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Effect of weather conditions on annual and intra-annual basal area increments of a beech stand in the Sopron Mountains in Hungary

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Abstract—We studied the effect of meteorological parameters such as average monthly temperature and sum of precipitation on basal area increment (BAI) of a beech stand in the Sopron Mountains in subalpine climate in Hungary between 1985 and 2007. The applied multivariate regression analysis takes into account the influence of the weather conditions on increments also in the previous two years. Results indicated that precipitation generally stimulated the BAI in the studied stand, while above average temperature during the growing season depressed it. One of the dominant periods for growing of basal area is the autumn of the penultimate year when precipitation and temperature has positive and negative effect on increment, respectively. In the main growing period (spring-early summer) the previous year's precipitation has positive, while autumn temperature has negative effect. Current spring to early summer precipitation enhances the beech growth, and in contrary, the mean temperature in June-July has negative effect on the BAI. There is a breakpoint in the trend of meteorological variables at about 1999. A significant decrease was observed in the growth of beech in the summer months in the period of 2000–2007 compared to growth between 1985 and 1999 probably caused by the changed meteorological conditions. The maximum growth shifted from June to May, and the relative share of spring months in the BAI has increased since 2000. Drastic loss in increments can be observed in July and August, which was partly compensated in autumn. The long-term trend of annual BAI is continuously decreasing; comparing the two periods, the average yearly increments decreased from 21 cm^2 to 12 cm^2. According to forecasted climate change, not only further loss in growth but also drastic decay in vitality and tolerance can be expected for beech at this site over the 21st century.

Key-words: beech, growth, basal area increment, climate change, production

1. Introduction

At the beginning of the 1990's, several studies reported a more intensive growth of forests over Central Europe in the last third of the 20th century than before (*Pretzsch*, 1992; *Bräker*, 1996; *Spiecker et al.,* 1996; *Zingg*, 1996; *Kahle et al.*, 2008). Studying the reasons, it was found that the change in growth was related partly to the longer vegetation period (*Hasenauer et al.*, 1999), and partly to earlier blooming and leaf unfolding (*Menzel* and *Fabian*, 1999). Changes in the climatic conditions significantly enhanced the intensity of photosynthetic activity and respiration, resulting in change of growth (*Kozlowski et al.*, 1991; *Larcher*, 2001; *Somogyi*, 2008). However, the results are frequently contradictory when studying the relation of changing climate and tree growth in larger geographical scale. One of the reasons is that in the comparisons of different observations and measurements, the favorable or unfavorable climate conditions of the investigated areas were disregarded (*Mátyás et al.*, 2010). When water supply is not limited, the rising temperature can lead to substantial, even 50% increase in growth for beech in contrast to arid regions.

Numerous reports have been published concerning tree growth, especially for organic matter production of beech. These studies mainly focused on the causal relationships as consequences of changed climatic conditions. For example, *Dittmar et al*. (2003) studied the effect of climate on the growth of beech stands in European mountainous (>800 m) and hilly (<700 m) regions. They found that temperature and precipitation in the summer of the given year have an inverse effect on annual growth. While in higher regions there is positive relation with increasing temperature, higher precipitation reduces the yearly growth. For lower regions these relations are just the opposite.

Cool and wet autumn at the year before was found to enhance the radial growth of beech for a Romanian stand (*Kern* and *Popa*, 2007). On the other hand, the late summer high temperature has negative influence on the growth.

Ležík et al. (2011) studied the influence of climate on the yearly production in the whole growing season, on the basis of biweekly dendrometer observation in Slovakia. They showed a positive effect of precipitation at the beginning of growing season, and this influence tends to be reverse with time during summer period with parallel growing importance of precipitation, especially at the end of summer and beginning of autumn.

Another Slovakian study reported positive effect of precipitation on beech growth in August in the previous year and in June-July in the same year; while temperature of the previous summer reduced the growth (*Petráš* and *Mecko*, 2011). Other investigations in Germany (*Scharnweber et al*., 2011; *van der Maaten*, 2012) and France (*Michelot et al*., 2012) pointed out positive effect of precipitation in the given year and negative influence of temperature.

In Slovenia (*Čufar et al*., 2008), it was found that the May and July precipitation enhances the production significantly; similarly to the precipitation in August of the previous year. Other dominant climate parameters are the temperature minima in March and the maxima in August.

In this study we analyzed the weekly observations of basal area increment (BAI) in a beech stand for 22 years (1985–2007) in relation to the main meteorological parameters determining the growth, i.e., monthly mean air temperature and sum of precipitation. The length of data series allows a reliable correlation analysis between the increments and meteorological factors as well as to fit a model to the growth by multivariate linear regression analysis. A relatively rich literature can be found dealing with annual growth rates based primarily on tree-ring derived parameters, however, the strength of this study is the length of the intra-annual time series offering a unique opportunity to analyze the intra-annual growth trends of European beech on a 22-year timescale. The results will support evaluation of future growth expectations; namely, which climate components and in which periods have the greatest effect on the basal area increment of trees. The aim of this study is to evaluate this effect.

2. Methods and materials

2.1. Characterization of the site of investigation

During the selection of the test stand, it was a primary criterion that the tree species, i.e., the beech (*Fagus sylvatica* L.) should be important in the given landscape from both an ecological as well as forest economical point of view. The Sopron Mountains lie at the border of Austria and Hungary (*Fig. 1*), where beech is indigenous (*Magri*, 2008; *Führer et al*., 2010). The forest type is *Oxalis acetosella* with a single crown-storied, completely closed beech forest. Its age at the beginning of the observations was 85 years based on the data of National Forestry Database in 1985. In the early 2008 the forest was harvested. Due to the forest restoration technology used between the World Wars, which succeeded in 5–15 years, there can be a difference of about 10 years among certain trees. The stand was on a slight, south-east facing slope at approximately 400 meters above the mean sea level. Coordinates are: 47° 39’20”N and 16° 28’58” E, the bedrock is gneiss, and the soil is a type of Luvisols according to the WRB 2014 classification system (*IUSS*, 2014). The climate is sub-alpine.

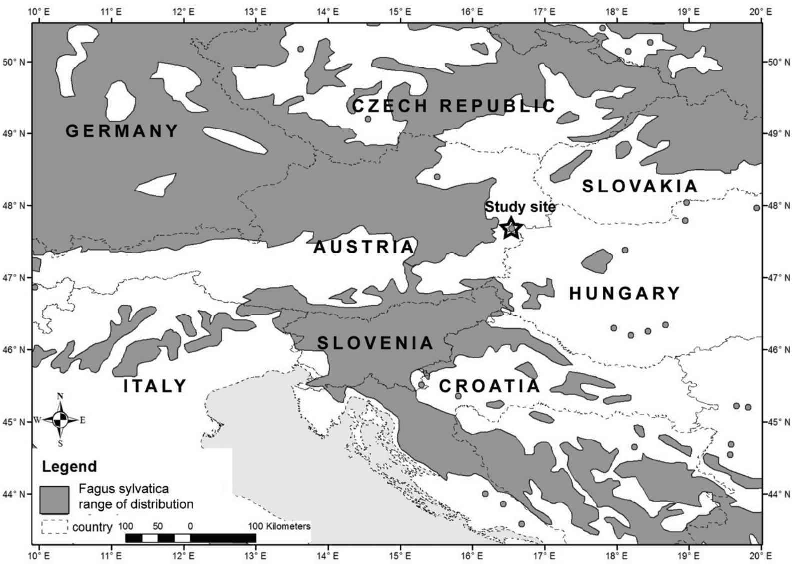

Fig. 1. Location of the study site and the distribution of beech (*Fagus sylvatica*). Distribution boundaries are retrieved from the *EUFORGEN* (2009) database.

The studied plot was a 50×50 m parcel, representing average stand in its characteristics. The height and diameter at breast height (DBH) of every tree were surveyed regularly. The stand was well growing; stem number was 362 pcs ha^{-1}, stand volume is 732 m^3 ha^{-1}, average DBH and height were 37 cm and 32 m, respectively.

Based on the survey – trunk by trunk –, we determined the social position (dominant, co-dominant, suppressed) of trees and the structure of the stand. Using the results of this analysis, we selected seven beech trees (*Table 1*) with average parameters, representative for the whole stand. Suppressed trees were not considered in the selection since their growth is heavily affected by their social status beside weather.

Table 1. Initial data of trunks equipped by dendrometers at the start of measurement; *d*=diameter at breast height (DBH); *BA* = basal area; *h* = tree height

Number of trunks	***d* (cm)**	***BA* (cm^2)**	***h* (m)**
11	37.5	1103	32.0
14	38.2	1147	32.0
15	37.7	1117	33.0
16	33.2	864	31.5
19	41.7	1368	33.8
20	37.7	1117	32.2
21	37.8	1125	31.0
mean	**37.7**	**1120**	**32.2**

2.2. Dendrometer measurements

We installed Liming-dendrometers (*Liming*, 1957) on selected trees for weekly observations, and the change of perimeter over 22 years (1985–2007, without the year of 1998) was recorded. Following forestry practice, the bronze dendrometer-bands were installed permanently at breast-height. It should be emphasized that the circumferential change represents the total change in circumference outside the bark and not necessarily the actual wood increment. The largest source of noise could be the thermal expansion of the stem. Linear thermal expansion coefficient of bronze is 17–18 μm m^{-1} °C^{-1} (*Hidnert* and *Krider*, 1947). Respecting that the monthly mean air temperature is similar at the start and at the end of yearly observations (March: 3.0 ± 2.32 °C and November: 2.8 ± 2.02 °C), differences in thermal expansion in March and November are practically negligible. For vegetation period, however, we estimated the anomaly caused by thermal expansion by comparing the circumferential increment of trees with thermal expansion. The calculated error was below 1 percent.

In spite of weekly observations, first of all we aimed to get information of monthly, seasonal, and yearly increments. Beside monthly growth increments of different stages of growing periods (initial: April, main: May-August, and final:

September-October), monthly meteorological parameters were also analyzed. The separation of the different growth stages (*Table 2*) enables the examination of change in these growth stages in relation to climate conditions over the long (more than two decades) observation period. To assess the effect of climate variability, investigation of yearly distribution of growth intensity is indispensable. Many papers have been published studying increments on a shorter (daily) time-scale (e.g., *Deslauriers et al.*, 2003; 2007a; 2007b). In these studies, with the applied measurement methodology, short-term growth of trees was separated from swelling and shrinkage caused by temperature and humidity. These observations are suitable to find deeper eco-physiological relationships. However, our observations, due to the potential, future application of the results in forestry practice, aimed the exploration of organic matter production of longer periods (within a year) as a function of weather parameters.

