$  is the average temperature of the months July and August,  $P_{V-VII}$  represents the amount of precipitations during May-July and  $P_{VII-VIII}$  is the amount of precipitations during July-August (Führer *et al.*, 2011). Führer and collaborators consider that the climatic

conditions are favourable for beech at FAI values that are less than 4.75.

- *Fagus Favourability Index*:

$FI = \frac{P}{Alt}$ , also known as the Continentality Gams index, is the result by reporting the annual precipitation to the altitude of the test site. IFF values between 1 and 2 are favourable for the beech (Satmari, 2010).

- *Mayr Tetratherm*:  $= \frac{t_v + t_{vI} + t_{vII} + t_{vIII}}{4}$ ,

where  $t_v - t_{vIII}$  represent the temperatures for the maximum aridity period of the year (May-August). Tetratherm values indicate a climate restrictiveness of an area for some plant formations. Values between 13 and 18 degrees are optimal for the beech (Satmari, 2010).

In order to calculate the correlations with the climatic factors the dendrochronological residual series were used. The correlations coefficients between standardized radial growth indices and climatic factors (air temperature and precipitation) were calculated using the R software.

## Results and Discussion

### *The climate of the testing sites*

Both in the Bacău Hills and the Braşov Depression, where the plots are located, the climate is D.f.b.x. after Köppen classification, respectively a boreal climate with wet winters and with sufficient precipitations all around the year (Df), at least 4 months a year the mean temperature exceeds 10 °C (b), the maximum of precipitations quantity is in May-June, and the minimum of precipitations quantity is in late winter (x).

In the plot from Şercaia the vegetation conditions are optimal for beech (Table 2), where climatic parameters are optimal, except for the Ellenberg index exceeding the optimal value with a unit. Similarly, in the plots Zărneşti 1 (1050 m a.s.l.) and Livezi (580 m a.s.l.) were recorded favourable conditions for beech, while in the plots from higher and lower elevation, vegetation conditions are very limitative (such as Zărneşti 2 - 1300 m a.s.l.).

### *Characterization of the studied populations*

Although according to the climatic indices analysis, the beech population from Fântânele 1 (F1), located at lower elevation (230 m), should be an unfavourable area for the beech, the biometric characteristics of this population are remarkable. This population has the highest average age (138 years, Table 4) and the lowest density of trees per hectare (132, Table 3). In this plot

there were recorded trees with 106 cm dbh and with heights up to 43 m (Table 3).

But in this plot more curved trunks were found compared with the other plots (Table 3). The other population from Fântânele (F2) has also a high bioaccumulation capacity, having beech trees with up to 45 m height and up to 73 cm dbh. The stem trunk quality is better than those of F1 plot. The volume per hectare of F2 plot (883.5 m<sup>3</sup>) is 31% higher than the volume recorded of F1 population. Both populations (F1 and F2) have a similar average radial growth, slightly lower for F2 even if this plot is of lower age (Table 4). The superiority of F1 plot regarding the radial growth is more accentuated in the past 10 years (the growth average - 1.61 mm for F1 and 1.27 mm for F2, Fig. 3). The third beech plot researched from the Bacău area is the youngest one, with an average age of 85 years, having also the highest value for the average radial growth (Table 4). The negative correlation between radial growth and trees age has been already reported (i.e. Rozas *et al.*, 2015). In this plot the maximum height of the trees is approximately 10 m lower than in the other plot from the same area (Table 3).

The maximum tree height from the Braşov beech populations is lower than the maximum height of Fântânele (F1 and F2) and similar to the tree height from the much younger population from Livezi, Bacău area (Table 3). The three plots from Braşov are the same age, of approximately 100 years, which allows a comparative analysis of growth, without the risk of being influenced by the reducing of annual ring width with age. Thus, a significant reduction of the average growth can be observed with the increasing of the altitude (Fig. 3, Table 4). The Z2 plot being at the highest altitude (1300 m) has an average growth (1.46 mm) approximately 34% lower than the S plot (Şercaia), which is located at the optimal altitude (650 m) and enjoys optimal vegetation conditions for beech (Table 4). The same observation is valid for the average growth of the past 10 years, this being 51% lower for the Z2 plot which is located at 1300 m altitude (Fig. 3). In the plot situated at the highest altitude were recorded the lowest value of average radial growth and also the lowest averages from the past 10 years of all the 6 plots (Fig. 4). For the plot located at the highest altitude, the reduction of growth in the past 50 years represents a constant trend, while in the other areas there are fluctuations in time (Fig. 4).

