

# Productivity of Pedunculate Oak Provenances in the Republic of Croatia – Importance for Forest Restoration

Martina Đodan, Sanja Perić, Andrija Barišić\*

Croatian Forest Research Institute, Jastrebarsko

\* Corresponding author: Andrija Barišić, e-mail: andrijab@sumins.hr

## Abstract

The management of pedunculate oak (*Quercus robur* L.), one of Croatia's most important tree species from both socio-economic and ecological perspective, is facing increasing challenges. Various biotic and abiotic threats are affecting overall forest stability. Given the significant variability in the morphological and physiological properties of this tree species, research into provenance productivity plays an important role for the forestry sector. Therefore, this study analyses the productivity of 16 pedunculate oak provenances on two sites in Croatia's lowlands: Gajno in Central Croatia and Slavir in Eastern Croatia. Both trials were established in 1988 in a randomised block design in four repetitions by the Croatian Forest Research Institute. Data were collected from 2017 to 2025 (diameter at breast height (DBH) and tree height (h)). Tree volume (v) was calculated, and descriptive statistics, RM-ANOVA, MANOVA, and Tukey post hoc tests were used for data analysis. The results revealed statistically significant differences in volume in the Gajno site, with Velika Gorica provenances exhibiting the highest productivity across the studied years. Provenances Gunja (in 2017), Motovun (in 2021), and Morović (in 2023) displayed the lowest values. In the Slavir site, the highest productivity was recorded in the Guševac provenance, while the lowest was observed in the Velika Gorica provenance across the studied years, even though a statistically significant difference was not proven. Analysis between the two sites confirmed statistically significant differences, with Slavir showing higher productivity. Since the local provenances showed the highest volume, it is recommended to use them for forest restoration programs in the Croatian lowlands. Attention should also be given to the Vrbanja provenance, which displayed above-average volume at both sites, indicating good adaptability to a wider range of site conditions. The findings highlight the importance of scientifically based provenance selection for forest restoration programs, particularly in the context of climate change adaptation. Continuous monitoring and silvicultural measures are imperative for enhancing resilience and ensuring the long-term sustainability of achieving optimal provenance productivity for a given site.

**Keywords:** adaptation, forest management, provenance selection, tree volume, *Quercus robur*

**DOI:**  
<https://doi.org/10.31298/sl.150.3-4.2>

## How to Cite:

Đodan, M. et al., 2026: Productivity of Pedunculate Oak Provenances in the Republic of Croatia – Importance for Forest Restoration. Šumarski list 150 (3–4): 117–125, 2026. <https://doi.org/10.31298/sl.150.3-4.2>



This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

## INTRODUCTION

Pedunculate oak (*Quercus robur* L.) is one of the most economically valuable tree species with a wide natural distribution across Europe (Eaton et al. 2016). This mostly applies to timber, which generates the highest monetary value from the sale (Teslak et al. 2013). Pedunculate oak forests are the most significant and valuable forests situated in Croatia's lowland (Gračan and Perić 1993, Tikvić et al. 2009). Pedunculate oak's mortality has repeatedly occurred over the past three centuries (Thomas et al. 2002), but has become more pronounced in the last decade (Krutovsky et al. 2025). These forests are gradually losing their overall stability due to intensifying climate change (Mikac et al. 2020, Kesić 2021), along with more frequent and intense events, such as droughts, irregular precipitation distribution, and severe storms (IPCC 2021). Climate change, combined with rising harvest levels across Europe, has intensified over the last decade, largely driven by the implementation of bioeconomy policy goals (Ceccherini et al. 2020). Furthermore, the decreased frequency of mast years and the decline in acorn quantity and quality pose another significant challenge for forestry, especially in the forest restoration activities (Anić 2025). Such issues can lead to significant shifts in forest composition and structure (Klepac 2000, Ortmann-Ajkai et al. 2017), including a reduction of the forest ecosystem services. Moreover, climate change causes shifts in the site suitability for forest tree species (Dolos et al. 2015), which add to the complexity of forest restoration. However, it also reveals the resilience of certain individuals, provenances, and species to overcome the threats (Fady et al. 2016), making appropriate provenance selection and related scientific efforts crucial for successful restoration and pre-restoration actions in the face of climate change. Repeating forest restoration activities is costly and time-consuming, so proper planning is crucial to avoid unnecessary repetitions (Đodan and Perić 2022). Identifying stress factors, monitoring changes in site conditions, and selecting suitable provenances have an important role in both restoration and pre-restoration of pedunculate oak forests, especially given the considerable variability in the morphological and physiological properties within the species (Perić 2001). Initial studies on the success of different provenances of pedunculate oak in Croatia began at the end of the 1980s (Gračan 1986, Komlenović et al. 1988, Gračan et al. 1991, Gračan 1993, Gračan and Perić 1993, Perić 2001). The results obtained so far on the performance of pedunculate oak provenances in Croatia, conducted across different developmental stages from outplanting to 38 years of age, confirm the importance of proper provenance selection for both forest restoration and pre-restoration. Ensuring that future forests possess sufficient adaptive capacity to withstand climate change-related events is considered essential (Kramer 2016). Therefore, the objectives of this research are to: (1) determine the productivity of different provenances to support restoration and pre-restoration activities in Croatia's lowland areas and raise the resilience of pedunculate oak forests, (2) determine whether there are differences in provenance productivity between sites, and (3) provide recommendations for the provenance selection in restoration and pre-restoration actions.