Table 2. Mean meteorological data (*p*: precipitation, *t*: temperature) in the reference (1961–1984) and observation (1985–2007) periods in different time intervals. The significance level in temperature differences was calculated by t-test.

Growing periods	**Months**												**Measurement intervals**						**t-test for *t***
													1961–1984		**1985–2007**		**1961–2007**		
	1	2	3	4	5	6	7	8	9	10	11	12	***p* (mm)**	***t* (°C)**	***p* (mm)**	***t* (°C)**	***p* (mm)**	***t* (°C)**	**significance level**
Year	█	█	█	█	█	█	█	█	█	█	█	█	757	7.5	764	8.2	761	7.9	0.0013**
Dormant	█	█	█								█	█	211	–0.3	230	0.2	221	0.0	0.2023
Growing				█	█	█	█	█	█	█			546	13.1	533	13.9	540	13.5	0.0001**
Initial				█									62	7.6	54	8.3	58	8.0	0.0663*
Main					█	█	█	█					355	15.7	342	16.8	349	16.2	0.0001**
Intensive						█							100	15.5	89	16.1	95	15.8	0.9950
Critical							█						93	17.5	79	18.8	86	18.2	0.0200**
Final									█	█			129	10.7	137	11.0	133	10.9	0.3798

* indicates significance levels, below 0.1,
** indicates significance levels, below 0.05

2.3. Characterization of climate

For characterization of the climate of the test site – generally and for the examined period –, we used gridded climate data interpolated from homogenized monthly precipitation and temperature series derived from the network of the Hungarian Meteorological Service (*Szentimrey et al.*, 2010; *Lakatos et al.*, 2013). By homogenization the effect of any disturbance affecting the measurements over the studied period is removed, keeping the signal of the climate change. Beside the climate characterizations, we attempted to find relationship between increments and monthly precipitation and temperature variations in the different years.

2.4. Evaluation methods

The basal area implement (BAI) is steadily increasing or asymptotically stabilizing for mature trees (*Bouriaud* and *Popa*, 2009; *Fekedulegn et al*., 2003; *Muzika et al*., 2004; *Piovesan et al*., 2008). Since studied trees were obviously mature specimens (older than 85 years), from the beginning to the termination of observations the prevailing negative BAI trend (see Results) cannot reflect a biological trend; therefore, the otherwise mandatory detrending step was neglected and the raw BAI series were used.

According to a survey of European literature, both simple monthly mean weather data (*Dittmar et al*., 2003; *Szabados*, 2006; *Kern* and *Popa*, 2007; *Maxime* and *Hendrik*, 2011; *Scharnweber et al*., 2011) and data for longer periods (*Pichler* and *Oberhuber*, 2007; *Novák et al*., 2010) were used in studying the relationship between weather conditions and growth of trees. The delayed effect of changing weather conditions are taken into account applying pre-defined periods within a year (*Briffa et al*., 2002; *Büntgen et al*., 2006; *Gutiérrez et al*., 2011). Weather conditions of these periods can be represented by the combination (sums or averages) of parameters for different months. For this purpose, beside the analysis of monthly increments, we used the CReMIT method (Cyclic Reverse Moving Intervals Technique, *Pödör et al*., 2014). A brief description is provided in the Appendix.

The basal area increment and organic matter production of trees are closely related to the transpiration (water flux) and photosynthetic activity. These physiological processes relate to leaves so the quantity and quality of foliage fundamentally affect the growth of trees. For deciduous species, the area and quality of leaves, reproduced year-by-year, depend on the quality and quantity of shoots. Many studies take into account the effect of meteorological parameters of the previous year (*Dittmar et al*., 2003; *Di Filippo et al*., 2007; *Kern* and *Popa*, 2007; *Maxime* and *Hendrik*, 2011; *Scharnweber et al*., 2011; *Michelot et al*., 2012; *Tegel et al*., 2014). According to *Gruber* (2004), the number of shoots is determined by the circumstances of initiation of bud growth (primordia): i) this process is determined two years before the appearance of leaves on shoot; ii) the differentiation of primordia into short or long shoots happens a year before the formation of foliage. The more buds are developing long shoots the higher is the probability of higher leaf number; iii) the morphological quality of leaves (surface area and thickness) are determined in the given year, especially in April and May.

We were looking for relationships between climatological statistics and the increments of trees by linear regression analysis, and checked the significance of the found relationships by t-test.

2.5. Multivariate regression models

Based on the above calculations, we constructed multivariate linear regression models for all possible, at least two-component subgroups of independent variables. Using the significant ($p<0.1$) components, we generated all of the mathematically possible multivariate climate index (CI) models for temperature and precipitation and for the two components together on monthly and periodic level, and for the combination of these terms. Then, from the derived regression equations we selected the relevant and statistically significant ones ($p<0.05$). Beyond the ecophysiological considerations we selected them according to the value of the corrected coefficient of determination (R2adj). R2adj, in contrast with the simple coefficient of determination, takes into account the number of parameters as well as observations used in the model; hence, it is more suitable for comparison of multivariate models. In this way, taking into account the relevant and the most significant parameters, we derived the climate indices that have relatively the strongest influence on the increment over the 22 years.

2.6. Breakpoint analysis

A long data series usually includes significant breakpoints. This is true for not only our increment data series but also for our homogenized climate dataset, which – as we mentioned above – is still affected by climate change. During analyses we have to try to separate the data – though by controlled way – into sub-intervals as objectively and uniformly as possible by a principle equally applicable for all of variables. However, changes occur in longer time-interval we can still mark out breakpoints that relatively sharply separate the data series into fragments. There are different methods in the literature to mark breakpoints to detect shift in data series, e.g., by comparison of partial means by Students' t-test, by minimizing the standard deviation, by cumulative sum of anomalies, by Pettitts' non-parametric approach (*Pettitt*, 1979), and by analyzing the signal to noise ratio (*Sneyers*, 1992; *Mares* and *Mares*, 1994).

In our work, we applied the first approximation based on the theory that the difference in averages of sub-intervals separated by breakpoints are significantly higher than that of sub-intervals separated randomly. We tried to divide our meteorological time series into only two parts. To compare means we applied the t-test. This method supposes the normal distribution of meteorological datasets, which was verified by the Shapiro-Wilk test.

3. Results

3.1. Climate description of the test site

Between 1961 and 2007, the average yearly precipitation amount was 761 mm. The share of this was 540 mm in the growing period (April-October), while the rest (only 221 mm) was measured in the dormant period (November-March) (*Table 2*). This means that, beside the water stored in the soil in the dormant period, the water supply was enough in the physiologically active growing season for organic matter production. Regarding the share of precipitation in the different growing periods, the ratios were 11% in the initial growing period (58 mm), 65% in the main growing period (349 mm), and 24% (133 mm) in the final growing period. In the most intensive growing period in June, the average precipitation of 47 years was 95 mm month^{-1} (18%).

The annual mean air temperature at the test site was 7.9 °C. Average temperatures of growing and dormant periods were 13.5 and 0.0 °C, respectively. The average temperature in the different phases of growing season were: 8.0 °C in the initial, 16.2 °C in the main, and 10.9 °C in the final periods.

Due to their high temperature, July and sometimes August are the most critical months; in these months the mean monthly temperature exceeds the 18 °C, and the daily maxima are frequently between 30 and 35 °C. These high extremes substantially depress the photosynthetic activity. Weather conditions changed comparing the measurement period (1985–2007) to the previous years (1961–1984), especially in temperature, where an evident increase can be observed between the two periods (*Table 2*). The performed t-test shows that – excluding the dormant and final periods – there are statistically significant differences between the two examined periods at the $p<0.1$ significance level. The mean air temperature of the main growing season was higher by 1.1 °C in the measurement period. The difference is even higher in the critical month (July) when it is 1.3 °C, accompanied by a reduced amount (14% less) of precipitation. This means that the probability of drought was higher in the measurement period than before.

The mean growing season air temperature shows an evident (significant) change, especially for the period of BAI measurements (*Fig. 2*). Regarding the extremes, there were five years (1962, 1965, 1978, 1980, 1984) with lower than 15 °C mean temperature for the main growing phase during the reference period (1961–1984), while in the observation period there was not any years with the same mean temperature below 15 °C. Furthermore, in the main growing period of reference years (1961–84), year with average temperature higher than 17 °C occurred once (1983), whilst it was observed seven times in the following 23 years (1992, 1994, 2000–2003, and 2007). We can also see that the highest monthly mean temperature in the main growing season was 17.4 °C (1983) in the reference period, in contrast with 19.4 °C (2003) in the observation period.

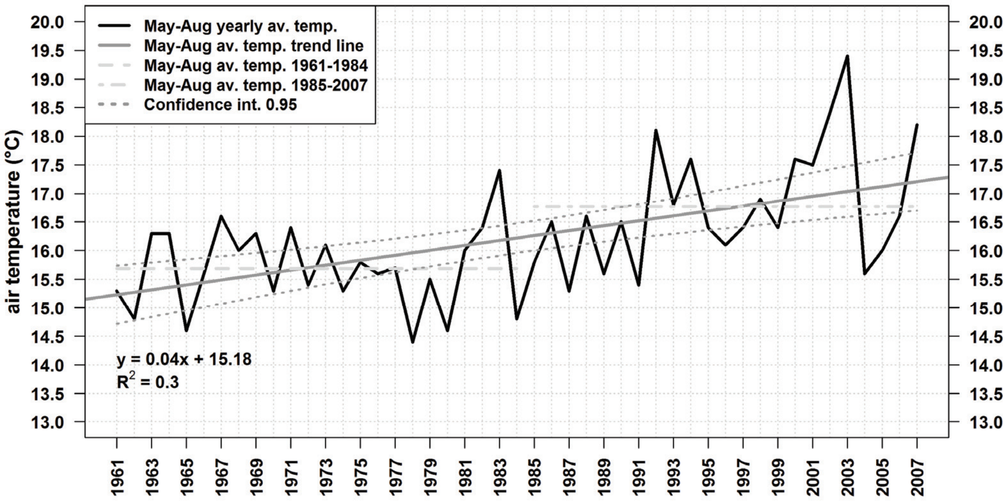

Fig. 2. Trend of average air temperature in the main growing season at the test site in the reference years (1961–1984) and in the observation period (1985–2007) (n=47, p<0.001).