The mean radial growths (higher with 32% than those described by Leca (2014) for other beech stands from Braşov area with the same age) do not reveal vulnerabilities to fluctuations in environmental factors for the studied beech populations. Vulnerability analysis of forest species from the Southern Carpathians (the Retezat and Bucegi - Piatra Craiului Massifs) reflected a superior resistance of beech to environmental disturbances (Badea *et al.*, 2011), in comparison with other analyzed species.

Table 2. Bioclimatic indices from the analysed plots

Plot	MAT (°C)	SAP (mm)	ATVS (°C)	SPVS (mm)	I <sub>A</sub>	FFI	EQ	FAI	MT (°C)
Fântânele 1 230 m a.s.l.	<b>9.3</b>	572	18.3	348	30	<u>2.5</u>	38	<u>5.87</u>	19.0
Fântânele 2 430 m a.s.l.	<b>9.3</b>	572	18.3	348	30	<b>1.3</b>	38	<u>5.87</u>	19.0
Livezi 580 m a.s.l.	<b>8.6</b>	595	<b>17.4</b>	352	32	<b>1.0</b>	34	<u>5.25</u>	<b>18.2</b>
Şercaia 650 m a.s.l.	<b>8.3</b>	<b>649</b>	<b>16.7</b>	<b>409</b>	<b>35</b>	<b>1.0</b>	31	<b>4.5</b>	<b>17.3</b>
Zărneşti 1 1050 m a.s.l.	4.6	773	9.2	487	53	0.7	<b>14</b>	<b>2.1</b>	9.5
Zărneşti 2 1300 m a.s.l.	<u>3.1</u>	<b>823</b>	<u>6.1</u>	<b>518</b>	<b>63</b>	<u>0.6</u>	9	1.3	<u>6.4</u>

MAT= mean annual temperature, SAP= sum of annual precipitation, ATVS/SPVS= average temperature/sum of precipitation of the growing season (May - September), I<sub>A</sub>= De Martonne aridity index, FFI= *Fagus* favourability index, EQ= Ellenberg index, FAI= forestry aridity index, MT= Mayr May-August average temperature. **bold**= optimal value, normal= acceptable value, underlined= limitative value, according to Şofletea and Curtu (2007). The climatic data were collected from the Făgăraş and Bacău weather stations.

Table 3. Trees characteristics

Plot	No. of trees / 2500 m <sup>2</sup> Altitude a.s.l.	Variable	Diameter at breast height (cm)	Total height (m)	Average trees volume (m <sup>3</sup> )	Pruning height (m)	Forking height (m)	Stem shape (indices)	Stem straightness (indices)
Fântânele 1	33 trees	Mean	53.4 a	35.1 a	5.11 a	16 a	11 ac	1.5 ab	2.5 a
		Std. dev.	18.7	5.6	4.4	5.2	4.5	0.7	1.7
		Amplitude	106-24	43-21	22-0.5	26-6	17-5	3-1	5-1
Fântânele 2	67 trees	Mean	43.6 b	39.4 b	3.30 b	25 b	16 b	1.4 b	1.9 ab
		Std. dev.	10.6	2.9	1.9	4.7	3.9	0.6	1.2
		Amplitude	73-24	45-30	9.8-0.8	36-15	21-7	3-1	5-1
Livezi	74 trees	Mean	39.9 c	27.8 c	1.94 c	16 a	9 a	1.6 ab	2.1 a
		Std. dev.	10.7	2.3	1.2	2.6	5.1	0.6	1.2
		Amplitude	67-19	33-23	5.6-0.3	22-9	17-2	3-1	5-1
Șercaia	82 trees	Mean	35.1 d	27.3 c	1.55 c	13 c	12 c	1.6 a	1.5 b
		Std. dev.	10.4	4.0	1.0	4.9	3.9	0.5	1.1
		Amplitude	63-12	34-13	4.6-0.1	21-3	18-5	3-1	5-1
Zărnești 1	75 trees	Mean	37.9 cd	27.0 c	1.89 c	13 c	10 ac	1.5 ab	1.5 b
		Std. dev.	13.9	4.2	1.6	5.1	4.9	0.7	1.1
		Amplitude	71-14	34-17	7.3-0.1	24-2	20-4	3-1	5-1
Zărnești 2	134 trees	Mean	27.5 e	21.1 d	0.80 d	10 d	8 a	1.7 a	2.0 ab
		Std. dev.	11.2	3.5	0.8	4.5	4.4	0.8	1.7
		Amplitude	61-12	30-12	3.9-0.1	19-2	17-2	3-1	5-1

