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ANALYSIS OF THE CLIMATE ARIDITY IMPACT ON MACRONUTRIENT CONCENTRATION IN EUROPEAN BEECH LEAVES (*Fagus sylvatica* L.), USING CLIMATE INDICES

Tatjana ĆIRKOVIĆ-MITROVIĆ[1], Ljiljana BRAŠANAC-BOSANAC[1], Jelene BOŽOVIĆ[1], Vanja STOJANOVIĆ[1], Mihajlo MARKOVIĆ[1], Sabahudin HADROVIĆ[1], Nevena ČULE[1]*

Abstract. *The aim of this study is to analyse the affect of climate aridity impact, through to the climate indices – Forest Aridity Index (FAI) and Ellenberg climate quotient (EQ), on the nitrogen (N), phosphorus (P), potassium (K) content and N/P, N/K ratio in leaves of European beech in Serbia. The analysis of the macroelements concentration in the leaves shows that beech leaves contain: N – 9.82-19.62 mg/g, P – 0.82-1.53 mg/g, K – 4.83-11.11 mg/g. N/P ratio is 8.61-16.39 and N/K ratio 0.95-2.81. FAI index was in a range of values 3.19-7.10, and EQ quotient was in a range of values 15.27-30.24. Based on the research of the macronutrient content in beech leaves and the FAI and EQ at different altitudes, it can be concluded that FAI and EQ were statistically significant correlated with N and P content, and with N/K, respectively. An increase in indices values linearly causes a decrease in the concentration of key macronutrients N and P. The only parameter examined on which warmer and drier climate (through to the FAI and EQ index), did not have a statistically significant effec,t was the concentration of K.*

Keywords. nitrogen, phosphorus, potassium, Forest Aridity Index (FAI), Ellenberg climate quotient (EQ), Serbia

ANALIZA UTICAJA ARIDNOSTI KLIME NA KONCENTRACIJU MAKRONUTRIJENTA U LISTOVIMA EVROPSKE BUKVE (*Fagus sylvatica* L.), KORIŠĆENJEM KLIMATSKIH INDEKSA

Izvod: *Cilj ove studije bio je da se analizira uticaj aridnosti klime, putem klimatskih indeksa – Indeksa aridnosti šuma (FAI) i Elenbergovog klimatskog koeficijenta (EQ), na sadržaj azota (N), fosfora (P), kalijuma (K) i odnos N/P, N/K u lišću bukve u bukovim šumama u Srbiji. Analiza koncentracije makroelemenata u listovima pokazuje da listovi bukve sadrže: N – 9,82-19,62 mg/g, P – 0,82-1,53 mg/g, K – 4,83-11,11 mg/g. Odnos N/P je 8,61-16,39, a odnos N/K 0,95-2,81. FAI indeks je bio u rasponu vrednosti 3,19-7,10, a EQ u rasponu vrednosti 15,27-30,24. Na osnovu istraživanja sadržaja makronutrijenata u listovima bukve i FAI i EQ na različitim nadmorskim visinama, može se zaključiti da su FAI*

[1] Institute of Forestry, Kneza Višeslava 3, Belgrade, Serbia
*Corresponding author. E-mail: tanjacirk@yahoo.com

i EQ statistički značajno korelirani sa sadržajem N i P, odnosno sa N/K, respektivno. Povećanje vrednosti indeksa linearno uzrokuje smanjenje koncentracije ključnih makronutrijenata N i P. Jedini ispitivani parametar na koji toplija i sušnija klima (koristeći indekse FAI i EQ) nije imala statistički značajan uticaj, bila je koncentracija K.

Ključne reči: *Fagus sylvatica* L., azot, fosfor, kalijum, Forest Aridity Index (FAI), Ellenberg climate quotient (EQ)

1. INTRODUCTION

European Beech (*Fagus sylvatica* L.) as the most widespread woody species in Serbia. It has a great importance in forest ecosystems, wide ecological amplitude and growth on elevations from 50 to over 2,000 m. That indicate great adaptability of the species to different environmental conditions (Ćirković-Mitrović et al., 2023, Marković et al., 2025).