The changes are represented also by the climate classification of the years according to forestry climate categories. Based on the forestry aridity index (FAI) developed for Hungary (*Führer et al.*, 2011), there were 18 years (75%) with beech climate category between 1961 and 1984, while in the observation period there was only 11 years (48%) (*Table 3*). Hence, drier and warmer years than beech climate, i.e., hornbeam-oak, sessile oak-Turkey oak, and forest-steppe climate were more frequent in the observation period (52%) than before (25%). It means that the climate did not evidently belong to beech category during the observation period. Respecting the whole 47 years we can conclude, that in most part of the period, the site can be characterized as beech climate zone (in 62% of years), whilst other years (38%) were characterized by warmer-drier weather conditions as *Table 3* shows.

Table 3: Share of years in different forestry climate categories according to Forestry Aridity Index by *Führer et al.* (2011)

Periods	Forestry climate categories			
	Beech	**Hornbeam-oak**	**Sessile oak-Turkey oak**	**Forest-steppe**
Reference years 1961–1984	18 (75%)	2 (8.3%)	2 (8.3%)	2 (8.3%)
Observation period 1985–2007	11 (48%)	9 (39%)	2 (8.7%)	1 (4.3%)
Total 1961–2007	29 (62%)	11 (23%)	4 (8.5%)	3 (6.4%)

There were substantial variations in the precipitation and temperature conditions among different months also in the observed period. On the basis of the above mentioned t-test and breakpoint analysis, we were looking for years in the period of 1985–2007, where precipitation and temperature averages before and after the given year were significantly different concerning simple monthly and special periodic data (*Table 4*). We supposed, that when significant change is observed in the given year or one year before/after in monthly or periodic climatic variables determining the growth, a parallel change is expected in the basal area growth as well in the same period. In the vegetation period (April-October), significant change of temperature and precipitation were observed between 1990 and 2000 over the 22-year-long period of investigations. While in the months determining the growth, the precipitation amount was decreasing, upward shifts were observed for the temperature after the breakpoint. For example, the mean temperature in June was higher by 1.86 °C after 1992 and the average yearly precipitation amount were lower by 41 mm after 1998 than before.

Table 4. Breakpoint analysis of monthly precipitation and temperature data

Months	**Precipitation (mm)**				**Temperature (°C)**			
	Year	**Before**	**After**	**Difference**	**Year**	**Before**	**After**	**Difference**
4	2000	58.46	43.86	–14.60	1998**	7.82	9.08	1.26
5	2000**	101.09	66.42	–34.67	1993	12.84	14.07	1.23
6	1998**	112.88	71.43	–41.45	1992**	14.85	16.71	1.86
7	1996*	67.11	97.98	30.87	2001*	18.51	19.62	1.11
8	1990**	113.6	85.82	–27.78	1990*	17.53	18.82	1.29
9	1995	68.19	92.97	24.78	1995	13.95	13.05	–0.90
10	1990**	28.32	60.64	32.32	1998	7.99	9.01	1.02
9–10	1990**	91.72	148.06	56.34	1990	11.31	10.83	–0.48
5–8	2000	384.28	311.50	–72.78	1992**	15.99	17.14	1.15
4–10	2000*	574.45	498.87	–75.58	1998**	13.56	14.37	0.81

significance levels: *indicates $p<0.1$; **indicates $p<0.05$

3.2. Interannual, seasonal, and monthly variation of increments

The annual average increment calculated from weekly observations was 17.9 cm^2, with a minimum of 5.52 and a maximum of 31.3 cm^2 in the whole observation period. The growth begins in the first half of April and ends by the middle of October. Data in *Table 5* shows that 88% of organic matter is produced in the main growing season, while its fractions are only 5.3% and 6.2% for the initial and final periods, respectively. These results are in accordance with previous results from Hungary (*Somogyi*, 2008; *Mátyás et al*., 2010). Increments of different trees differ not only in yearly growth but also in the share in growth of the different growing periods. For example, the tree with poor growth (No. 14) showed that the less increment is produced in the main growth period the larger is the production in the initial and final period compared to an "average" tree.

Table 5. Absolute (BAI) and relative (RBAI) increments of beech trees in different growing periods in average and in cases of trees with the largest (No. 15) and the smallest (No. 14) growth

Growing periods	**Average tree**		**Tree No. 15**		**Tree No. 14**	
	BAI (cm^2)	**RBAI (%)**	**BAI (cm^2)**	**RBAI (%)**	**BAI (cm^2)**	**RBAI (%)**
Initial	0.94	5.3	1.74	5.5	0.56	10.2
Main	15.9	88.5	27.8	88.8	4.33	78.4
Final	1.11	6.2	1.81	5.7	0.63	11.4
Total	17.9	100	31.3	100	5.52	100

BAI records showed quite strong coherence among the measured trees for all seasons and the full period as well. The temporarily stable and good coherence is substantiated by the high mean within-tree correlation coefficients (at least $r=0.37$ in all cases at $p=0.05$ or lower significance level), which validates that a common signal is captured by the averaged BAI record (*Fig. 3*). The annual BAI shows a significant decreasing trend during the investigated period. According to the findings of *Fekete* (1958) and *Mendlik* (1967), beech stands between the ages of 80–120 years grow slowly but significantly in basal area. A negative trend in BAI of mature trees is a strong indication of a stress induced decline in tree growth (*Pedersen*, 1998; *Jump et al*., 2006; *Peñuelas et al*., 2008; *Piovesan et al*., 2008). The trend can be correlated with the evident temperature increase in the given period (*Fig. 2*).

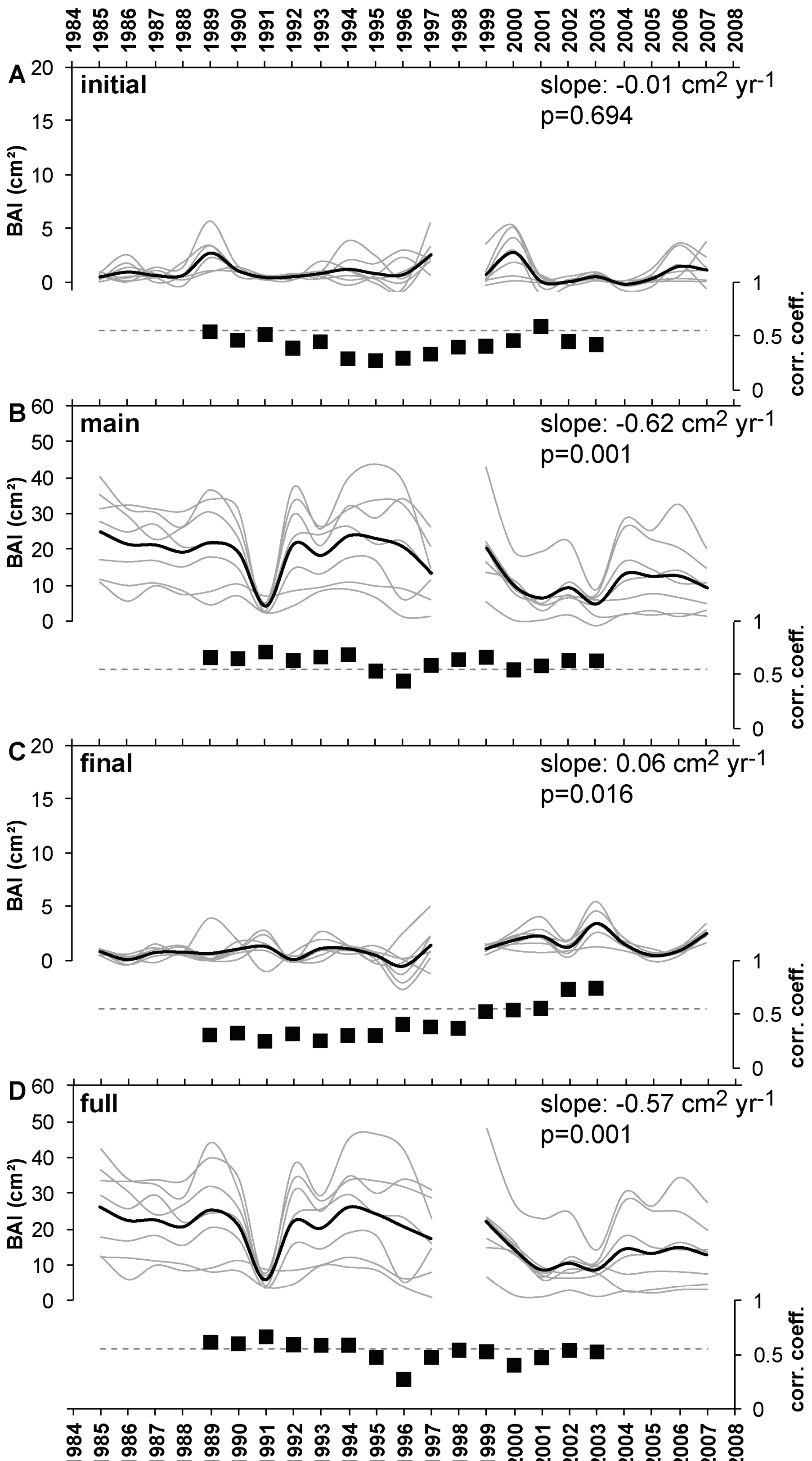

Fig. 3. Aggregated basal area increment (BAI) records of the 7 monitored beech trees and their coherence. The measurement records (A: initial period, B: main period, C: final period, D: full growing period) are shown as thin grey curves. The slope of the linear regression and the corresponding p-value are displayed at the top right corner. The average coefficients of between-tree moving window correlation calculated in 9-year windows are shown below the curves (black square). Dashed horizontal lines show the p=0.1 level.

The year of 1991 was extraordinary, because the mean growth was only 5.77 cm^2 that is only one third of the multi-year average (*Table 6*). In this year, the share of growth in the initial and final periods was higher than the average: 8% (0.44 cm^2) and almost 23% (1.31 cm^2), respectively, while in the main period it was only 70% (4.02 cm^2).