Each plot has a square-shape and an area of 2500 m<sup>2</sup> (50 x 50 m). Std. dev.= standard deviation, Amplitude= Maximal to minimal values. The different letters show the significant differences between plots (Man-Whitney U-Test, p<0.05)

Table 4. Cores characteristics

Plot	Number of cores	Age (years)			Radial growth (mm)			R bar	EPS
		Mean	Minimum	Maximum	Mean	Minimum	Maximum		
F1	21	138	107	164	1.953	1.256	3.080	0.401	0.922
F2	21	106	97	126	1.887	1.290	2.505	0.368	0.905
L	20	85	72	96	2.374	1.194	4.049	0.374	0.907
S	19	101	85	120	1.959	1.212	2.737	0.445	0.924
Z1	20	106	89	124	1.760	1.174	2.639	0.332	0.881
Z2	17	100	85	111	1.463	1.083	1.927	0.328	0.850

F1= Fântânele 1, F2= Fântânele 2, L= Livezi, S= Șercaia, Z1= Zărnești 1, Z2= Zărnești 2.

30 cores/plot were collected but only those which have been crossdated were used. Rbar is the mean correlation coefficient among tree-ring series. EPS is the expressed populations signal.

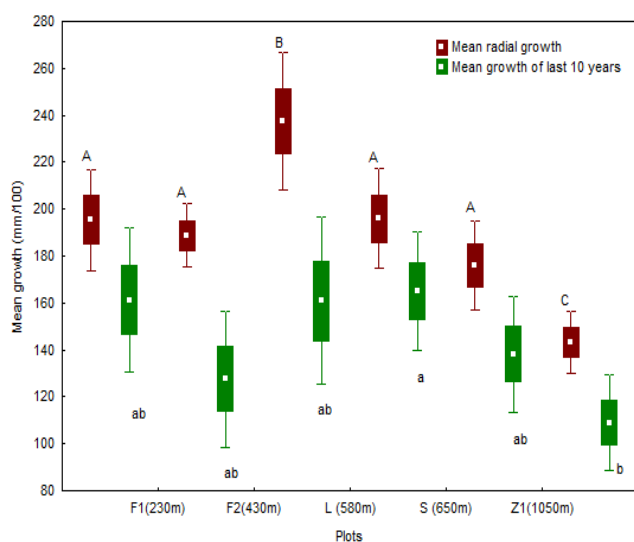


Fig. 3. Mean radial growth of entire tree life and mean radial growth of the last 10 years (2005-2014). Box values represent the standard error and whiskers values the confidence interval. F1 -Fântânele 1, F2 - Fântânele 2, L - Livezi, S - Șercaia, Z1 - Zărnești 1, Z2 - Zărnești 2). The different letters show the significant differences between plots (Man-Whitney U-Test, p<0.05)