Nitrogen (N), phosphorus (P) and potassium (K) as essential macronutrients play very important role in plant growth metabolism, regulation of physiological mechanisms and ecosystem material and energy cycles (Ågren, 2004). N is important for the synthesis of chlorophyll and enzymes, P is a major metabolite in photosynthetic reactions and other energetic reactions. K is vital for plant growth because he improve disease resistance in plants, improve the size of seeds and quality of plant (Kumari et al., 2022). The content of N, P and K in leaves affects to function of plant enzymes, biochemical processes and integrity of plant cells (Uchid, 2000). Leaf nutrient stoichiometric relationships (N/P ratio, N/K ratio) are essential for photosynthesis and plant growth and development (Taylor et al., 2017, Wang et al., 2022). Numerous studies have indicated that climatic factors influence the leaf nutrient content, the functional traits of plant leaves by controlling plant metabolism, growth and development processes (Zhang et al., 2020, Krüger et al., 2021, Ognjenović et al., 2023, Köhler, 2023).

Light is one of the most important environmental factors influencing plant growth and development, plant morphology and metabolism. The concentration of nutrients in assimilation organs is different in the leaves that have been developed in full light from the ones that have grown in the shade (Kolić, 1988). Representative samples of leaves were taken from the upper third of the crown (sun-exposed foliage).

The content of nutrients in leaves has strong seasonal dynamics. Therefore, the amount of macronutrients in the leaves of the same tree vary in the spring, summer and autumn periods. The concentration of macronutrients in the leaves of broadleaved species at the beginning of the phenophase of leaf color change is taken as a representative of the tree nutritional status. It is the time when the sampling is performed on broadleaved sample plots.

The aim of this study is to analyse the affect of climate aridity, trough the aridity gradient (FAI and EQ), on content of nitrogen, phosphorus and potassium in the leaves of European beech in beech forests in Serbia.

2. MATERIALS AND METHODS

The sampling of leaves for the analysis of the nutrient status was conducted on five trees on 20 sample plots under pure beech stands on the territory of Serbia in 2022. Collected leaves was analyzed in the Laboratory of the Institute of Forestry Belgrade.

The samples are used to determine: total N (mg/g) by Kjeldahl (Dzamic et al. 1996, according Kjeldahl 1883), P content (mg/g) by colorimetric and K content (mg/g) by flame-photometric method (methods described in Tamm, 1955).

The non-reactive method, as a special scientific method, was used for the collection of the data on climate characteristics during the period 2002-2022. Its basic techniques were used: content analysis or observing the documents and use of the existing statistics, documents and their secondary analysis.

Based on the data of Republic Hydrometeorological Service of Serbia from main meteorological stations closest to the sample plots, the data on mean monthly and annual air temperature (°C), monthly and annual sum of precipitation (mm) were analysed. Due to the accuracy of the climate indices, an interpolation of climate parameters was performed for each sample area using vertical gradients based on data from the two nearest meteorological stations at the lowest and highest altitudes.

Forest Aridity Index (FAI) was calculated by the equation (1). Higher values represent warmer, drier climate (Führer et al. 2011), Ellenberg climate quotient (EQ) was calculated by the equation (2). A higher EQ index reflects an increase in climate aridity (Ellenberg and Leuschner, 2010).

$$\mathbf{FAI = 100\ T_{VII\text{-}VIII} / (P_{V\text{-}VII} + P_{VII\text{-}VIII})} \qquad (1)$$

$T_{VII\text{-}VIII}$ – average temperature in July and August (°C)
$P_{V\text{-}VII}$ – sum of precipitation from May to July (°C)
$P_{VII\text{-}VIII}$ – sum of precipitation in July and August (mm)

$$\mathbf{EQ = T_{VII}\ 1000 / P} \qquad (2)$$

T_{VII} – mean temperature of the warmest month (°C)
P – annual sum precipitation (mm)

Statistical analyses (Descriptive statistics, Linear regressions) were processed using statistical software Statgraphics (ver. XVI.I., 2009, Statpoint Technologies, Inc., Warrenton, VA, USA). Parameters considered with their measurement units were listed in Table 2.