Table 6. Absolute (BAI) and relative (RBAI) yearly increments in different growing periods in average and in a wet-cool (1991) and a dry-warm (2003) year

Growing periods	**1985–2007**		**1991**		**2003**	
	BAI (cm^2)	**RBAI (%)**	**BAI (cm^2)**	**RBAI (%)**	**BAI (cm^2)**	**RBAI (%)**
Initial	0.94	5.3	0.44	7.6	0.52	6.0
Main	15.9	88.5	4.02	69.7	6.09	70.8
Final	1.11	6.2	1.31	22.7	1.99	23.2
Total	17.9	100	5.77	100	8.60	100

Fig. 3 shows that in the years 1991 and 2001–2003, the yearly increment values were well below the average. The reason for rather low growth in 1991, beside biological reasons, can be the extreme weather in that year. The yearly precipitation was 849 mm, 12% higher than the multi-year average. However, the distribution of precipitation among the growing phases was unfavorable. The precipitation amount in the winter half-year (November 1990–April 1991), which is an essential water supply for the growth in April, was 190 mm, 32% less than the 47 year average (279 mm). It suggests that recharge of the shallow groundwater reservoir of soil in the dormant and the initial periods were only partial.

In the following two months (May–June), when growth is generally the highest, the precipitation was 329 mm, 84% higher than the multi-year average (178 mm). In the same time, the mean monthly air temperature in these months was 14.4 °C lower by 2.2 °C than the average. Consequently, because of suppressed transpiration induced by the higher humidity and the lower temperature, the intensity of photosynthesis reduced as well, resulting in lower assimilation. This deficit in growth was not recovered in later phases not even with the 330 mm precipitation in the rest of the growing cycle. The growth in the final growing period is 23%, which ratio is systematically higher than that of the 22-year average (6.7%).

The year of 2003 was extreme as well. The yearly precipitation was only 558 mm, 27% less as usual. While precipitation in the dormant and initial periods (216 mm) was similar to the long-term mean (221 mm), in May and June, in the intensive period was only 108 mm, 39% less than the average

(178 mm). At the same time, the average monthly temperature in these months was 18 °C in contrast to the average, 14.5 °C. The means of daily maxima were 21 and 25 °C in May and June, respectively, so drought and heat stress were accompanied, suppressing the organic matter production. The BAI in this year was 8.6 cm^2, shared by 6% in the initial period, and 71% in the main growing period (*Table 6*). It seems that trees tried to partly compensate the loss of production by the largest growth detected for the final period (1.99 cm^2) in this year (*Fig. 3c*).

From the analysis of different years it seems, that the yearly BAI showed a great variability not only year-by-year but also in share among the different growing periods (*Fig. 4*). Generally, when the increment is less in the main period, the ratio is higher in the final stage. This kind of relationship cannot be found in growth between the initial and the main period. The highest growth in the initial period (2.84 cm^2, and 20%) was observed for the year of 2000. This phenomenon can be attributed to the favoring weather conditions, i.e., in the dormant and initial periods the precipitation was 340 mm in total, 21% higher than the 47-year average. The water supply from soil was enough to start the physiological processes, and at the same time the mean monthly temperature was higher by 1.1 and 3.4 °C than the averages (2.9 and 7.9 °C) in March and April, respectively, both favoring the early and intensive growing.

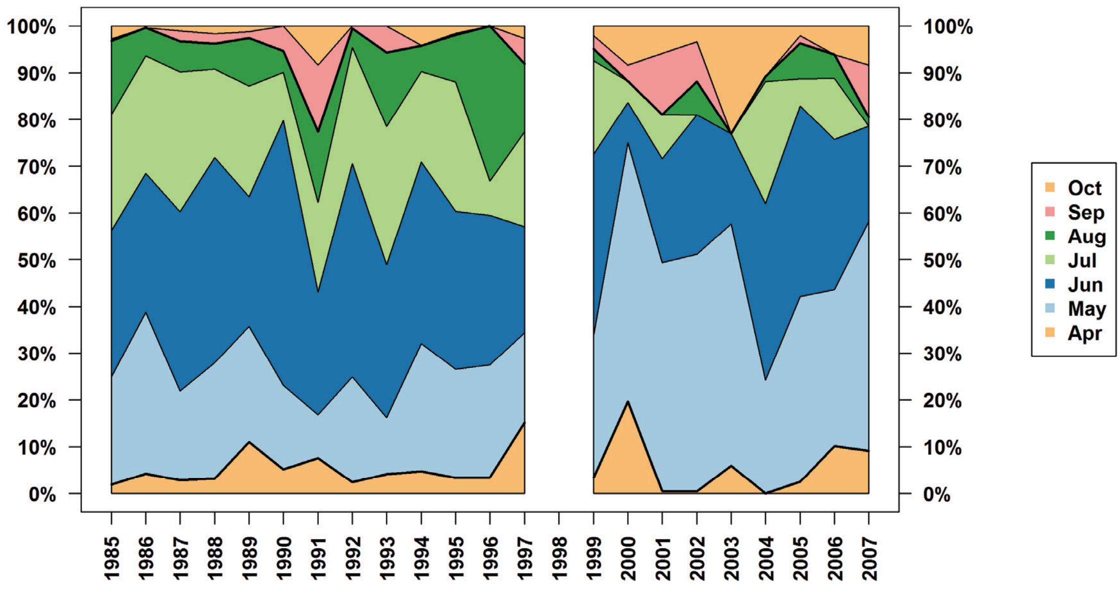

Fig. 4. Share of relative monthly increments of different years.

The length of the initial period was relatively short in agreement with observations in the last two decades: the transition period between winter and summer passes quickly. On the other hand, the main growing period became warmer and warmer, and in July and August, the photosynthesis frequently halted almost completely because of the high daily temperature and low humidity (*Lin et al.* 2012). Later, when hot days were over, it starts again, especially from the beginning of fall to the middle of it. Measurements confirm that ratio of organic matter produced in the final growing cycle is higher and higher, and the magnitude is in a close relationship with growing conditions prevailed in the previous periods; i.e., when organic matter production is low in the main period it is higher than the average in the final cycle. While BAI in the initial period does not show any significant variation during the 22 years, growth significantly decreased in the main and increased in the final periods (*Fig. 5*).

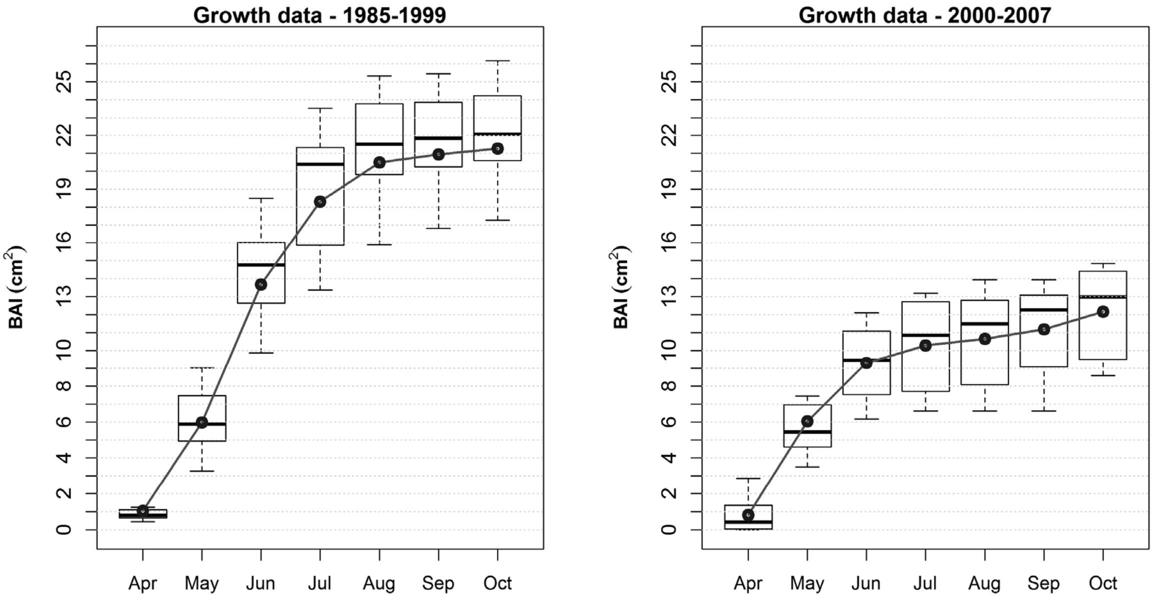

Fig. 5. Cumulative average monthly increments in the periods of 1985–1999 and 2000–2007.
circle: arithmetic mean,
horizontal black line: median,
bottom and top of boxes: lower (Q1) and upper (Q3) quartiles,
error bars: minima and maxima when they are within the 1.5 times of interquartile range (IQR); otherwise the 1.5 times of IQR from Q3 and Q1.

Analyzing the monthly increments separately, we can observe the highest average growth in June (6.08 cm^2), followed by May (5.05 cm^2), July (3.31 cm^2), and August (1.52 cm^2) during the examined 22 years. On the basis of breakpoint analysis with exception of May, September, and October, significant changes are detected between 1999 and 2001 in each month in the main growing period (May-August), and in the whole vegetation period (April-October) (*Table 7*). The breakpoint analysis clearly shows significantly higher mean increments in years before breakpoint in summer, while the trend is just opposite for autumn. For this reason, we analyzed separately the increments of the 1985–1999 and 2000–2007 time intervals. The mean monthly increments differed significantly in the two periods (*Fig. 6*), not only in absolute value but also in the share of the month in the total yearly growth. In years before breakpoint (1985–1999), the highest average increment was detected in June (7.69 cm^2), followed by increments, in order: May: 4.94 cm^2, July: 4.64 cm^2, August: 2.19 cm^2, April: 1.04 cm^2, September: 0.45 cm^2, and October: 0.30 cm^2. In contrast, after the breakpoint (2000–2007), the highest mean BAI appeared earlier, in May: 5.23 cm^2. It means a 6% increase compared to the monthly averages in earlier years. However, it was followed by a dramatic decrease in June, July, and August: 3.26; 0.99; and 0.37 cm^2 (–57; –79; –83% changes), respectively, that was only partly compensated by the slight growth enhancement detected in September (0.52 cm^2) and October (0.98 cm^2). Data clearly showed a drastic decrease in average yearly increments (from 21.19 cm^2 to 12.15 cm^2) in the second period. While the trend of growing does not differed substantially in April-May (*Fig. 3a*), the cumulative increments decreased by 32; 44; 48 % in June, July, and August of the second time interval, respectively (*Fig. 5*). The cumulative deficit in increments till August (48%) compared to the first period is partly compensated (down to 43%) by the relatively higher increments in September and October.