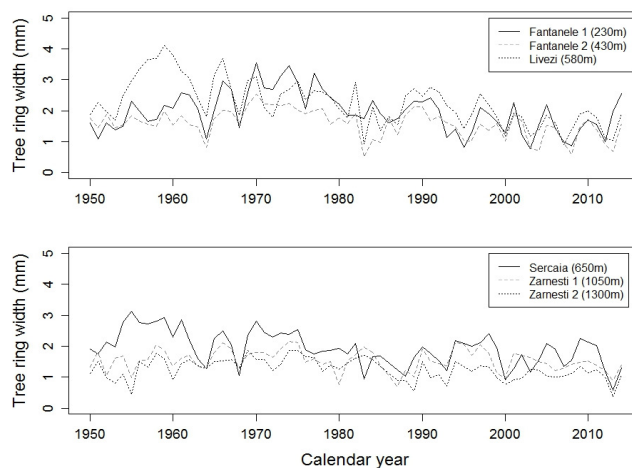


Fig. 4. The growth curves (mean width) of the studied plots during 1950-2014

#### Seedlings analysis

In the area situated at the lowest altitude (Fântânele 1), 74% of the identified seedling has monopodial growth or slightly inclined trunk and lateral shoots have slight damages not affecting their growth (Table 5).

In the plot from Fântânele 2, assessed seedlings are approximately 2-3 years old and they are less numerous than in the other plots. In this plot as well as in the whole forest stand the

Table 5. Description of seedlings from the 5/plot circular surfaces installed

Plot	Number of seedlings	Seedling height/ amplitude (cm)	Seedling stem quality (numbers/classes)				Seedling stem viability (numbers/classes)			
			1	2	3	4	1	2	3	4
Fântânele 1	31	21 (10-80)	4	19	2	6	2	28	1	0
Fântânele 2	13	10	0	8	5	0	0	3	4	6
Livezi	26	33 (15-100)	1	11	3	11	0	18	8	0
Șercaia	45	78 (20-180)	22	12	4	7	15	26	2	2
Zărnești 1	23	44 (10-200)	8	6	2	7	11	12	0	0
Zărnești 2	0	-	-	-	-	-	-	-	-	-

Seedling stem quality: 1= monopodial growth; 2= sloping trunk; 3= curved trunk; 4= forking. Seedling stem viability: 1= unharmed lateral stems; 2= below 10% stems harmed; 3= 10%-50% stems harmed; 4= over 50% stems harmed.

crown density of the stand is 0.8-0.9 and the seedling is absent. In the plot from Livezi, where the crown density of the stand is  $\leq 0.7$  the seedling occurs on 30% of the area. In the plot from Șercaia, seedling has monopodial growth or slightly inclined trunk (Table 5). In the plot from Zărnești 1, which is located at 1050 m altitude, 61% of identified seedlings have monopodial growth or slightly inclined trunk, while 30% of these have bifurcation (Table 5). In the plot seedlings are recorded especially on the slope facing SE and SW, where the crown density of the stand is much lower (0.55, compared to 0.8 from the north aspect of the surface). In the plot from Zărnești 2, which is located at the highest altitude, no seedlings have been identified, the main reason being the high canopy closure of the stand (0.9). The seedlings are missing over the entire surface of stand.

Therefore, beech seedlings were identified in most of the plots and its density was influenced by the canopy closure of the stand, which limits the amount of light on the ground level. Currently, the presence and the quality of seedling (Silva *et al.*, 2012), do not indicate a vulnerability of the analyzed beech forests to major environmental fluctuations, if we agree with the hypothesis proposed by Silva.

#### The influence of climatic factors on the annual radial growths

In Bacău, the records showed a general increasing trend both for the air temperature and rainfall, throughout the period under analysis. In Brașov, starting from 1985 onwards, the records for the air temperature exhibited an upward trend. However, the records for rainfall, showed a slight downward trend over the entire period under analysis (Fig 5).