Site characteristics and parameters with their measurement units of the 20 sample plots of European beech forests in Serbia are listed in Table 1.

Table 1. *Site characteristics and parameters of the 20 sample plots of European beech forests in Serbia*

Sample plot	Latitude	Longitude	Elevation (m. a.s.l)	Soil type (FAO, 1988)	Orientation	MAT (°C)	MAP (mm)	FAI	EQ
1	42.568320	21.759793	850	Dystric Cambisols	N	7.8	679	4.81	23.66
2	42.531670	22.010776	868	Eutric Cambisols	NW	7.6	682	4.70	23.23
3	44.258629	21.880964	619	Rendzic Leptosols	S	10.8	667	6.40	27.90
4	44.387401	22.015005	495	Eutric Cambisols	E	11.2	664	6.82	29.33
5	43.895096	21.279792	421	Dystric Cambisols	N	11.4	662	7.10	30.24
6	43.384575	20.314288	1263	Eutric Cambisols	N	8.9	685	4.70	21.78
7	44.074552	21.805287	1145	Dystric Cambisols	S	9.3	682	4.96	22.76
8	43.769662	20.073291	471	Eutric Cambisols	NE	9.1	792	4.61	23.92

Sample plot	Latitude	Longitude	Elevation (m. a.s.l)	Soil type (FAO, 1988)	Orientation	MAT (°C)	MAP (mm)	FAI	EQ
9	43.851364	19.951284	455	Albic Luvisols	E	9.1	787	4.65	24.14
10	43.782423	20.322966	536	Albic Luvisols	NW	8.9	813	4.48	23.02
11	43.913889	19.476367	1098	Chromis Cambis.	NW	7.3	994	3.49	16.86
12	43.887200	19.358633	1150	Mollic Leptosols	S	7.2	1,011	3.41	16.40
13	43.546115	20.054804	860	Eutric Cambisols	N	8.0	917	3.87	19.17
14	43.392095	20.041293	1305	Dystric Cambisols	NE	6.7	1060	3.19	15.27
15	43.734226	20.463361	383	Albic Luvizols	NW	9.3	764	4.80	25.20
16	43.653042	20.485219	949	Dystric Cambisols	W	7.7	946	3.72	18.26
17	44.177959	20.346633	401	Dystric Cambisols	W	10.9	789	5.04	26.37
18	44.453023	19.253250	560	Rendzic Leptosols	SW	10.3	790	4.90	25.27
19	44.100643	19.610776	1035	Eutric Cambisols	E	8.6	793	4.45	22.24
20	44.128757	20.074041	630	Eutric Cambisols	N	10.0	791	4.83	24.78

Abbreviations: MAT – mean annual temperature (2002-2022.); MAP – mean annual precipitation (2002-2022.); FAI – Forest Aridity Index, EQ – Ellenberg climate quotient (EQ)

3. RESULTS AND DISCUSSION

Descriptive statistics for Beech foliar content of N, P, K and N/P, N/K ratio (average, min, max, Standard deviation, Coeficient of variation) with their measurement units are listed in Table 2.

