https://doi.org/10.17221/37/2020-JFS

# The radial increment of European ash (*Fraxinus excelsior* L.) under climate change, Ukraine

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**Citation:** Koval I., Maksymenko N. (2020): The radial increment of European ash (*Fraxinus excelsior* L.) under climate change, Ukraine. J. For. Sci., 66: 288–298.

**Abstract:** The aim of the study was to compare the response of the radial increment of European ash (*Fraxinus excelsior* L.) in the Western and Eastern forest steppe of Ukraine to climate change. The growth-climate relationships were estimated for 1961–1987 and 1988–2014 in Western and Eastern parts of the forest steppe. The results indicate that the sensitivity of the ash radial increment in stands of the Western and Eastern forest steppe to climate variations in the second period (1988–2014) was increased compared to the first period (1961–1987). In the second period correlation analysis and response function showed a negative effect of summer droughts on the ash radial increment for both stands. Also a negative effect of winter precipitation on tree rings of ash trees in the Western forest steppe during the second period was detected. The radial growth response to climate change showed an increase in the response of European ash radial growth to climate change, which was confirmed for European ash for both stands in the Western and Eastern forest steppe.

**Keywords**: ring width; response function; correlation analysis; temperature; precipitation

European ash (*Fraxinus excelsior* L.) is a broad-leaved fast-growing tree species common in most parts of Europe, highly-valued for its ecological properties and occurrence in many forest site types. Decline and significant mortality of ash trees were first recorded in the early 1990s in Poland, in the Czech Republic, in Lithuania, Hungary, Iran, and other countries ( Kowalski 2006; Karpavičius, Vitas 2006; Dobrowolska et al. 2011; Matsiakh, Kramarets 2014; Szabo 2008; Vacek et al. 2015; Davydenko, Meshkova 2017; Khedive 2017). Reasons for these events could be worsening of the health of forests connected with climate changes and groundwater level, simplification in the structure and species composition of forests, invasion of ash trees by the fungus *Hymenoscyphus fraxineus (Hymenoscyphus pseudoalbidus, Chalara fraxinea)*, etc. (Meshkova, Borysova 2017; Langer 2017; Vacek et al. 2017; Shvidenko et al. 2018; Meshkova et al. 2019).

Ash forest stands in Ukraine cover an area of more than 153.8 thousand hectares including more than 131 thousand hectares (85.3%) that are forests of European ash (*Fraxinus excelsior* L.) (Matsiakh, Kramarets 2014). Many scientific researches in Ukraine are devoted to forest properties, reforestation methods, improvement of qualitative composition of ash stands and features of damage by pests, ash mortality, anthropogenic factors that decrease forest resilience (Lavnyy 2000; Davydenko,

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Meshkova 2017; Koval 2017; Maksymenko, Klieshch 2018; Maksymenko et.al. 2018).

Radial growth is an integral bioindicator which reflects the tree response to environmental changes (Ray 2010; Lockwood, LeBlanc 2017). The loss of forest resilience under unstable ecological conditions can be reflected in the variability of the radial growth of trees and its constant suppression. Climatic conditions belong to the main factors provoking a decline of the radial growth of ash in the last decades (Karpavičius, Vitas 2006).

The tree life cycle in the forest is tens or even hundreds of years. They are formed in "old climates" and sometimes they cannot quickly adapt themselves, like herbaceous meadow plants, to new conditions. The assumption that the most common cause of global forest decline is climate change of global nature is nowadays almost a non-alternative hypothesis, but it is extremely relevant to identify specific mechanisms for the development of mass drying (Lockwood, LeBlanc 2017). In trees, the wood retains a 'memory' of the past and tree-ring width allows us to explore the effects of environmental variations, especially climate variables, on radial growth (Fritts, Swetnam, 1989).

Additionally, tree rings integrate multiple environmental and physiological signals (Rusalenko 1986). Researches on relationships between climatic factors and ash radial increment require better understanding of connection between environmental factors and tree growth processes to introduce good forestry practices and verify ecological effects of introduced projects (Okoński 2017).

The aim of the study was to compare the response of the radial increment of European ash (*Fraxinus excelsior* L.) in the Western and Eastern forest steppe of Ukraine to climate change. The specific question addressed in our study is: which climate variables influenced ash tree-ring width at the study sites in stands of Western and Eastern parts of forest steppe for the periods 1961–1987 and 1988–2014? Our main hypothesis was an increase of the sensitivity of ash radial increment to climate variations in the Western and Eastern forest steppe.

The response of the radial growth of European ash in the Western and Eastern forest steppe of Ukraine to environmental changes has not been sufficiently studied, and this study enables us to improve our understanding of ash health condition in the face of climate change.