The standard indices of growth (see Fig. 6) show that the years with the lowest growth in all plots under analysis were

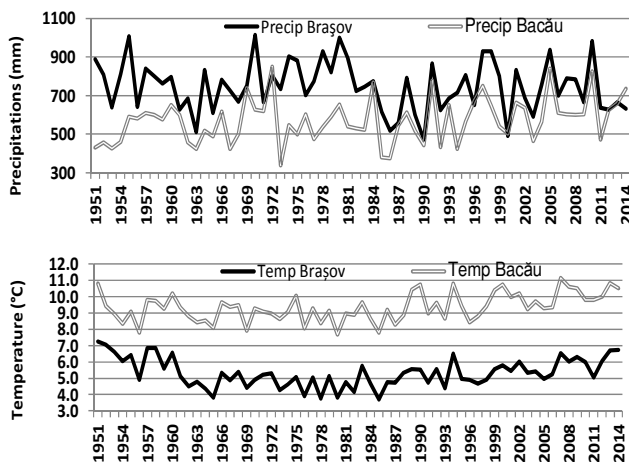


Fig. 5. The dynamic of the annual temperature and precipitations from the analyzed plots

1964, 1968, 1983, 1985, 1987, 2000, 2003, 2007, 2012 and 2013. With the exception of 1968, all the other years mentioned above are known in Romania as 'dry' years (Sandu, 2013). At the opposite end, the years with the highest rates of growth in all areas were: 1959, 1969, 1974, 1990, 1994, 1997, 2001, 2005 and 2014. Out of this second set of years, 1969, 1974, 1990, 1997, 2005 and 2014 are known in Romania as 'rainy' years (Sandu, 2013).

Table 6 and Fig. 7 show the correlations between residual radial growth indices and climatic factors. For all three plots studied in Bacău, radial growth indices showed a negative correlation with temperature of the June, current year. In addition, the analysis showed that the intensity of this correlation is inversely proportional to the altitude (Fig. 7). The radial growths were negatively influenced by the temperatures registered in the month of September the previous year. However, the amount of rainfall recorded for the same month had a significantly positive influence on the tree growth. For the populations in Bacău - especially from the one located at the lower altitudinal limit - the negative correlation with summer temperature and the positive correlations with summer precipitations point to the fact that the summer (i.e. June) water availability is the main driving factor of growth for beech trees, in accordance with the results from other studies (Bouriaud *et al.*, 2004; Michelot *et al.*, 2012; Oladi *et al.*, 2011). In addition, the results suggest that the water availability during September (the previous year) was an important factor for the growth formation, probably due the contribution of the soil water reserve.

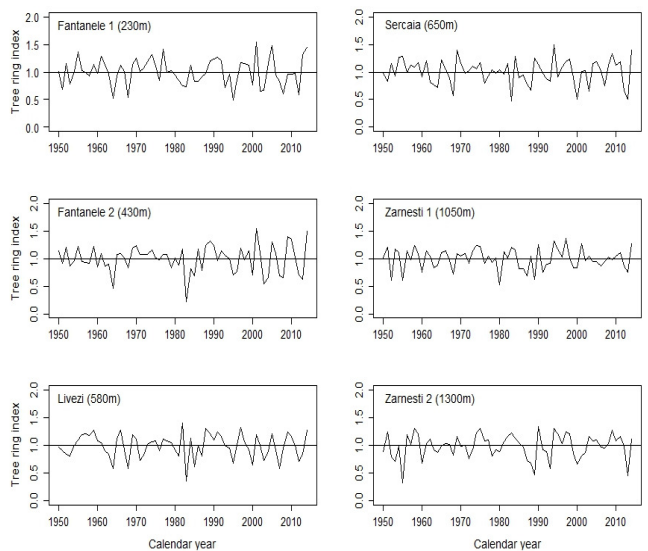


Fig. 6. Residual chronologies of the studied plots at Bacău (left) and Brașov (right)