## MATERIALS AND METHODS

### Research Area

The experimental sites, Gajno (in northwestern Croatia, near Jastrebarsko) and Slavir (in eastern Croatia, near Vinkovci), are identical provenance tests established by the Croatian Forest Research Institute in 1988. Experimental sites are situated in the lowland areas and are characterised by different environmental conditions. On the Gajno site, the average annual precipitation ranges from 1000 to 1500 mm, while the average annual air temperature is around 11°C (Zaninović et al. 2008). The most prevalent soils in this area are pseudogley and amphigley, while the dominant vegetation is composed of pedunculate oak and common hornbeam (*Carpino betuli-Quercetum roboris*) and pedunculate oak with dyer's greenweed (*Genisto elatae-Quercetum roboris*) communities (Perić 2001).

In the Slavir site, average annual precipitation varies from 600 to 700 mm, with an average annual air temperature around 12°C (Zaninović et al. 2008). In this area, soils are classified into two groups: automorphic soils and hydromorphic soils. The microrelief exerts a significant influence in this region, affecting the distribution of water across the area. The dominant vegetation is composed of pedunculate oak and common hornbeam (*Carpino betuli-Quercetum roboris*), pedunculate oak with dyer's greenweed (*Genisto elatae-Quercetum roboris*), and a forest of narrow-leaved ash with summer snowflake (*Leucoia-Fraxinetum angustifoliae*) communities (Perić 2001).

### Study Design

The study includes 16 provenances (Table 1), 15 of which are from Croatia and one from Serbia. When establishing the provenance tests, the natural distribution range of pedunculate oak was considered, spanning from the easternmost provenance (Morović) to those in the far west of Croatia (Motovun) (Figure 1). This approach covers the entire distribution range of pedunculate oak within Croatia.

At each experimental site, 6400 seedlings were planted. The experimental sites were established with two-year-old seedlings in a randomised block design with four replications (Figure 2). In each of the four replications, 100 seedlings from each provenance were planted (Figure 3), i.e., 4 replications × 16 provenances × 100 seedlings. The seedlings were planted at a spacing of 1.5 × 1.5 meters.