## MATERIAL AND METHODS

Temperate broadleaf forests in the Western and Eastern forest steppe were the objects of this study regarding the impact of climate variables on the radial increment of European ash (*Fraxinus excelsior* L.) (Figure 1, Table 1). The data of Kharkiv

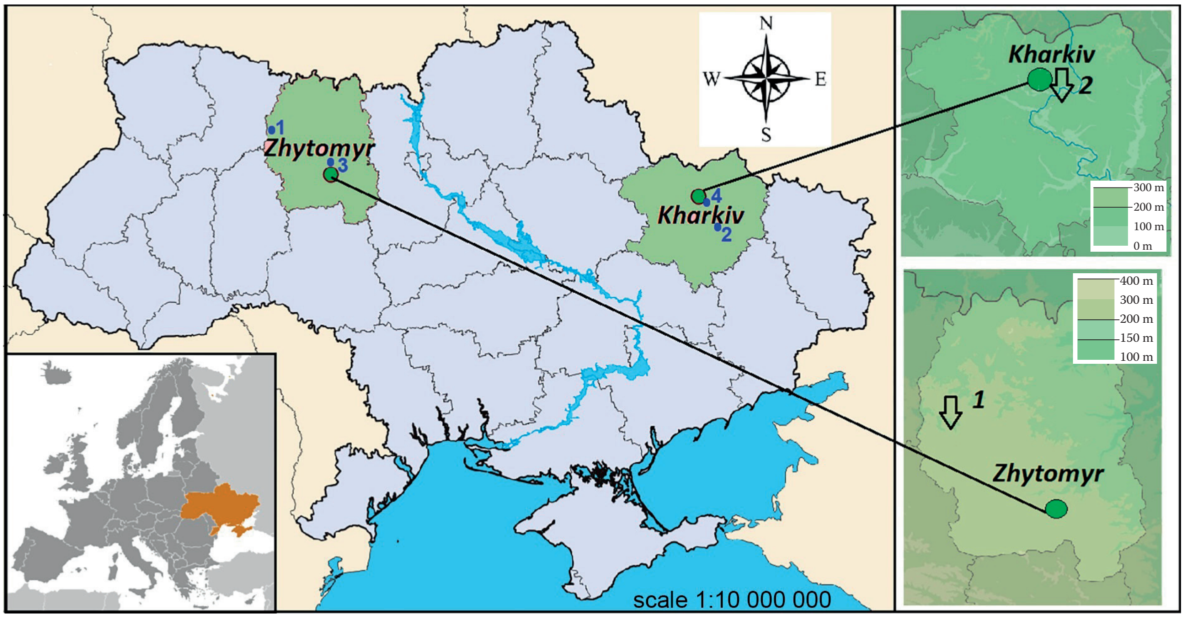


Figure 1. Geographic location of research objects and weather stations (1 – site of extracting cores in Western forest steppe, 2 – site of extracting cores in Eastern forest steppe, 3 – Zhytomyr Weather Station, 4 – Kharkiv Weather Station)

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Table 1. Overview of basic characteristics of research plots

| | Geographic coordinates | Altitude (m) | Species | Age | Diameter (cm) | Height (m) | Stand volume ($m^3 \cdot ha^{-1}$) | Soil type |
|---|---|---|---|---|---|---|---|---|
| Western forest steppe | 50°32'36'' N 27°27'36'' E | 214 | Fe, Qr, Cb, Pt, Ag, | 85 | 34 | 28 | 370 | dark grey podzolic |
| Eastern forest steppe | 49°43'29'' N 36°35'29'' E | 106 | Qr, Fe, Ap, Ac | 100 | 39 | 18 | 402.58 | dark grey podzolic |

Fe – *Fraxinus excelsior* L., Qr – *Quercus robur* L., Cb – *Carpinus betulus* L., Pt – *Populus tremula* L., Ag – *Alnus glutinosa* (L.) *Gaerth.*, Ap – *Acer platanoides,* Ac – *Acer campestre*

(geographic coordinates 49°55'28'' N, 36°17'24'' E, elevation above sea level 155 m) and Zhytomyr (geographic coordinates 50°15'53'' N, 28°40'36'' E, elevation above sea level 228 m) weather stations were used (Figure 1). A distance between research object 1 and Zhytomyr weather station is 84 km, and between research object 2 and Kharkiv weather station it is 52.1 km. Continuous data on daily mean temperatures and daily total precipitation have been available from both weather stations since 1961. The climatic conditions of the forest steppe are characterized by an increase in continentality (the difference between winter and summer temperature) and a decrease in precipitation from the west (600 mm per year) to the east (350–400 mm per year). While the mean monthly air temperature during the year varies from –4 to +18°C in the western regions of the forest steppe, in the eastern regions – from –7 to +21°C (Figure 2).

Temperatures in early spring, winter and growing season have increased in the last time. Winter is getting milder and also an increase in precipitation in the cold period has been recorded in the Western and Eastern forest steppe (Marynych, Shyshchenko 2005).

Standard dendrochronological techniques have been used (Cook 1990). The cores were extracted with the Pressler borer from 20 trees at a height of 1.3 m. After air drying, the core surfaces were prepared with razor blades and the surface contrast was enhanced with chalk.