Table 6. Indices of correlation between radial growth and climatic factors

Climatic Factors	Bacău			Braşov		
	Fântânele 1	Fântânele 2	Livezi	Şercaia	Zărneşti 1	Zărneşti 2
	230 m	430 m	580 m	650 m	1050 m	1300 m
Average annual temperature	0.04	0.05	-0.05	0.02	0.05	-0.10
Average temperature of the vegetation season	<b>-0.25</b>	-0.09	-0.17	-0.06	0.06	-0.08
Sum of the annual precipitations	<b>0.26</b>	0.23	<b>0.34</b>	<b>0.26</b>	0.06	0.05
Sum of precipitations of the vegetation season	<b>0.26</b>	0.19	0.23	<b>0.27</b>	0.09	0.05
Ellenberg index	-0.23	-0.15	<b>-0.31</b>	<b>-0.28</b>	-0.06	-0.13
FAI index	-0.19	-0.12	-0.23	<b>-0.37</b>	-0.14	-0.22
De Martonne aridity index	0.24	0.21	<b>0.34</b>	<b>0.25</b>	0.03	0.08
Mayr Tetraterma	<b>-0.28</b>	-0.13	-0.20	-0.14	0.05	-0.09
Fagus favourability index	<b>0.26</b>	0.23	<b>0.34</b>	<b>0.26</b>	0.06	0.05

The significant correlations ( $p < 0.05$ ) are bolded.