### Research Methods

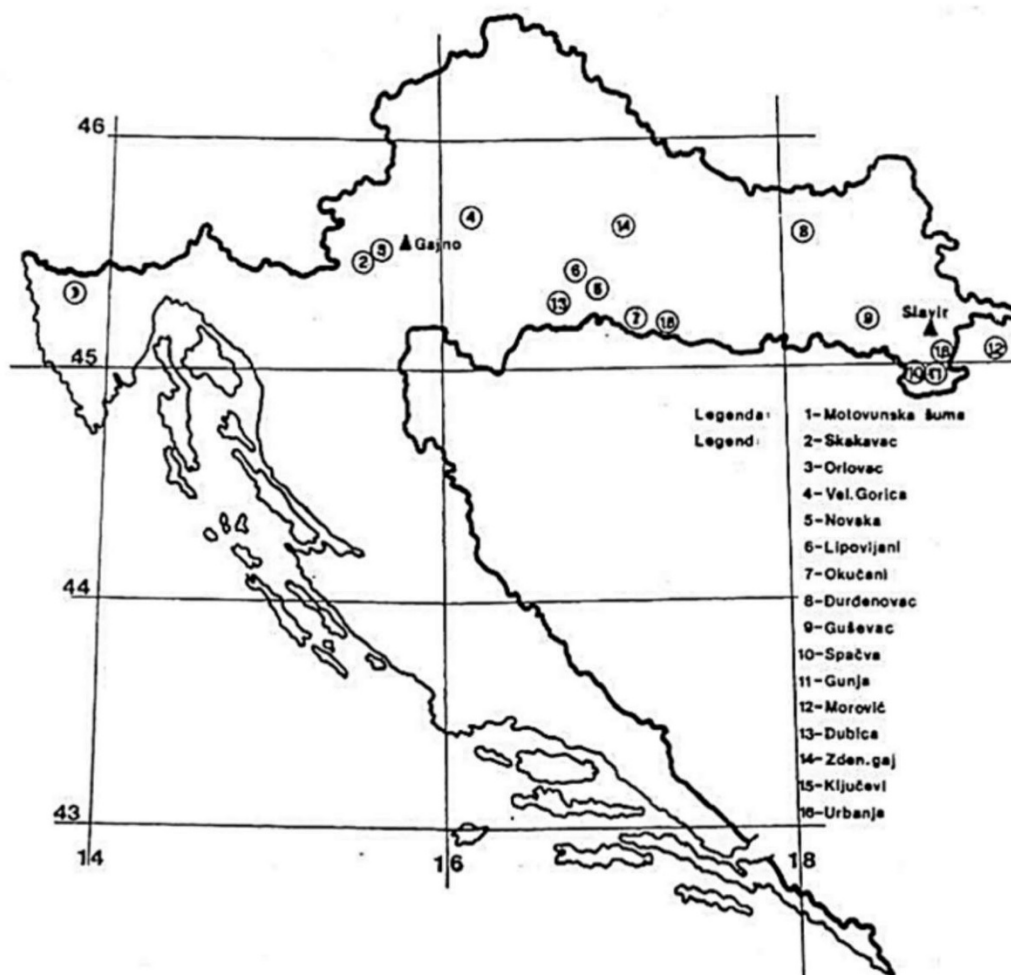
Data on tree heights (Haglöf / Vertex IV device) and breast height diameters (calliper) were collected. At the Gajno site, data were collected in 2017, 2021, and 2023. At the Slavir site, data were collected in 2023 and 2025. During the inventory, breast height diameters were permanently marked to ensure consistency in subsequent measurements and to minimise potential measurement errors. From the collected data on height and diameter at breast height, the volume of each tree was calculated. Tree volume was calculated using the following formula (Špiranec 1975):

$$V_{BR} = b_0 \times d_{1,30}^{b_1} \times h_T^{b_2} \times f$$

Total tree volume with bark up to a diameter of 7 cm ( $V_{BR}$ ) was estimated based on measured breast height diameter ( $d_{1,30}$ ) and total tree height ( $h_T$ ), using the Schumacher-Hall function. The parameters of the function were  $b_0 = 0.00005$ ,

**Table 1** Pedunculate oak provenances used in the experimental sites, with basic information on each provenance (adapted from Gračan 1993).

No.	Provenance	N latitude	E longitude	Altitude (m)	Soil	Forest office
1	Motovun	45°20'	13°50'	90	Fluvisols	Buzet
2	Skakavac (Domačaj lug 14)	45°29'	15°42'	112	Eugleys	Karlovac
3	Orlovac (Rečički lug 48)	45°33'	15°44'	112	Pseudogley	Karlovac
4	V. Gorica (Tur. lug 8a, 9b)	45°40'	16°10'	98	Fluvisols	Zagreb
5	Novska (Trstika 20b)	45°02'	16°55'	143	Eugleys	Nova Gradiška
6	Lipovljani ("J. Kozarac" 43a)	45°26'	16°49'	143	Eugleys	Nova Gradiška
7	Okučani (Ljeskovača 8b, 12b)	45°11'	17°10'	95	Eugleys	Nova Gradiška
8	Đurđenovac (Đurđ. niz. šume)	45°34'	18°08'	97	Eugleys	Vinkovci
9	Guševac (Trstenik)	45°13'	18°29'	96	Eugleys	Vinkovci
10	Spačva (S. Radiševo)	44°56'	18°50'	85	Eugleys	Vinkovci
11	Gunja (Desičevo)	44°57'	18°49'	86	Eugleys	Vinkovci
12	Morović (S. Mitrovića)	45°02'	19°11'	82-85	Metamorphosed Loess	Sremska Mitrovića
13	Dubica (Pos. šume)	45°17'	16°44'	98	Eugleys	Sisak
14	Zdenački gaj (Prespinjača 2a)	45°37'	17°04'	160	Eugleys	Bjelovar
15	Ključevi 34a	45°11'	17°21'	95	Eugleys	Nova Gradiška
16	Vrbanja (Vrbanjske šume 102a-1, 113-f, 114-g)	45°01'	18°59'	85	Eugleys	Vinkovci


**Figure 1** Provenances and experimental sites' locations on the map of the Republic of Croatia (adopted from Gračan et al. 1991).