The tree ring widths were measured using digital Henson equipment (Henson Co., California, USA), to the nearest 0.01 mm. We visually crossdated all cores using the skeleton-plot technique (Stokes, Smiley 1996). The correct dating of measured tree ring series was checked using the COFECHA program (Tree-Ring Lab, Tucson, USA), which identifies segments within each ring width series that may have erroneous crossdating or measurement errors. Then the average ring width series were calculated for each stand (Holmes 1983; Grissino-Mayer 2001).

The degree of year-to-year change in tree ring widths was evaluated by calculating the mean sensitivity of tree rings for each sample following the formula (Cook 1990):

$$K = \frac{1}{(n-1)} \sum_{(t=1)}^{(n-1)} \frac{2\,(x_{(t+1)} - x_t)}{(x_{(t+1)} + x_t)} \quad (1)$$

$K$ – mean sensitivity;
$N$ – the total number of rings;
$x_t$ – tree ring width in year (t).
The value of mean sensitivity ranges from zero to two (Cook 1990).

Interseries correlation coefficients were calculated among individual tree ring chronologies to indicate the extent to what trees respond to environmental change synchronously (Cook 1990).

Residual chronologies were calculated using the ARSTAN program (Tree-Ring Lab, Tucson, USA) with the purpose to enhance the climate signal in ring width series. First, a negative exponential curve or a linear regression line was fitted to the ring series. The second step used a cubic smoothing spline with a frequency response cutoff set at two-thirds of the length of each series. In this way most of the low-frequency variability in each ring series that is assumed to be unrelated to climate like tree aging and forest stand development was removed. Dimensionless indices were created by dividing the observed ring width value by the predicted ring width value (Cook 1984; Cook, Holmes 1996; Rozas 2005).

The RESPO program (Tree-Ring Lab, Tucson, USA) computes response functions of tree growth

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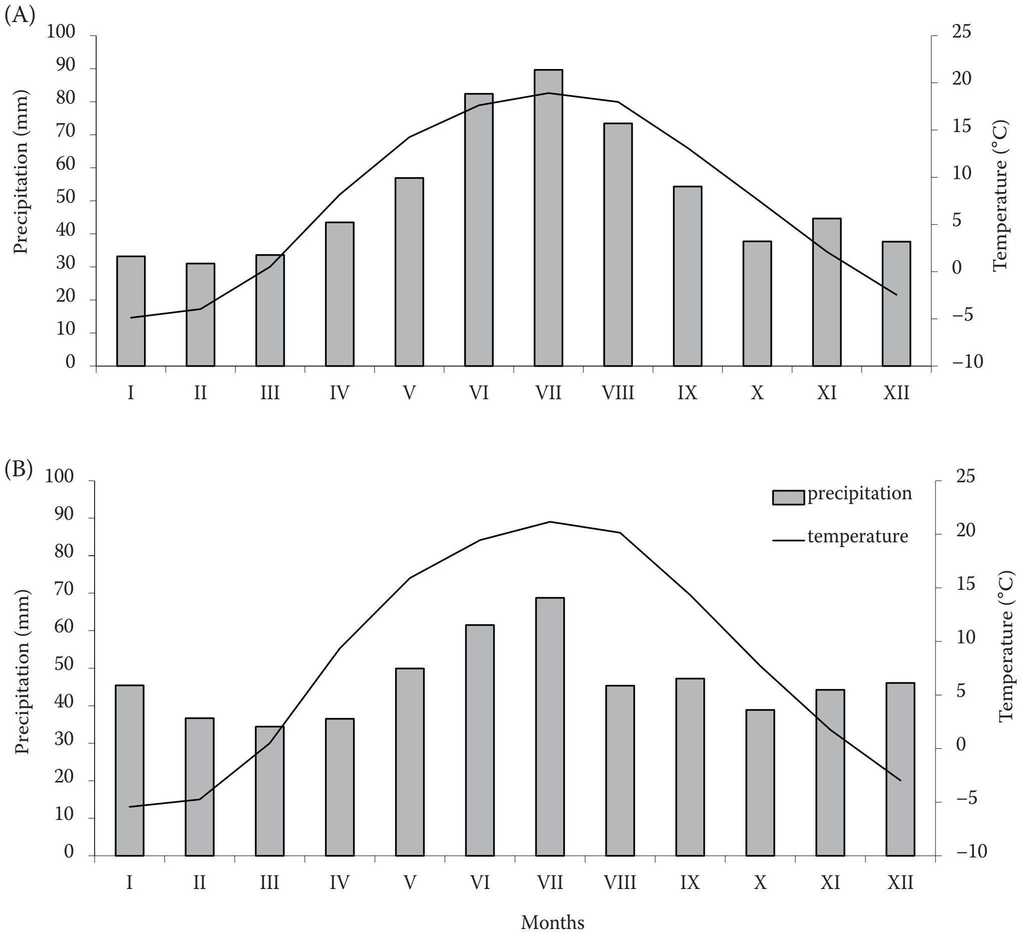


Figure 2. Climatograms of (A) Zhytomyr and (B) Kharkiv weather stations for 1961–2014

to climate by means of principal components, using two methods for selecting the components for regression. The correlation function was also calculated along with the response function. Regression weights were used for subsequent plotting (Holmes 1996). In response function analyses, the variation of ring width indices was estimated through multiple regressions, after extracting the principal components of the climatic predictors to avoid any intercorrelation between them (Fritts 1976). This includes a bootstrap method to assess statistical significance of the regression coefficients in response functions. Multiple regression analysis was also carried out by considering, as growth predictors, those climatic variables which showed a significant effect on tree ring growth, as revealed by correlation and response functions (Holmes 1996).