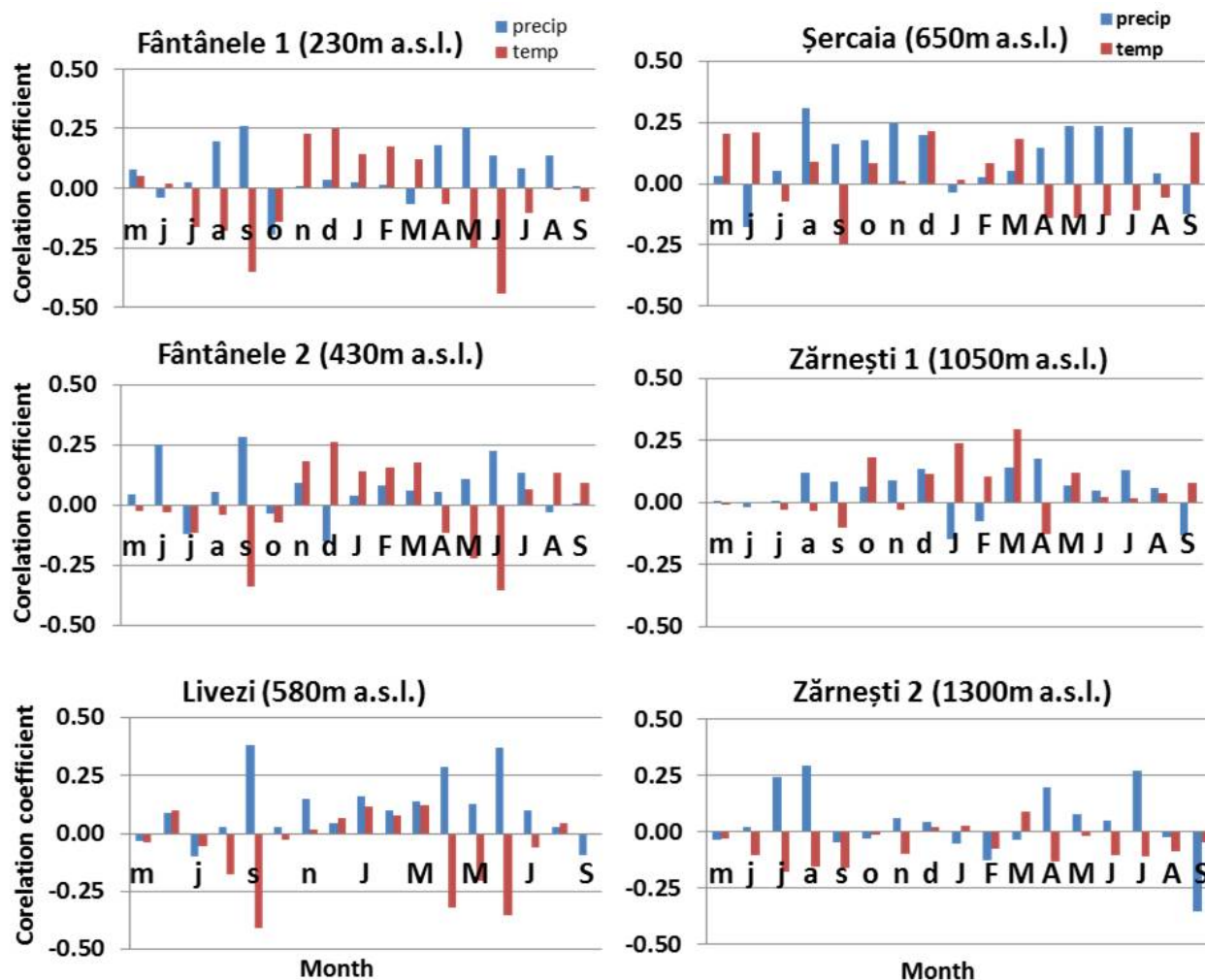


Fig. 7. The influence of monthly temperature and precipitation values of the previous year (small letters) and the current year (capital letters) on the radial growth of trees. Values higher than 0.25 / -0.25 are significant ( $p < 0.05$ )

Concerning the beech populations in Brasov, the results showed very few significant correlations with climatic factors. The growth of the beech from plot located in Şercaia (although positioned in an ecologically optimal environment) seemed to have been negatively influenced by the August rainfall and by the temperature recorded in September last year. However, the rainfall recorded this year in the growing season seems to have a positive impact on the growth. Against expectations, the results recorded showed no strong correlation with altitude. Only the radial growth of the plot located at 1050 m a.s.l. was positively

and significantly influenced by the temperature at the beginning of vegetation season (i.e. May, Fig. 7).

Vavřík *et al.* (2013), found in a study carried out in Brno (Czech Republic) at an altitude of 630 m a.s.l. that the cambial activity of beech began in May, with the maximum cambial activity being recorded in the second half of June. The complete formation of the annual tree ring has been recorded at the beginning of September (i.e. all wood cells had been formed by the cambium by mid-August and the fiber lignifications process had finished during the first half of September). The phenology

of the annual ring formation varies from year to year, but shows a direct correlation with the environmental factors - temperature and precipitations. The temperature seems to be the determining factor in the ending of cambium activity (Vavřík *et al.*, 2013).

The results published in this study align themselves with the results recorded in previous studies, which showed a negative correlation between the temperature of the growing season and the radial growth; and a positive correlation between rainfall - especially rainfall in the growing season - and growth (Jump *et al.*, 2007; Leca, 2014; Piovesan *et al.*, 2005; Tegel *et al.*, 2014). The water available in the months of May-June is essential for the values of radial growth in the current year and for the survival of beech in the long-term (Czúcz *et al.*, 2011; Di Filippo *et al.*, 2007; Dittmar *et al.*, 2003; Lebourgeois *et al.*, 2005).

In the years with the low values of the aridity index (1985, 1986, 2000, 2003) the tree rings are narrow. In the years in which the aridity index was in the optimal interval for beech (1959, 1970, 2009, 2014) were recorded higher values of the radial growth. For high values of De Martonne's index (50-54) - which mark the upper limit in terms of altitude for beech - active growths have been recorded in the following years: 1970, 2005 and 2010. These results suggest that the amount of rainfall - which is directly proportional with altitude - is crucial to the development of beech trees.

## Conclusions

The analysis of the phenotypic traits, of tree growth dynamic and of natural regeneration along different environmental conditions shows that the investigated forest genetic resources have not been vulnerable to the climatic factors recorded for the last period. However, the negative correlation between air temperature and tree growth gives some predictions regarding a possible vertical displacement (from lower altitudes to higher altitudes) of the lower limit of beech distribution in the future.

Overall, the high values of the radial growth have been recorded for the rainy years. Similarly, high values for radial growth have been recorded in the situations where the aridity index had been recorded to be in the optimal range for beech. The primary limiting factor for beech forests located at the low altitudes is the temperature recorded in the growing season, also associated with a reduction in rainfall.

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