Table 2. *Descriptive statistics for Beech foliar content of N, P, K and N/P, N/K ratio*

Sample plot	N (mg/g)	P (mg/g)	K (mg/g)	N/P	N/K
1	11.52	1.18	8.08	9.76	1.43
2	14.89	1.23	6.13	12.11	2.43
3	10.17	0.93	6.07	10.88	1.68
4	9.82	0.83	6.38	11.82	1.54
5	11.54	1.08	8.42	10.72	1.37
6	16.80	1.39	10.64	12.12	1.58
7	16.18	0.99	7.61	16.39	2.12
8	15.40	1.32	8.93	11.67	1.72
9	13.20	1.12	4.83	11.79	2.73
10	16.10	1.46	8.54	11.03	1.88
11	16.90	1.26	6.32	13.41	2.67
12	18.10	1.23	6.87	14.72	2.64
13	17.60	1.41	6.74	12.52	2.61
14	19.62	1.50	8.45	13.04	2.32
15	10.46	1.13	7.81	9.22	1.34
16	15.60	1.45	5.56	10.75	2.81
17	10.50	1.22	11.11	8.61	0.95
18	10.04	0.82	7.20	12.23	1.39
19	17.90	1.35	7.90	13.26	2.27
20	18.10	1.53	10.45	11.83	1.73
Average	**14.52**	**1.22**	**7.70**	**11.89**	**1.96**
Minimum	**9.82**	**0.82**	**4.83**	**8.61**	**0.95**
Maximum	**19.62**	**1.53**	**11.11**	**16.39**	**2.81**
Standard deviation	**3.28**	**0.21**	**1.70**	**1.80**	**0.56**
Coefic. of variation	**22.57**	**17.46**	**22.05**	**15.11**	**28.81**

The analysis of the concentration in the leaves shows that beech leaves contain 9.82-19.62 mg/g of N, 0.82-1.53 mg/g of P and 4.83-11.11 mg/g of K. Similar results were obtained by Pavlova et al. (2016) in their research on the different localities in Bulgaria. European beech leaf N concentration in Italian regions (Bussotti et al. 2005) was higher than in Serbia, and had values from 20.3 to 32.5 mg/g. The values for N obtained by this research are lower, while the values for P and K are within the limit values for Europe (N – 18.60-28.20 mg/g, P – 0.81-1.82 mg/g, K – 3.80-10.60 mg/g) (Rautio et al. 2020). N/P ratio is 8.61-16.39 and

N/K ratio 0.95-2.81. The suggested thresholds for growth of beech trees are 2.5-3 for N/K and 10-15 for N/P (Bussotti et al. (2005), according Flückiger et al. (1986) and Bonneau (1988)).

FAI for research area for sample plots was in a range of values 3.19-7.10. Similar results have been obtained in research Stojanovic et al. (2012). According to Führer et al. (2011), reference FAI values for beech forests are <4.75.

EQ in this research was in a range of values 15.27-30.24. Areas with lower EQ values (less than 30) are characterised by a humid climate and are dominated by beech in Europe (Ellenberg, 1988, Jahn, 1991; Fang and Lechowicz, 2006, Führer et al. 2011). The difference between the reference values for Hungary and the obtained results can be explained by the fact that beech in Serbia has adapted to a warmer climate, because it is located further south.

In this study it is found that with increasing values of FAI and EQ (which characterizes aridity), the concentrations of N and K decrease, while the concentration of P is uniform (Figure 1, 2).