We calculated mean temperature and accumulated precipitation for each month from June of the previous year to August of the current year. An interval of 16 months was selected to define the climatic predictors: from June of the year prior to ring formation (t–1) to September of the year in which the growth ring was formed (t). Correlation coefficients between the residual ring width indices and each of the climatic variables were calculated in order to derive correlation functions (Blasing et al. 1984).

The growth-climate relationships were estimated for 1961–1987 and 1988–2014 for Western and Eastern parts of the forest steppe by taking the monthly mean temperatures and total precipitation records as climatic predictors, and the residual index chronologies as dependent variables. The second period is characterized by an average annual temperature increase by 17% for the Western forest steppe and 13% for the Eastern forest steppe (Figure 3). While temperatures in the growing season increased by only 5–7%, March temperature almost twice, temperatures in winter months (from December of the previous year to January of the current year) increased significantly by 30 to 68%

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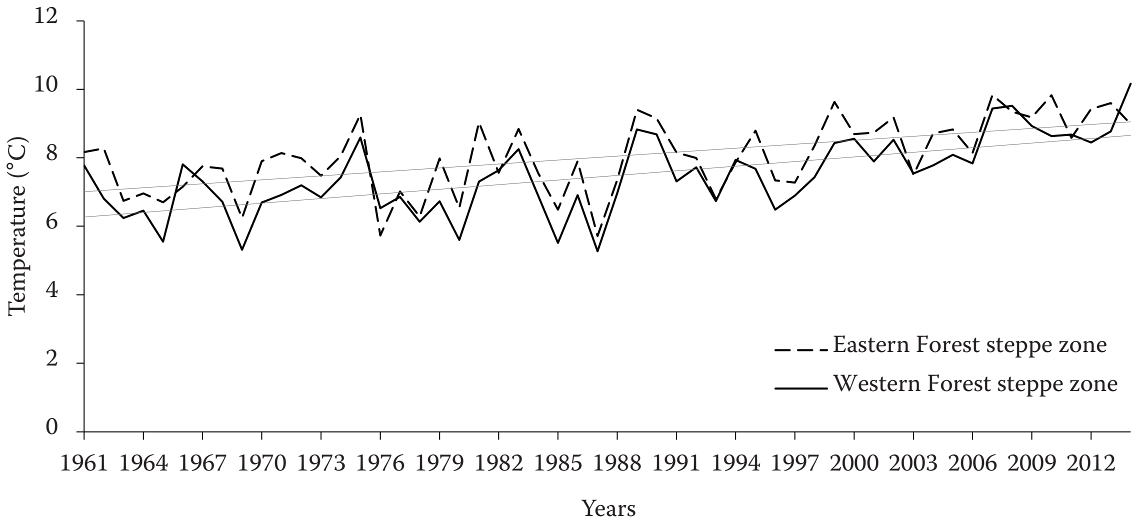


Figure 3. Dynamics of temperatures according to Zhytomyr Weather Station (Western forest steppe) and Kharkiv Weather Station (Eastern forest steppe) and a long-term trend for 1961–2014

in the second period. In the Western forest steppe there is no change in the rainfall sums between the first and second period. On the other hand, in the Eastern forest steppe the sum of precipitation increased by 9% during the growing season but it decreased by 14% during winter.

## RESULTS AND DISCUSSION

Two tree ring chronologies were developed within the Western and Eastern forest steppe. Figure 4, whereby most ring series showed an age-related decrease in ring width. The mean ring width of ash trees in the Eastern forest steppe was reduced by about 10% compared to that in the Western forest zone (Table 2).

Intercorrelation coefficients and mean sensitivity of the tree ring series indicate the signal strength in tree ring chronologies, which is quite high. This confirms the data suitability for analysing the relationship between climate and ash radial growth. At the same time, a tree ring chronology of the ash