Table 7. Break-point analysis of increments

Month	Brake-point (year)	Increment (cm^2)		
		Before	After	Difference
4	2001*	1.16	0.51	–0.65
5	1990	5.92	4.79	–1.13
6	2000**	7.69	3.26	–4.43
7	2000**	4.64	0.99	–3.65
8	1999**	2.31	0.39	–1.92
9	1990	0.28	0.53	0.25
10	1994**	0.24	0.79	0.55
9, 10	1990*	0.62	1.17	0.56
5, 8	2000**	19.45	9.85	–9.60
4, 10	2000**	21.42	12.15	–9.27

significance levels: *indicates $p<0.1$; **indicates $p<0.05$

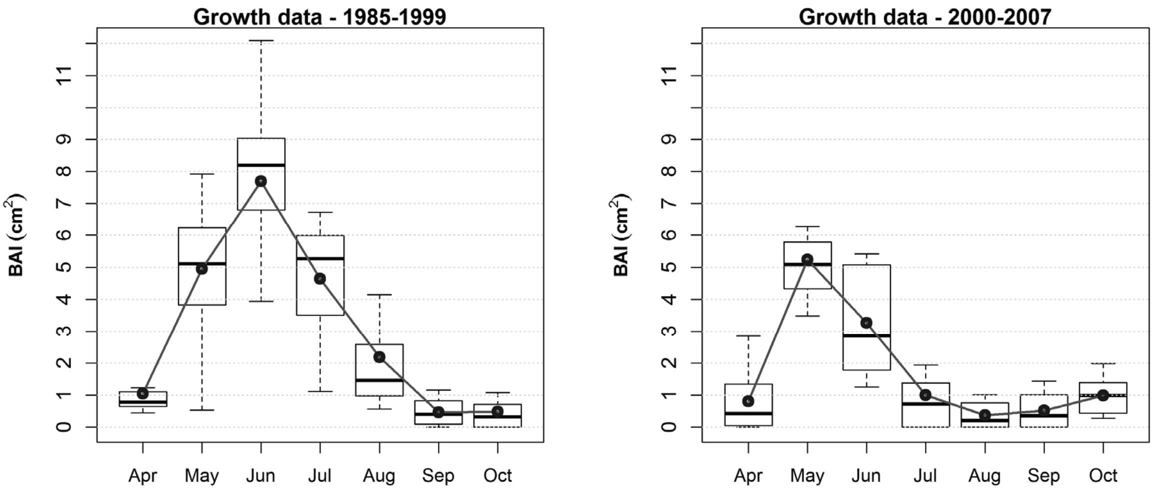

Fig. 6. Absolute average monthly increments in the periods of 1985-1999 and 2000-2007. Legends: refer to *Fig. 5*.

3.3. *Relationship between increments and meteorological parameters*

For evaluation we applied the linear correlation analysis based partly on monthly and partly on periodic (mean temperature and precipitation sum of a few neighboring months) components (CReMIT). Significant relations between them are compiled in *Table 8*. From correlation coefficients (r), the direction and the rate of the effect can be studied.

Table 8. Significant correlations between BAI and monthly (M) or periodic (P) meteorological variables

M	t_{-2} (Oct)	t_{-1} (Jun)	t_{-1} (Nov)	t (Jun)	p_{-2} (Jun)	p_{-2} (Nov)	p_{-1} (May)	p (Apr)	p (Jun)
r	–0.41*	–0.42*	–0.53**	–0.53**	0.50**	0.49**	0.44**	0.45**	0.46**

P	t_{-2} (Oct-Nov)	t_{-1} (Apr-Jun)	t_{-1} (Oct-Nov)	t (Jun-Jul)	p_{-2} (Jul-Sep)	p_{-2} (Oct-Nov)	p_{-1} (May-Jun)	p (Feb-Apr)	p (Apr-Jun)
r	–0.44**	–0.45**	–0.66**	–0.43**	–0.47**	0.47**	0.44**	0.47**	0.42*

r=correlation coefficient; *t*=temperature; *p*=precipitation; significance levels: *=$p<0.1$; **= $p<0.05$
lower indices –1 and –2 refer to the year before and two years before, respectively

It depends on many factors which month or time period has significant effect on the growth of European beech. *Jump et al.* (2010) and *Mátyás* (2010) found increasing climatic effect at the trailing edges compared to other sites. *Maxime* and *Hendrik* (2011) pointed out the importance of elevation above sea level in the investigation of climate and production relationship. *Dittmar et al.* (2003) showed that relations clearly depend on the elevation. These facts support the possible effects of site-specific features in relationships in many cases.

For monthly components (m), there are significant inverse relationships at 90% probability level between BAI and temperature in October two years before ($t_{-2(Oct)}$) and in June one year before ($t_{-1(Jun)}$), as well as at 95% level for temperature in November one year before ($t_{-1(Nov)}$) and in June in the same year ($t_{(Jun)}$). The negative sign indicates that the temperature conditions in the examined stand are out of optimum range for the beech species (*Čufar et al.*, 2008; *Petras* and *Mecko*, 2011; *Scharnweber et al.*, 2011; *Michelot et al.*, 2012). For monthly precipitation correlations are positive at 95% probability level in all cases (two years before in June: $p_{-2(Jun)}$ and November: $p_{-2(Nov)}$, one year before in May: $p_{-1(May)}$, and in the same year in April: $p_{(Apr)}$ and June: $p_{(Jun)}$), i.e., the higher precipitation favors growth (*Lebourgeois et al.*, 2005; *Werf et al.*, 2007; *Čufar et al.*, 2008; *Prislan et al.*, 2013). Significantly affecting components can be observed in the main periods of important physiological processes (budding, defoliation in previous year, organic matter production).

We handled maximum three consecutive months as a period. Over these periods we calculated average temperatures and precipitation sums. It can be noted that the months that are dominant in correlation for monthly components are also dominant in the periodic components.

The results of the multivariable linear regression analysis are displayed in *Table 9*, where beside the corrected coefficient of determination (R^2_{adj}), the simple coefficient of determination (R^2) are also indicated. The R^2_{adj} considers the number of independent variables in the models.

Based on the climate indices, CI_{tm} and $CI_{pm,}$, calculated from only monthly data, it can be concluded that monthly precipitation ($R^2_{adj} = 0.65$) has higher influence on growth than monthly temperature ($R^2_{adj} = 0.44$). This supports the finding of *Gutiérrez et al.* (2011), i.e., temperature affects the organic material production in shorter (days, weeks) periods than that of precipitation. The same findings were published firstly by *Ellenberg* (1988) and justified later also by others (*Geßler et al.*, 2007; *Werf et al.*, 2007). The relation is more significant, $R^2_{adj} = 0.71$, in the case of joint climate index (CI_{tpm}), regarding monthly temperature and precipitation data.

Table 9. The selected climate index models (CI)

Model	$\mathbf{R^2_{adj}}$	$\mathbf{R^2}$
$CI_{tm} = -1.44\times t_{-1(Nov)} - 1.79\times t_{(Jun)} + 49.82$	0.44	0.49
$CI_{pm} = 0.10\times p_{-2(Nov)} + 0.06\times p_{-1(May)} + 0.07\times p_{(Apr)} + 0.03\times p_{(Jun)} - 1.04$	0.65	0.70
$CI_{tpm} = 0.09\times p_{-2(Nov)} + 0.06\times p_{-1(May)} - 0.87\times t_{-1(Nov)} + 0.04\times p_{(Apr)} - 0.9\times t_{(Jun)} + 22.25$	0.71	0.77
$CI_{ts} = -2.01\times t_{-2(Oct-Nov)} - 1.28\times t_{-1(Apr-Jun)} - 2.80\times t_{-1(Oct-Nov)} - 0.04\times t_{(Jun-Jul)} + 61.18$	0.55	0.62
$CI_{ps} = 0.06\times p_{-2(Oct-Nov)} + 0.04\times p_{-1(May-Jun)} + 0.02\times p_{(Apr-Jun)} - 1.39$	0.45	0.54
$CI_{tps} = -0.03\times p_{-2(Jul-Sep)} - 2.13\times t_{-2(Oct-Nov)} - 2.88\times t_{-1(Oct-Nov)} + 0.04\times p_{(Feb-Apr)} - 0.02\times p_{(Apr-Jun)} - 0.42\times t_{(Jun-Jul)} + 57.83$	0.65	0.73
$CI_{tpms} = 0.96\times t_{-2(Oct)} + 0.1\times p_{-2(Nov)} - 1.34\times t_{-1(Apr-Jun)} + 0.03\times t_{-1(May-Jun)} - 1.31\times t_{-1(Oct-Nov)} + 0.06\times p_{(Apr)} - 0.01\times p_{(Jun)} - 0.98\times t_{(Jun)} + 37.84$	0.71	0.81

t=temperature, *p*=precipitation, m=monthly, s=seasonal
lower indices –1 and –2 refer to the year before and two years before, respectively

The coefficient of determination calculated for the periodical additive temperature climate index (CI_{ts}) is $R^2_{adj} = 0.55$, a little higher than that for monthly components. In contrast, the same coefficient for precipitation (CI_{ps}) is lower than for the monthly components, $R^2_{adj} = 0.45$. That is, for periodic climate indices the temperature has higher influence than precipitation. When considering the additive effect of periodic temperature and precipitation parameters (CI_{tps}), we can conclude that the relation is less significant than for monthly components ($R^2_{adj} = 0.65$).

Corrected coefficient of determination of model calculated both with monthly and periodic components (CI_{tpms}) gives a strong relationship with $R^2_{adj} = 0.71$. Temporal variations of observed and modeled basal area increment are presented in *Fig. 7* for models of CI_{tpm}, CI_{tps}, and CI_{tpms}. Except of a few years (e.g., 1991), it is evident that observed values fits well within the upper and lower confidence limits of the models.

We have analyzed the relationship between monthly increments and meteorological variables. As we pointed out in the breakpoint analysis, year-by-year changes in meteorological conditions may be reflected in changes of increments. From results in *Table 7* it can be seen, that, e.g., substantial decrease occurred in June in increments from 2000. Two years before this decrease, a significant precipitation decrease started in June (*Table 4*, *Fig. 8*) accompanied by a delayed increase in growth in the following years. Mean temperature in June still increased well before this decrease (since 1992), probably also affecting the increments in June of later years. Therefore, we examined by linear regression analysis the relationship between increments and meteorological variables (precipitation, temperature) in each month of the vegetation period. *Table 10* shows significant relationships in increments as the function of mean temperature and precipitation in May and June. In May, July, and August, the joint effect of temperature in the given month and a month before in the increments is more significant than that of the given month. The sign of correlation coefficient shows a positive effect of temperature in the monthly growth in spring (April, May), while later, rising temperature does not favor the increments.