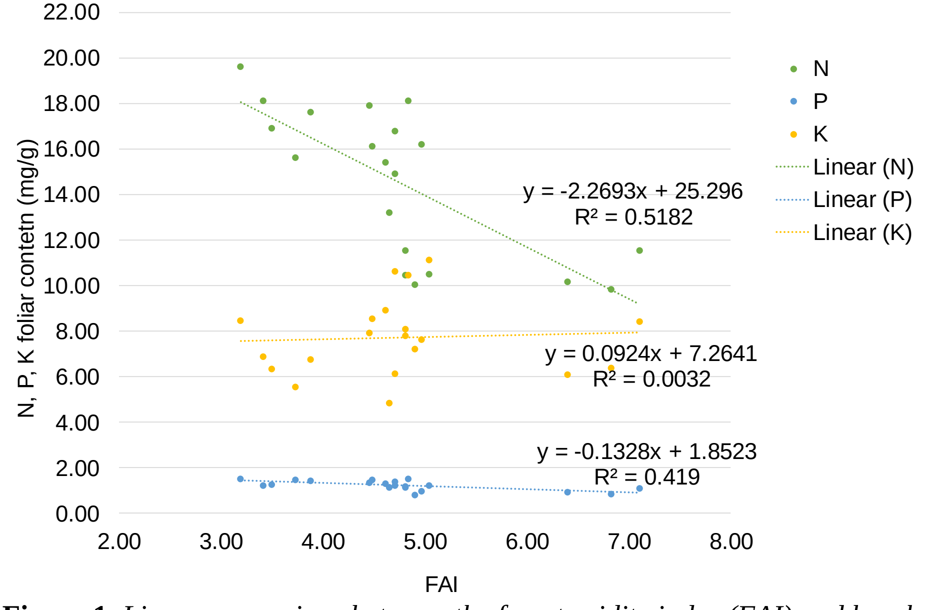

Figure 1. *Linear regressions between the forest aridity index (FAI) and beech foliar N, P, K content at the 20 saple plots*

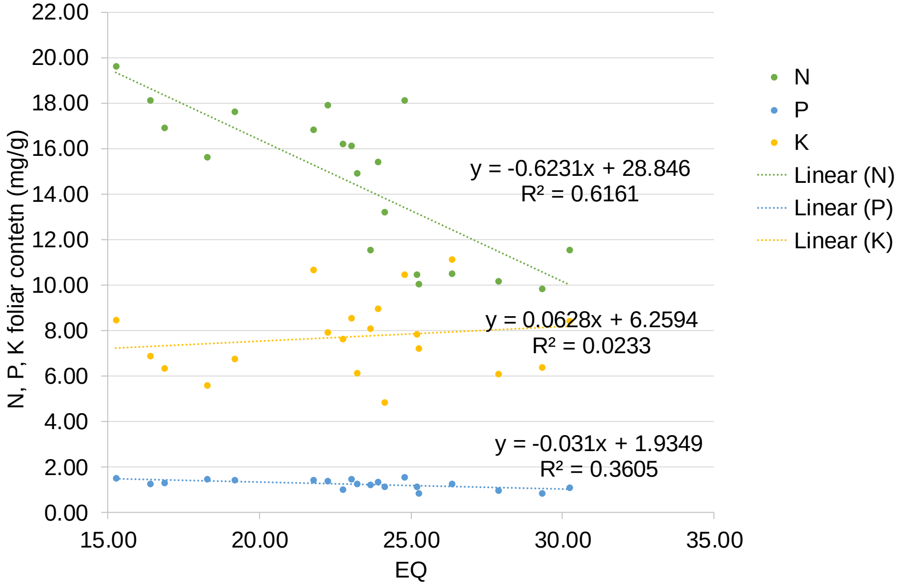

Figure 2. *Linear regressions between the Ellenberg climate quotient (EQ) and beech foliar N, P, K content at the 20 saple plots*

The N/P and N/K ratio in leaves decrease with increasing FAI and EQ values (Figure 3, 4).