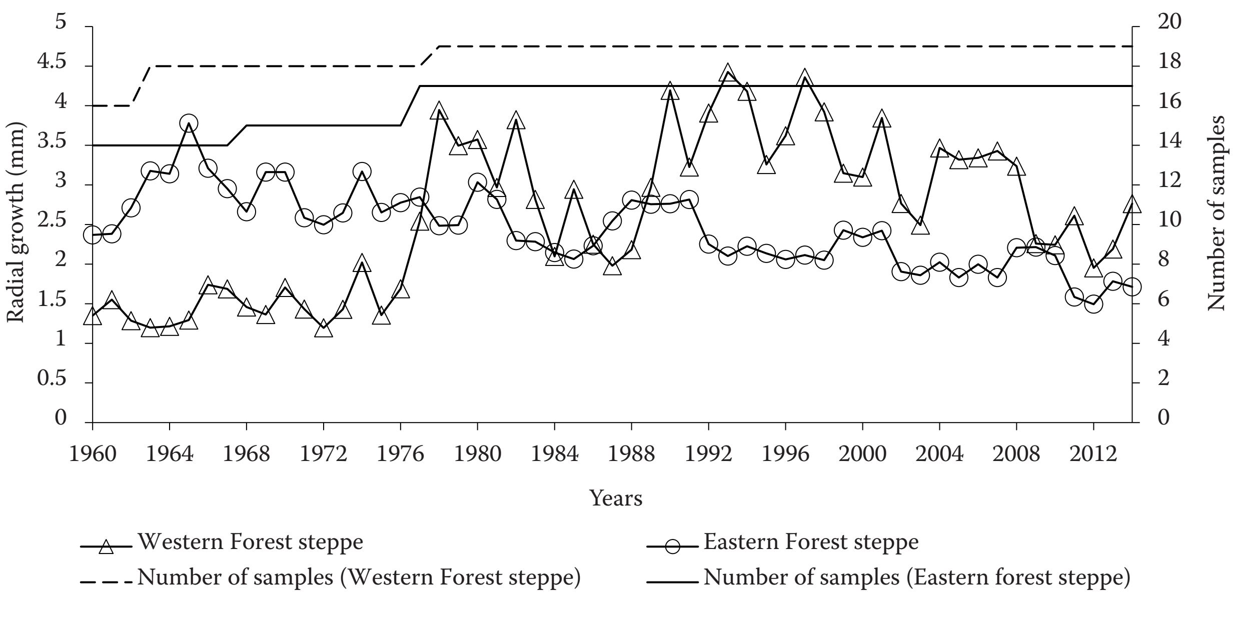


Figure 4. Dynamics of ash radial growth in the Western and Eastern forest steppe

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Table 2. COFECHA descriptive statistics of tree ring series of European ash for the Western and Eastern forest steppe zone

| | Interval | No. of rings | Intercorrelation coefficient | RW (mm) | SD | Autocorr | Mean sensitivity |
|---|---|---|---|---|---|---|---|
| Western forest steppe zone | 1960–2014 | 610 | 0.407 | 2.40 | 5.168 | 0.765 | 0.228 |
| Eastern forest steppe zone | 1940–2014 | 919 | 0.441 | 2.16 | 1.243 | 0.684 | 0.289 |

RW – ring width, SD – standard deviation, Autocorr – lag-1 autocorrelation

radial increment in the Eastern forest steppe compared to the Western forest steppe is more sensitive to variations of environmental conditions. The high first-order autocorrelation indicates that radial growth was strongly influenced by conditions in the preceding year for both stands (Table 2).

Correlation and response analyses between radial increment and climatic factors for 1961–1987 and 1988–2014 were carried out. Ash stands in the Western and Eastern forest steppe became more sensitive to warming in the second period (1988–2014) compared to the first period (1961–1987). During the first period the temperature did not significantly limit the growth of ash in the Western part of the forest steppe, at the same time for the Eastern part the radial growth was negatively affected by the temperature of previous September and the temperature of current July. In the second period, in both stands, temperature in the growing season of the previous year negatively influenced the ash radial increment of the current year. Significant correlations ($P < 0.05$) from –0.30 to –0.72 were observed.

So the ash radial increment was negatively correlated with temperature at both sites. For stands growing in the Eastern forest steppe, the negative influence of temperatures on tree rings was stronger. The ash radial growth in the Eastern forest steppe was more strongly influenced by drought stress compared to the Western forest steppe in the second period because we found a negative correlation between the index tree chronologies and temperature during the months of May to September for the Eastern part of forest steppe and temperature of May and September for the Eastern forest steppe (Figures 5–7).

Dendroclimatic research on *Quercus robur* L. in the Kharkiv Green Belt (Eastern forest steppe) detected a significant positive effect of precipitation from April to June and a negative effect of temperatures from July to August on oak rings for 1957 to 1987. Only a negative effect of March temperature on the tree rings was found in 1988–2011 (Koval, Kostyashkin 2015).

Results of dendroclimatic research on oak and ash trees in the Western forest steppe revealed that *Quercus robur* L. trees adapted themselves to an increase of temperature and groundwater level in contrast *to Fraxinus excelsior* L. Droughts during the vegetation season and warm winters have caused tree diseases with root decay and mortality of ash trees. In 2013–2014, up to 90% of ash trees declined on the sample plot (Koval et al. 2015).

The study characterized associations between climate variables and radial growth of white ash (*Fraxinus americana* L.) in the eastern USA showing that total ring width was positively correlated with precipitation and negatively correlated with temperature during the months of May to July, when most radial growth occurs. These spatially replicated correlations indicate that white ash growth is most strongly influenced by drought stress in the first half of the growing season (Lockwood, LeBlanc 2017). Drought stress makes trees more susceptible to pathogens (Huberty, Denno 2004).