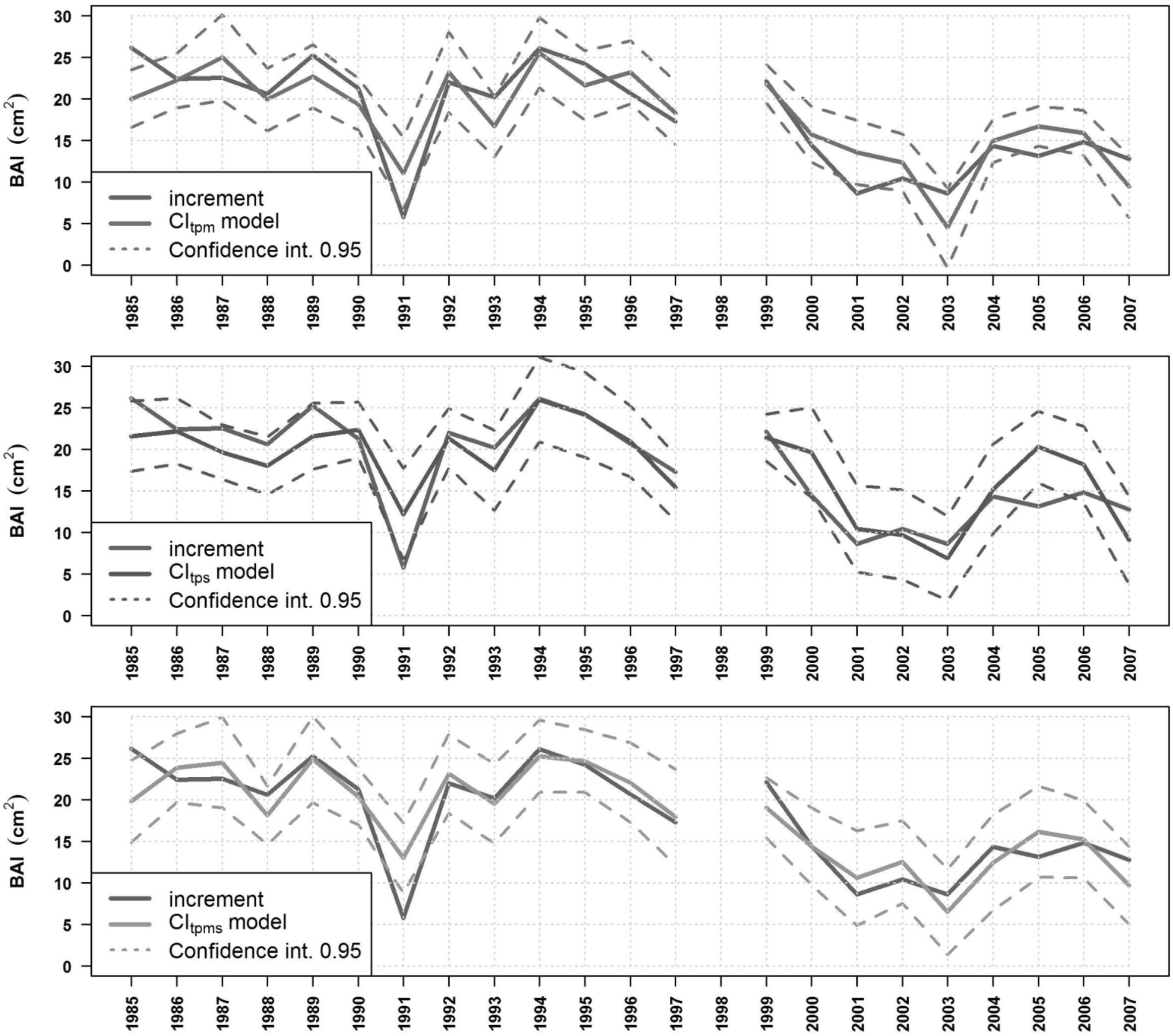

Fig. 7. Variation of the measured and modeled basal area increment (BAI) for models of CI_{tpm}, CI_{tps}, and CI_{tpms} (n=22, p<0.001).

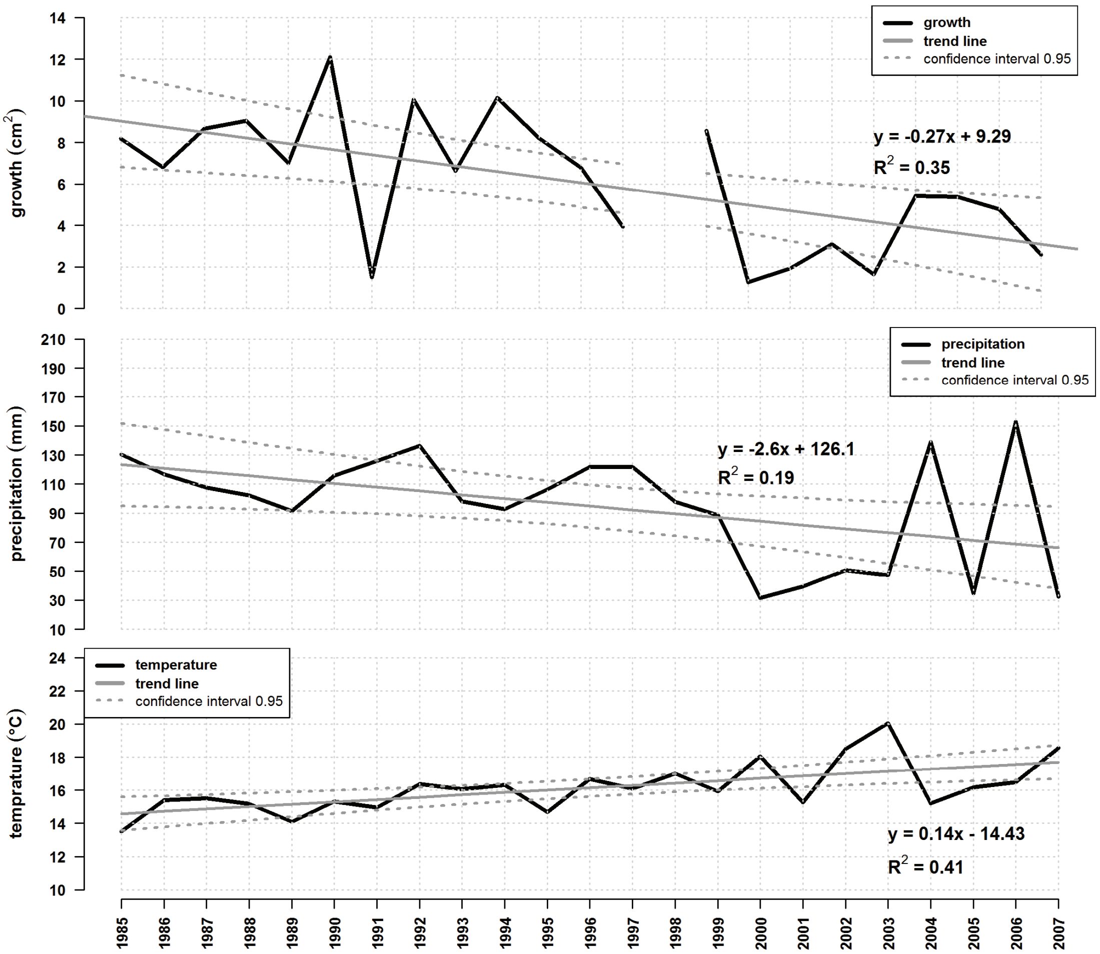

Fig. 8. Trend of increments (n=22, p<0.01), mean temperature, and precipitation in June (n=23, p<0.001).

Table 10. Correlation coefficients (r) of regression between monthly increments and meteorological variables

Meteorological parameters	Months						
	4	5	6	7	8	9	10
Precipitation in the given month	0.301	–0.371*	0.507**	–0.245	0.264	0.415*	–0.049
Precipitation in the given and preceding months	0.266	–0.125	0.250	0.236	0.288	0.167	–0.161
Mean temperature in the given month	0.196	0.392*	–0.506**	–0.051	–0.321	–0.273	–0.048
Mean temperature in the given and preceding months	0.315	0.653**	–0.412*	–0.488**	–0.489**	–0.157	–0.030

significance levels: *indicates *p*<0.1; **indicates *p*<0.05

4. Discussion

The largest growths were detected in May and June in the studied beech stand over the studied 22 years. Average BAI observed were 5.02 and 6.08 cm^2 (28 and 34%) in May and June, respectively (alltogether 62% of yearly growth). While in May trend could not be observed for growth (y = –0.0018×x + 5.0698, R2=4x 10–5), there was a negative significant trend in June (*Fig. 8*; y = –0.27×x + 9.29, R2=0.35). As a consequence, while in the first 11 years of observation the mean BAI in June was almost the double of that of May (8.03 vs. 4.84 cm2), in the second 11-year period growth in May exceeded the production of June (5.20 vs. 4.12 cm^2). This phenomenon was related to the positive trend of average temperature and the negative trend of increments in June over the years (*Fig. 8*) (there is no significant trend for precipitation in June). In contrast, in May there is a positive relationship between the BAI and the mean temperature (*Fig. 9*). This shows that the intensive growing period started earlier in the 2000s, which projects an increase of sub-Mediterranean climate influence at the observation site, obviously modifying the spread of beech. Our results underline the determining effect of May and June in organic matter production of beech in agreement with other studies from Europe (*Dittmar et al*., 2003; *Lebourgeois et al*., 2005; *Di Filippo et al*., 2007; *Garamszegi* and *Kern*, 2014).

It is worth also mentioning, that the total BAI loss and the increased BAI in the final period is accompanied with opponent changes in growth signal coherence. Mean within-trees correlation slightly decreased for the total and significantly increased for the final period following the detected breakpoint.

As it can be seen from the calculated regressions (*Table 8*) as well as from the climate indices (*Table 9*), increments of trees are influenced by the climate of different months or periods not only in the given year but also in the previous two years. Analyzing the data, the following general tendencies can be seen. Taking into account the sign and magnitude of coefficients in the tables, the precipitation has positive effect on growth while the influence of temperature is the opposite.