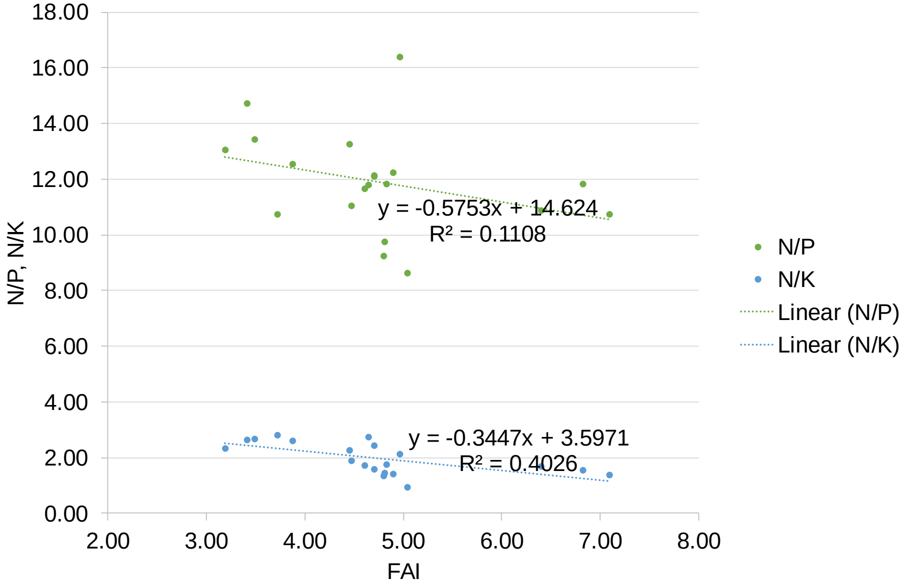

Figure 3. *Linear regressions between the forest aridity index (FAI) and beech foliar N/P, N/K ratio at the 20 saple plots*

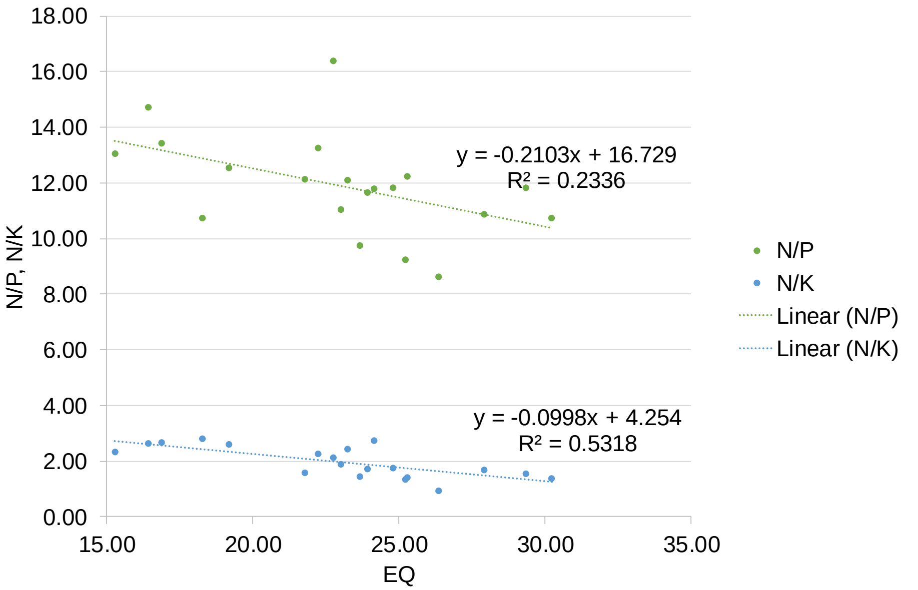

Figure 4. *Linear regressions between the Ellenberg climate quotient (EQ) and beech foliar N/P, N/K ratio at the 20 saple plots*

Table 3. *Correlation, determination and significance of regression analysis models*

	R^2	r	F	p
FAI				
N	0.5182	0.7199	19.40	0.0003
P	0.4190	0.6473	12.90	0.0021
K	0.0032	0.0566	0.06	0.8122
N/P	0.1108	0.3329	2.25	0.1511
N/K	0.4026	0.6345	12.15	0.0026
EQ				
N	0.6161	0.7849	28.88	0.0000
P	0.3605	0.6004	10.09	0.0052
K	0.0233	0.1526	0.43	0.5195
N/P	0.2336	0.4833	5.49	0.0308
N/K	0.5318	0.7292	20.53	0.0003