For the second period, temperatures of the growing season of the previous year negatively influenced the ash radial growth in both stands (Figures 5–7). The climatic conditions of the previous year had a strong impact on the growth of the current year (Battipaglia et al. 2009; Lebourgeois 2010; Latreille et al. 2017).

Precipitation positively influenced the ash radial growth in April in the Eastern forest steppe in the second period and in June in the Western forest steppe in the first period. Significant correlations ($P < 0.05$) vary from 0.45 to 0.53. A negative effect of precipitation in January and February on the ash radial increment was found for the second period in the Western forest steppe [significant correlations ($P \leq 0.05$) from –0.35 to –0.58 were observed].

In northern regions, the depth and duration of the snowpack strongly influences soil tempera-

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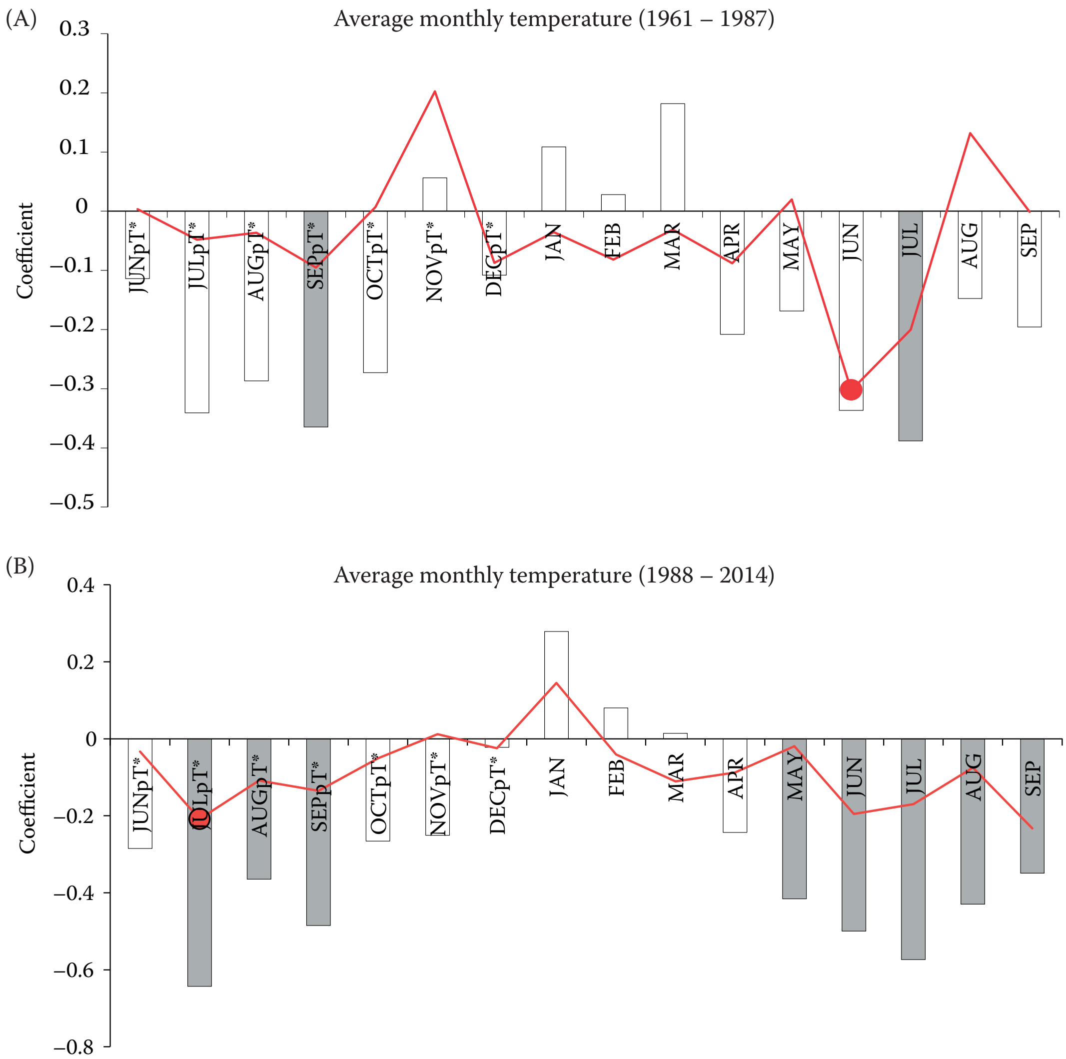


Figure 5. Pearson coefficients (columns) and response function coefficients (lines) between average monthly temperatures and index tree-ring series of European ash in the Eastern forest steppe zone

(grey bars indicate significant correlations ($P < 0.05$), red circles indicate significant correlations ($P < 0.05$) for the response function coefficient; asterisks (*) indicate the months of the previous year)

tures during winter and early spring. As the climate warms and snowpack depth and duration decline, soils are likely to experience colder more variable temperatures in winter, with important implications for ecosystem functions (Sanders-DeMott et al. 2019).