Precipitation in autumn (October, November) two years before a given year has generally positive effect on girth growth. In the previous year, positive influence of precipitation can be observed in spring in the most intensive growing periods (May, June). In the given year, the precipitation – in spite of a few exceptions – has dominantly positive effect in the period of February-July, especially in the initial growing period (April) and at the beginning of the main growing period (May, June) when majority of increment is realized. Negative influence of air temperature is realized in autumn (October-November) one or two years before the given year but the effect of temperature can also be observed in spring-summer one year before, and it is evident in the given year in early summer, mostly in June.

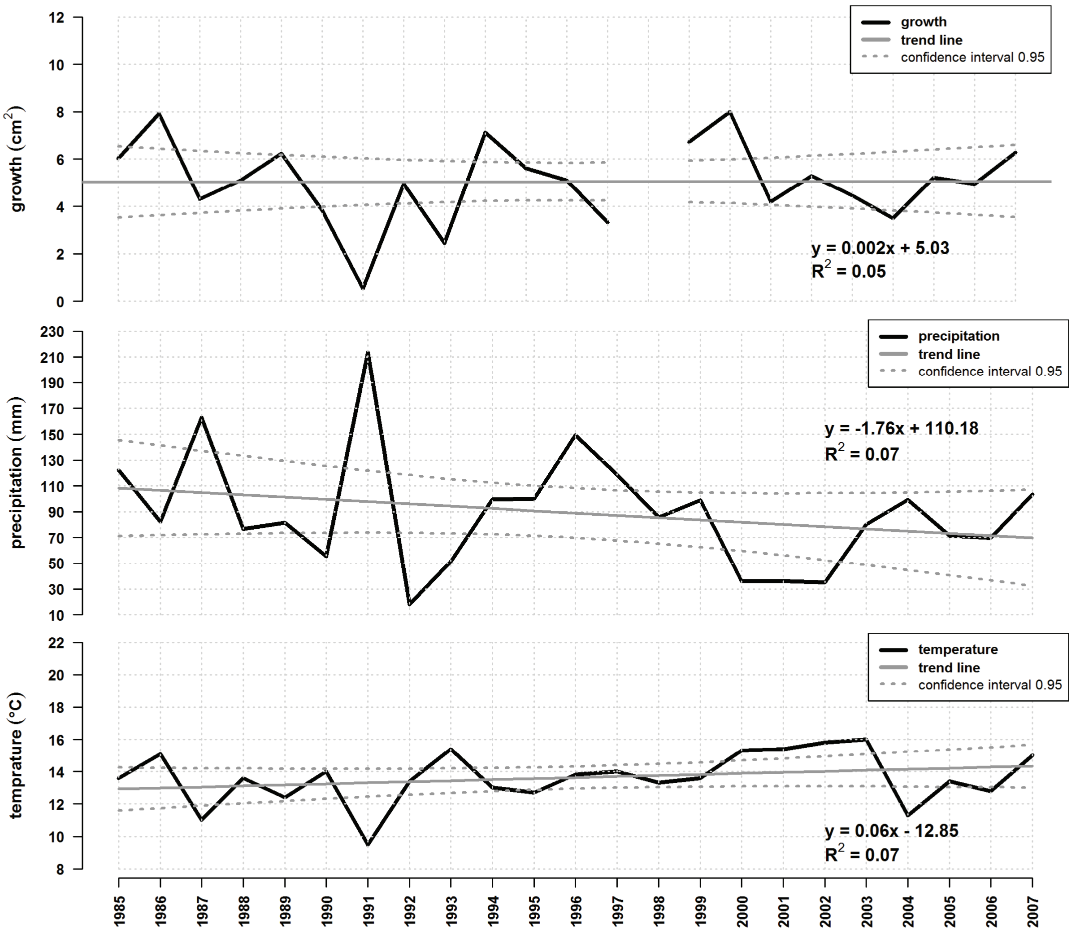

Fig. 9. Trend of increments (n=22, p<0.01), mean temperature, and precipitation (n=23, p<0.001) in May.

The examined stand according to the forestry aridity index (*Führer et al.*, 2011) definitely belonged to the beech climate zone. However, since the end of the 1980s, a drastic change was observed. The sum of precipitation decreased by 10%, nearly by 3%, and by 14% in the initial, main, and final growing stages, respectively, during the 1991–2007 period compared to the 1961–1990 reference period (*Table 11*). These changes are already higher than the forecasted data for 2035–2065 calculated by the REMO model (*Gálos et al.*, 2007). At the same time, temperature showed a steady increasing trend in almost each different growing (sub)period within the year. The change in the initial period is 0.7 °C, while in the main growing period it is as high as 1.2 °C. If the tendencies of precipitation and temperature keep on following the climate change scenario of the REMO model, living conditions of beech in the surroundings of the monitored stand will change to such an extent that can lead to not just increment decrease (*Piovesan et al.*, 2008), but also potential extinction.

Table 11. Climate parameters in the reference period (1961–1990), in the period of investigation (1991–2007), and forecasted by REMO model (*Gálos et al*., 2007) (2035–2065) in absolute and relative values

Growing Period (Months 1–12)	**Time intervals (years)**									
	1961–1990		**1991–2007**				**2035–2065**			
	***p* (mm)**	***t* (°C)**	***p* (mm)**	**d*p* (%)**	***t* (°C)**	**d*t* (°C)**	***p* (mm)**	**d*p* (%)**	***t* (°C)**	**d*t* (°C)**
Year (1–12)	753	7.6	774	2.8	8.4	0.8	775	2.9	9.5	1.9
Dormant (11–3)	216	–0.2	228	5.5	0.4	0.6	238	10.2	1.7	1.9
Growing (4–10)	536	13.2	547	2.1	14.1	0.9	537	0.2	15.1	1.9
Initial (4)	60	7.7	54	–10.0	8.4	0.7	63	5.0	9.0	1.3
Main (5–8)	352	15.8	343	–2.6	17.0	1.2	332	–5.7	17.7	1.9
Final (9–10)	124	10.8	150	21.0	11.0	0.1	142	14.5	13.2	2.4
Intensive (6)	100	15.3	86	–14.0	16.5	1.2	91	–9.0	17.4	2.1

The coinciding breakpoint detected in the series of climate and BAI suggests that the significant change in climate parameters affected the production as well. Both the strength and the sign of the relationship between the climate and the growth data changed, as it is illustrated by the correlation coefficients between the BAI and the FAI (*Führer et al*., 2011) or EQ (*Ellenberg*, 1988) drought indices (*Table 12*) separately in the two periods until and after 1999. While climate was favoring for growth of beech (1985–1999) represented clearly by beech climate (FAI=4.01), only the monthly precipitation sum in FAI from May to August had significant influence on the yearly production. The increase of summer precipitation negatively affected the yearly growth in this period. After the climate became dryer and warmer from 2000, the mean FAI has changed to the border of beech/hornbeam-oak climate (FAI=4.82), and this enhanced climate stress has stronger effects on the yearly growth. These results support the observations of *Mátyás* (2010) and *Garamszegi* and *Kern* (2014) who pointed out the increasing climate sensitivity of beech towards the border of beech/hornbeam-oak climate. This manifests not only in the decline or the fall of trees but also in the decrease of growth accompanied with unfavorable economic impact, i.e., the decreasing profitability of forest management (*Führer et al*., 2013).

An earlier basal area increment survey performed near the town of Gödöllő, Hungary, between 1974 and 1983 (*Járó* and *Tátraaljai*, 1985) for different species (ten deciduous and seven pine stands) showed that the growth generally started before the middle of April for all species of deciduous trees and ended before the end of August. Growth in September was observed in the case of only a few species, such as black locust, hornbeam, and ‘I-214’ poplar, and it lasted only for a few days. For pines, the growth started two weeks earlier and ended generally in the first third of October. Thus, the average length of the growing period for deciduous species was 139 and for pines it was 190 days.

Table 12. Correlation coefficients between average yearly BAI and drought indices (FAI, EQ); their precipitation (P_{FAI}, P_{EQ}) and temperature (T_{FAI}, T_{EQ}) components in periods of 1985–1999 and 2000–2007

Periods	P_{FAI}	P_{EQ}	T_{FAI}	T_{EQ}	**FAI**	**EQ**
1985–1999	–0.50*	–0.23	0.10	0.15	0.29	0.27
2000–2007	0.48	0.40	–0.75**	–0.37	–0.69*	–0.55

significance levels: * indicates $p<0.1$; **indicates $p<0.05$

According to our phenological observations parallel with BAI measurements in the Sopron Mountains, the beech came into leaf from the middle of April and ended at the end of the same month. The period of autumn discoloration of leaves ranged between the beginning and the end of October, while defoliation occurred till the middle of November. It means, that the average length of time period for photosynthetic, i.e., growing processes was 173 days.

Since the start of the initial growing period was the same in the Gödöllő region for 1974–83 as at the Sopron Mountains for 1985–2007, and the lengths were equally two weeks for both regions, the reason for the difference between the two growing periods is the different length of the main growing periods. In the Gödöllő region, the 103-day-long main growing period lasted till the middle of July, when 93.3% of organic material was produced. In the case of beech stand in the Sopron region the same portion of organic matter (93.3%) was produced, but it occurred till the end of August over a 140-day-long main growing period. The final period was of the same length at both areas, finished at the end of August and in the first third in October at Gödöllő and Sopron regions, respectively. The reason for the different length or timing of the main and final cycles, beside the differences in species, is the difference in climate conditions. Namely, whilst the average yearly precipitation in the Gödöllő region was 544 mm and the yearly average temperature was 9.5 °C, these values were much higher for precipitation (764 mm) and lower for temperature (8.2 °C) for the Sopron area in the measurement periods, i.e., the Gödöllő area is drier and warmer compared to the Sopron Mountain region.

Similar results to the Sopron region was reported for an old-growth beech near Solling, Germany (*Schulze*, 1970; *Schulze et al.*, 1977), where the number of days with positive carbon dioxide balance during a year reached 176, which implies that the growing period might be shorter. Partition of cambium can also be observed for beech at the later stage of growing period; that is, the initial rapid growth of beech may even stop at the end of July and in August, starting again in September, lasting to early October (*Schmitt et al.*, 2000; *Werf et al.*, 2007). This phenomenon was also observed near Sopron in 2003, when, as the consequence of extremely dry summer, the growth was suppressed in July and August and started again in September lasting till the middle of October when an additional 20% of yearly growth was produced.