R^2 – coefficient of determination; r – Pearson correlation coefficient; F – F-ratio; p – significance level. Values of p < 0.05 indicate statistical significance

The results of linear regression analysis indicate that climatic aridity, expressed through the calculated FAI and EQ, has a selective, but significant effect on the chemical composition of leaves at the studied sites (Table 3). The most statistically significant effect of aridity, through to the FAI index, was observed on N concentration (R^2=0.5182, p=0.0003), followed by P concentration (R^2=0.4190, p=0.0021), which indicates that warmer, drier climate conditions linearly cause a decrease in these macronutrients in leaves. In contrast, P concentration (p=0.8122) and N/P ratio (p=0.1511) showed complete statistical independence from fluctuations in the FAI index, while a highly significant effect was again observed for the N/K ratio (R^2=0.4026, p=0.0026). The most pronounced negative effect of climate, trough to the EQ index, was found on N concentration (R^2=0.6161, p<0.001) and the N/K ratio (R^2=0.5318, p=0.0003). In addition, a statistically significant negative effect was observed on P concentration (R^2=0.3605, p=0.0052), as well as on the stoichiometry of the N/P ratio (R^2=0.2336, p=0.0308). These results clearly confirm that an increase in the EQ index value, linearly causes a decrease in the concentration of key macronutrients (N and P). The only parameter examined on which warmer and drier climate (through to the EQ index), did not have a statistically significant effect was the concentration of K (p=0.5195).

Increased N availability changes nutrient status, leads to rises in the N/P ratio of ecosystems (Peñuelas et al., 2013). Numerous previous studies have shown that temperature is a key factor in determining changes in nutritional properties of leaves, especially mean annual temperature (Miatto et al. 2016, Wright et al. 2017, Tian et al. 2019). Higher leaf N enhances photosynthesis under low-temperature stress, and when temperatures are higher, plants coordinate metabolic processes by reducing the N and increasing P content.

According to Guo et al. (2021), the concentration of N in leaves decreases significantly with increasing temperature. Since FAI and EQ are temperature dependent, the results of this study are consistent with the results of previous mentioned studies.

4. CONCLUSION

Based on the research of the affect of climate aridity, trough the aridity gradient (FAI and EQ), on content of nitrogen, phosphorus and potassium in the leaves of European beech in beech forests in Serbia, it can be concluded that climate factors have significant influence on dynamic balance of N and P. With increasing values of FAI and EQ (which characterizes aridity), the concentrations of N and P decrease, while the concentration of K is uniform.

Wide ecological amplitude and growth on elevations from 50 to over 2,000 m indicate great adaptability of the species to different environmental conditions. Global problem of sustainable management, forest health and climate changes, long-term changes in foliar mineral concentrations deserve further attention. Continued monitoring and further research are needed to ensure that appropriate measures are taken to protect the forest ecosystems.

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ANALYSIS OF THE CLIMATE ARIDITY IMPACT ON MACRONUTRIENT CONCENTRATION IN EUROPEAN BEECH LEAVES (*Fagus sylvatica* L.), USING CLIMATE INDICES

Tatjana ĆIRKOVIĆ-MITROVIĆ, Ljiljana BRAŠANAC-BOSANAC, Jelene BOŽOVIĆ, Vanja STOJANOVIĆ, Mihajlo MARKOVIĆ, Sabahudin HADROVIĆ, Nevena ČULE

Summary

Nitrogen (N), phosphorus (P) and potassium (K) as essential macronutrients play essential roles in plant growth metabolism, regulation of physiological mechanisms and ecosystem material and energy cycles. Numerous studies have indicated that climatic factors influence the leaf nutrient content, the functional traits of plant leaves by controlling plant metabolism, growth and development processes. The aim of this study was to analyse the affect of climate aridity impact, through to the climate indices – Forest Aridity Index (FAI) and Ellenberg climate quotient (EQ) on content of nitrogen, phosphorus and potassium in the leaves of European beech in Serbia. To accomplish this, 20 plots were sampled in beech forests, located in Serbia at different altitudinal levels, varying from 383 to 1305 m.