The Crown Region situated in the Rocky Mountain area (United States) and the Waterton Lakes National Park (Canada) are getting hotter, snowpack is reduced, runoff occurs earlier in spring, and stream flows ebb earlier in the growing season. These hydrological changes could lead to significant changes in the timing of water availability and increased drought, resulting in negative effects on land and agriculture (Bixler et al 2018).

The sensitivity of ash stands of the Western and Eastern forest steppe to climate variations in the second period (1988–2014) increased compared to the first period (1961–1987). In 1988–2014, in both stands the influence of summer droughts on the ash radial growth increased. Ash trees in the Eastern forest steppe were more affected by summer droughts. The decrease of radial growth, the decline and even mortality of ash are closely related to hydrological conditions, as in the rainy and cooler periods a surplus of water in the soil is formed, or water deficit due to droughts (Karpavičius, Vitas 2006). A negative impact of moisture deficit on the radial growth of ash was also observed as a decrease in the radial growth of ash in the Kaunas

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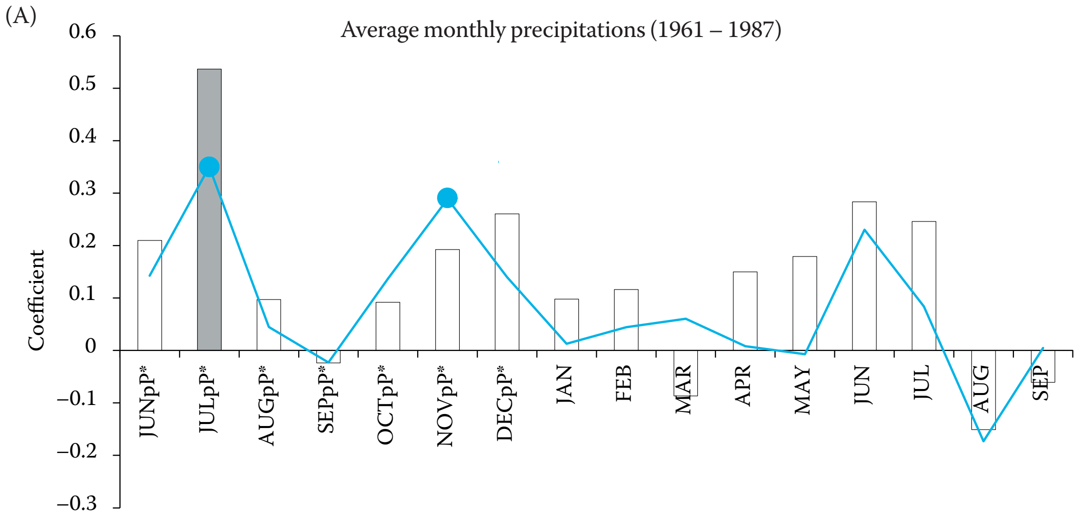


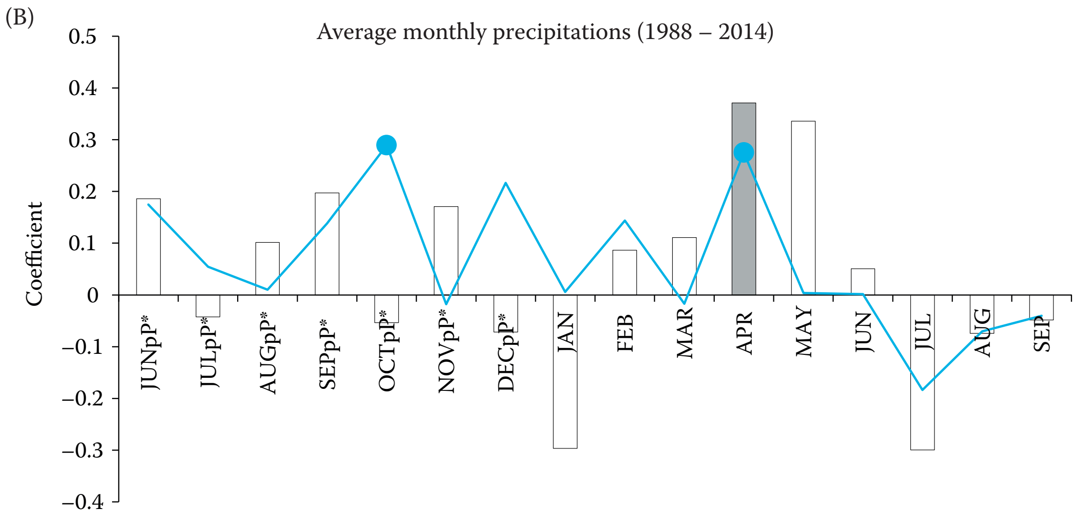


Figure 6. Pearson coefficients (columns) and response function coefficients (lines) between average monthly precipitations and index tree-ring series of European ash in the Eastern forest steppe zone

(grey bars indicate significant correlations ($P < 0.05$), blue circles indicate significant correlations ($P < 0.05$) for the response function coefficient; asterisks (*) indicate the months of the previous year)

Botanical Garden during 1990–1992 (Karpavičius, Vitas 2006).