Although, it can be generally stated that annual increment is largely determined by weather conditions in the given year and also in the previous two years, months with the strongest impact are probably determined not only by climate parameters, but also the genetic properties of trees beside the seasonality in temperature and precipitation characteristics. While in the neighboring Slovenia precipitation in May-June of the given year has the most important effect on increments of trees (*Čufar et al.*, 2008), and in the Mediterranean region (Albania, Macedonia) the June-September temperature has a negative effect on growth (*Tegel et al.*, 2014), in the Sopron Mountains, where both the yearly precipitation amount and the temperature is lower, the dominant parameter for growth is the precipitation in April and June. In addition, while in Germany the temperature in July in the given year and a year before are dominant for growth (*Gruber*, 2002), in the Sopron region the June temperature in the given year and a year before are determinant.

This overview suggests that further research efforts on beech physiology is needed to give successful explanation on which climatic conditions (monthly or periodic) are the primary drivers of organic matter production through biochemical processes. For this reason, calculation of universal climate index for general use is still not possible, but it can be done in a similar way for stands in different climate and genetic conditions.

As we have already seen above, there were substantial variations in precipitation and temperature conditions among different months during the observed period. On the basis of linear regression analysis, the growth in May and June significantly depends on the average temperature and precipitation. The sign of correlation coefficient shows a positive relation between growth and temperature in spring, but in the following months the relation is negative (*Table 10*). The effect of precipitation is just the opposite; in springtime the precipitation shows negative correlation with growth, while in the following periods the relation is positive.

The breakpoint analysis in the period of 1985–2007 indicates significant shifts in the monthly precipitation and temperature between 1990 and 2000 (*Table 4*). After the breakpoints we found positive and negative shifts for temperature and precipitation, respectively. We suppose that the observed decrease of increments (*Table 7*) is due to the change in meteorological conditions, and taking into account the predicted climate change scenarios these phenomena will proceed in the future. The change in meteorological conditions are reflected not only in the decrease of yearly increment but also in decreasing share of summer, increasing relative share of spring, and importance of autumn months' conditions in the yearly growth. In addition, growth in May became dominant after the breakpoint instead of June, and the share of July and August drastically decreased in that period (*Fig. 4*). E.g., the increments in July were zero in three years (2002, 2003, and 2007) and were, similarly, zero in four years in August (2000, 2001, 2003, and 2004). This phenomenon is in connection not only with the meteorological conditions of July/August in the given year but also with the climate in preceding months or periods even two year before.

The determining effect of May and June in organic matter production of beech were reported previously as well (*Dittmar et al*., 2003; *Lebourgeois et al*., 2005; *Di Filippo et al*., 2007). According to earlier observations (*Járó* and *Tátraaljai*, 1985), in Hungarian conditions the maximum growth can be observed in June for almost all of tree species. *Knott* (2004) examined a beech stand in an average year of 2001 (elevation: 470 m, DBH: 38 cm, yearly mean air temperature: 7.9 °C, precipitation: 761 mm year^{-1}). The increments for trees have the maximum in summer (increments in July, June, Aug, May are: 30.3%, 27.4%, 21.6%, and 16.0%, respectively). Precipitation in July and August was above the average. This could be the reason of the relatively higher increments in the summer months compared to our test site. This statement is, however, no longer valid for our beech stand, where the maxima of growth shifted to May. It may be an indirect indication of the climate change (*Werf et al*., 2007; *Ježík et al*., 2011; *Čufar et al*., 2012).

Signs of change in relative share of different months and the increasing share of spring in increments were reported earlier similarly to our findings. *Ježík* et al. (2011) investigated beech trees in 2003–2008 with similar climate conditions (elevation: 470 m, DBH: 32–36 cm, yearly mean air temperature: 7.9 °C, precipitation: 715 mm year^{-1}). They found that at the start of the vegetation season, increments positively correlated with temperature. In summer it was hampered by long-term heat waves and the positive influence of precipitation became more pronounced. In view of the predicted climate change, they expected a shift in the culmination of beech seasonal diameter increase towards May caused by warmer springs and a higher frequency of summer droughts and heat waves.

Werf et al. (2007) also pointed out the effect of drought in the year of 2003 to the increment. They measured the increments of beech when summer temperature was 2.1 °C higher and precipitation was 59% lower than the 100-year average (9.5 °C, 760 mm). In summer drought the growth ceased, but it recovered after the drought as it was observed in our test stand after a significant change in summer temperature and precipitation since 2000. The decrease in increment is evident in the dry season, since soil drought stimulates increased stomatal resistance with parallel decrease of photosynthetic activity for European beech (*Priwitzer et al*., 2014).

5. Conclusions

There were characteristic breakpoints both in meteorological parameters and in beech increments in the Sopron Mountains between 1999 and 2000. The negative shift in precipitation and positive shift in temperature caused a dramatic decrease in growth in summer. There was a shift in maximum monthly increments from June to May, indicating the effect of the climate change on seasonal growth of beech. Significant, dramatic decrease in growth can be observed in July and August that was not observed before. Due to the warmer spring and the arid summer months, the relative share of spring and importance of autumn months increased and expectedly will be increasing in the future. The phenomena of low or zero growth in July and August, observed often after 2000, probably will be more frequent in the future, taking into account the predicted climate change scenarios. The long-term trend of yearly basal area increment is continuously decreasing; the average yearly increments halved between 1985 and 2007.

According to multivariable regression analysis on independent variables derived by CReMIT, the yearly basal area increment is affected not only by meteorological parameters but also the climate of the previous two years. Precipitation generally favors organic matter production in contrast with temperature. Interestingly, one of the dominant periods for basal area increment is the autumn two years before a given year (October-November), when precipitation has positive influence and temperature has negative effect on the increment, i.e., the wet and cool autumn in that year favors organic matter production. Regarding the preceding year, precipitation in the main growing period (spring-early summer) has positive while temperature in autumn has negative effect. Finally, in the current year, precipitation in spring-early summer (especially in April-June) helps the growth of trees, and in contrary, the temperature in that period has negative effect on the increment. There is a negative relationship between the observed basal area increment and the mean temperature in June (July).

The share of basal area increment in the main growing cycle is continuously decreasing which is partly compensated by a parallel increase of it in the final growing period as the climate at the studied region, in the Sopron region, Hungary has become warmer. This phenomenon underlines the general observations made in Hungary. The warming climate has negative effect on the production of trees. According to forecasted climate change, when temperature in early summer in Hungary will be higher and higher, not only the loss in growth but also the drastic decay in vitality and tolerance of trees can be expected.

It seems that the rate of increments is controlled by weather parameters in earlier phenological phases in previous years as well as through the effect of different physiological processes described above (defoliation, bud structure production, cupules production, etc.), at least for the examined stand. The direct generalization of the observations is hardly possible regarding the high differences in species composition, genetics, climate, pedology, hydrology, etc., among the different regions, as we saw in the discussion through examples for other sites for Hungary as well as for Slovenia and Germany. However, the tools and methods applied in this paper are suitable to study other areas to determine which periods and which weather components have the greatest influence on the yearly increments of trees.

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Appendix

Brief description of CReMIT

Let be given a time series and its natural period denoted by *P*. The elements of this time series are stored in vector *ts*. Let the first element of *ts*, ts_1 be the chronologically latest element, and natural numbers will be assigned to the data accordingly:

$$ts = \begin{pmatrix} ts_1 \\ ts_2 \\ \vdots \\ ts_m \end{pmatrix}.$$

Let be denoted by *SP* ($1 \leq SP \leq P$) the starting point of the currently applied investigation, this is the *SP*th element of the vector *ts*. Special windows are applied on the vector *ts*, the time shifting (*i*) and width (*j*) values of a window are defined based on this index. The minimal value of time shifting can be 0 (*i*=0), and the minimal window width can be 1 (*j*=0). Based on the periodicity *P* of the basic time series, the above defined window will be periodically repeated with the maximum cycle number (*MCN*). The value of *MCN* depending on the defined parameters (*SP*, i, j) can be created:

$$MCN = \left[\frac{n-(SP+i+j)}{P}\right]+1,$$

where square brackets is for the integer part function.

The starting and end point indices of the windows created with the actual SP, i, and j values can be defined as $[SP + i + l \times P; SP + i + j + l \times P]$, where $0 \leq l \leq MCN$. Two temporal vectors are defined for the storage of the index values determining the limits of the windows using these parameters. Let us denote by:

$$index_{begin} = \begin{pmatrix} SP + i + 0 * P \\ SP + i + 1 * P \\ \vdots \\ SP + i + (MCN - 1) * P \end{pmatrix},$$

$$index_{end} = \begin{pmatrix} SP + i + j + 0 * P \\ SP + i + j + 1 * P \\ \vdots \\ SP + i + j + (MCN - 1) * P \end{pmatrix}.$$

By using the above defined index vectors, a pre-defined transformation function TR can be applied on the elements of the individual windows.

$$tr\_x_{SP,i,j} = \begin{pmatrix} TR(index_{begin}[1]; index_{end}[1]) \\ TR(index_{begin}[2]; index_{end}[2]) \\ \cdots \\ TR(index_{begin}[MCN]; index_{end}[MCN]) \end{pmatrix}$$

Based on the starting point ($1 \leq SP \leq P$), the maximum time shifting value I ($0 \leq i \leq I$), and the maximum window width J ($0 \leq j \leq J$) pre-defined on the basis of the task, all the potential $tr\_x_{SP,i,j}$ transformed vectors can be generated on a systematic way. The above mentioned MCN value defines the number of windows for the current parameters (SP, i, j) and the dimension of the transformed vector.

The different phases of the CReMIT are: i) data preparation, ii) creation of the secondary dataset, and iii) analyses of the whole datasets. Considering technical points of view, creation of secondary dataset can be determined by the maximum seasonal shift and length of the investigated period. Hence, by using an appropriate aggregation function (TR) (e.g., mean, sum, minimum, maximum) new, complex data sets can be derived consistently from the original data. The CReMIT has been applied for weather parameters in this work. The relevant time intervals to the growth data of the given year were selected using a maximum three years of shift compared to the data of increment, with a maximum of 12 month of an interval length. In this manner, beside the meteorological data for the given year, we involved the mean temperature and precipitation sum data also for the previous two years with a length of 1–12 months (secondary dataset).

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