The analysis of the macroelements concentration in the leaves shows that beech leaves contain: N – 9.82-19.62 mg/g, P – 0.82-1.53 mg/g, K – 4.83-11.11 mg/g. N/P ratio is 8.61-16.39 and N/K ratio 0.95-2.81. FAI index was in a range of values 3.19-7.10, and EQ quotient was in a range of values 15.27-30.24. Based on the research results, it was concluded that climate factors have significant influence on dynamic balance of nutrients N and K. With increasing values of FAI and EQ (which characterizes aridity), the concentrations of N and K decrease, while the concentration of P is uniform. The N/P and N/K ratio in leaves decrease with increasing FAI and EQ values.

Global problem of sustainable management, forest health and climate changes, long-term changes in foliar mineral concentrations deserve further attention. Continued monitoring and further research are needed to ensure that appropriate measures are taken to protect the forest ecosystems.

ANALIZA UTICAJA ARIDNOSTI KLIME NA KONCENTRACIJU MAKRONUTRIJENTA U LISTOVIMA EVROPSKE BUKVE (*Fagus sylvatica* L.), KORIŠĆENJEM KLIMATSKIH INDEKSA

Tatjana ĆIRKOVIĆ-MITROVIĆ, Ljiljana BRAŠANAC-BOSANAC, Jelene BOŽOVIĆ, Vanja STOJANOVIĆ, Mihajlo MARKOVIĆ, Sabahudin HADROVIĆ, Nevena ČULE

Rezime

Azot (N), fosfor (P) i kalijum (K), kao esencijalni makronutrijenti, igraju suštinsku ulogu u metabolizmu rasta biljaka, regulaciji fizioloških mehanizama i ciklusima materijala i energije ekosistema. Brojne studije su pokazale da klimatski faktori utiču na sadržaj hranljivih materija u listu, funkcionalne osobine listova biljaka kontrolišući metabolizam biljaka, procese rasta i razvoja. Cilj ove studije bio je da se analizira uticaj aridnosti klime, putem klimatskih indeksa – Indeksa aridnosti šuma (FAI) i Elenbergovog klimatskog koeficijenta (EQ), na sadržaj azota, fosfora i kalijuma u listovima evropske bukve u Srbiji. Da bi se to postiglo, izvršeno je uzorkovanje lišća na 20 oglednih površina u bukovim šumama, koje se nalaze u Srbiji na različitim nadmorskim visinama, u rasponu od 383 do 1,305 m.

Analiza koncentracije makroelemenata u listovima pokazuje da listovi bukve sadrže: N – 9,82-19,62 mg/g, P – 0,82-1,53 mg/g, K – 4,83-11,11 mg/g. Odnos N/P je 8,61-16,39, a odnos N/K 0,95-2,81. FAI indeks je bio u rasponu vrednosti 3,19-7,10, a EQ u rasponu vrednosti 15,27-30,24. Na osnovu rezultata istraživanja, zaključeno je da klimatski faktori imaju značajan uticaj na dinamičku ravnotežu hranljivih elemenata N i K. Sa povećanjem vrednosti FAI i EQ (koji karakterišu aridnost), koncentracije N i K se smanjuju, dok je koncentracija P ujednačena. Odnos N/P i N/K u listovima se smanjuje sa povećanjem vrednosti FAI i EQ.

Globalni problem održivog upravljanja, zdravlja šuma i klimatskih promena, dugoročne promene u koncentracijama folijarnih minerala zaslužuje dalju pažnju. Potrebno je kontinuirano praćenje i istraživanje, kako bi se osiguralo da se preduzmu odgovarajuće mere za zaštitu šumskih ekosistema.