Karpavičius and Vitas found that the ash radial growth responded positively to winter temperature and precipitation in Lithuanian forests, but in Hyrcanian forests (Iran) results of similar research demonstrated that the growth conditions are not favourable for this species, especially in terms of temperature (Karpavičius, Vitas 2006; Khedive 2017). In our research we have found the negative effect of winter precipitation only on the ash radial increment in the Western steppe for 1988–2014.

Research on stands growing in the middle course of the lowland section of the Warta River in the Lasy Czeszewskie Forest, Poland, showed that the pattern of relationships identified between climatic factors is consistent with the results of the tree ring width of ash. These relations for the months of the vegetation period are usually negative for temperature, and positive for precipitation in similar regional climatic conditions.

The climatic factors for the months of the previous year (frequently July, August, September) and current year (frequently May, June, July) are usually in relation with tree ring width (Okoński 2017).

In the eastern United States, the total ring width of white ash (*Fraxinus americana* L. Oleaceae) positively correlated with precipitation and negatively correlated with temperature during the months of May to July, when most radial growth occurs.

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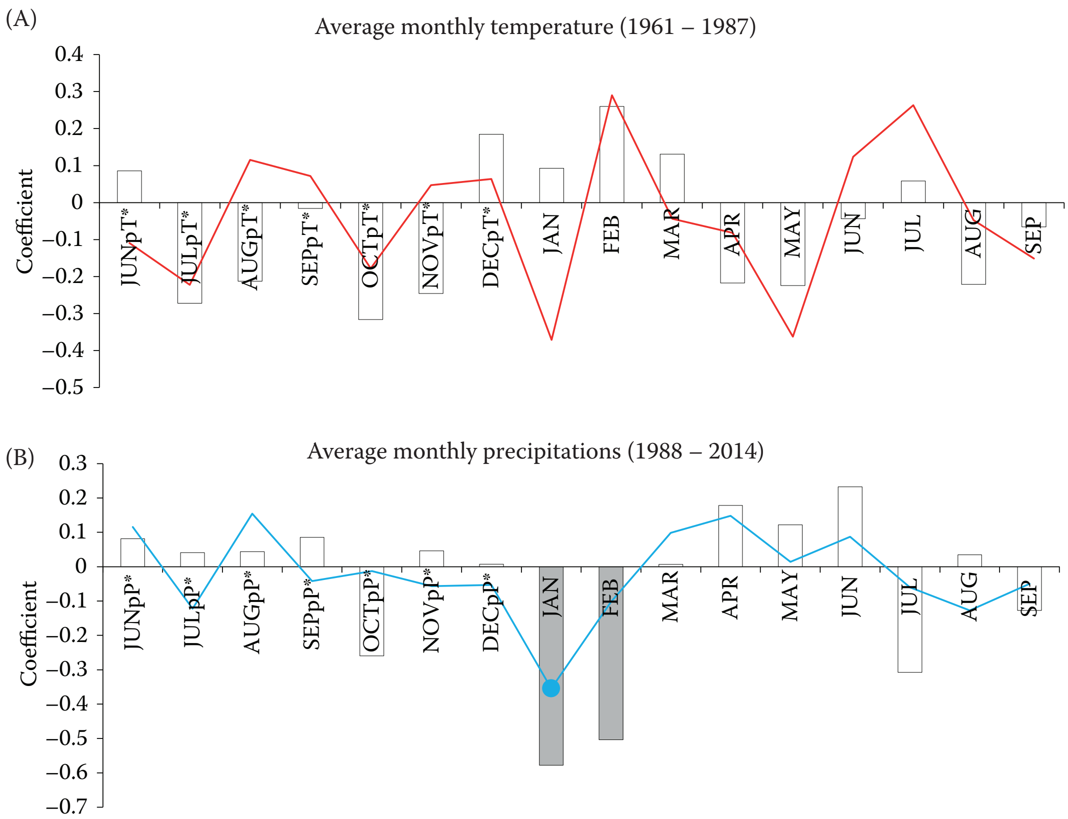


Figure 7. Pearson coefficients (columns) and response function coefficients (lines) between average monthly temperatures (A) and monthly precipitation (B) and index tree-ring series of European ash in the Western forest steppe zone

(grey bars indicate significant correlations ($P < 0.05$), circles indicate significant correlations ($P < 0.05$) for the response function coefficient; asterisks (*) indicate the months of the previous year)

These spatially replicated correlations indicate that white ash growth is most strongly influenced by drought stress in the first half of the growing season (Lockwood, LeBlanc 2017).

## CONCLUSION

The sensitivity of the ash radial increment in stands of the Western and Eastern forest steppe to climate variations in the second period (1988–2014) was increased, compared to the first period (1961–1987). In the second period correlation analysis and response function revealed an increase in the negative effect of summer droughts on the ash radial increment for both stands. The radial growth also responded negatively to higher winter precipitation in the Western forest steppe during the second period. So the hypothesis about an increase in the response of the ash radial increment to climate change was confirmed for both stands in the Western and Eastern forest steppe.

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Received: April 7, 2019
Accepted: June 23, 2020