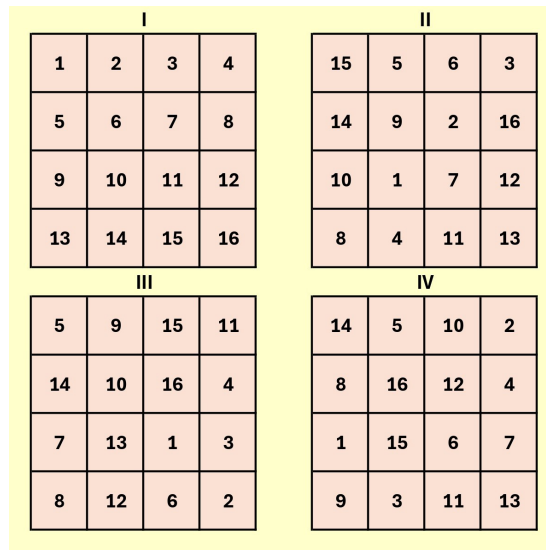


Figure 2 Layout of the randomized block design at the experimental sites (Perić 2001).

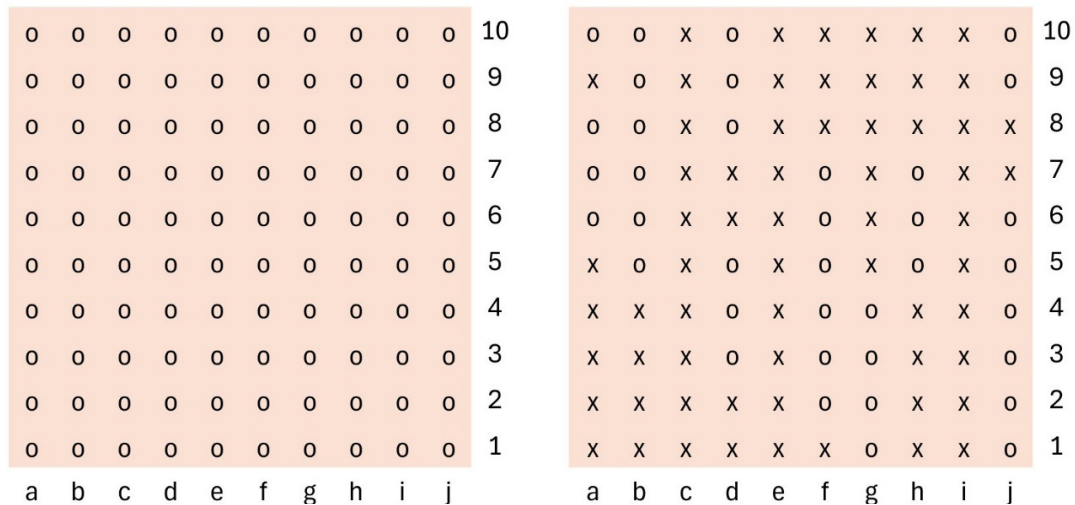


Figure 3 Initial planting schematic view of a provenance within one replication (left), and follow-up schematic view of survival after 38 years (right).

O = living trees; X = dead trees

$b_1 = 2.04838$ ,  $b_2 = 0.89212$ , and Meyer's correction factor was  $f = 1.00374$ . Descriptive statistics, Repeated Measures Analysis of Variance (RM ANOVA), Multivariate Analysis of Variance (MANOVA), and Tukey Post Hoc Test were used for data analysis in the Statistica software (Cloud Software Group, Inc. 2023). Using descriptive statistics, we extracted data on the number of living trees (NLT) in the last year of measurement for each provenance, as well as mean volume values (MVV) and standard deviation (SD) across the studied years. With RM ANOVA, we tested differences between provenances for volume, since the condition of variance homogeneity was proved. When a significant statistical difference was found between provenances, we used the Tukey post hoc test to determine which provenances differed from others. A MANOVA was performed to examine volume differences between sites and to evaluate the interaction effect between site and provenance. A Type I error ( $\alpha$ ) of 5% was considered statistically significant.

## RESULTS

### Gajno Site

Descriptive statistics of the Gajno site include the NLT, MVV, and SD for 16 provenances, across the studied years (2017, 2021, 2023), as presented in Table 2.

The lowest NLT was recorded for the Gunja provenance, while the highest NLT was recorded for the Orlovac provenance. The highest MVV was recorded for the Velika Gorica provenance in all researched years. The lowest MVV was recorded in the Motovun provenance in 2017 and 2021, while the Morović provenance had the lowest MVV in 2023. The Đurđenovac provenance had the largest SD in 2017, while the Lipovljani provenance had the largest SD in 2021 and 2023. The smallest SD was recorded in the Guševac provenance in 2017 and 2023, and in the Okučani provenance in 2021.

The Tukey post hoc test revealed a significant difference for the Velika Gorica provenance compared to provenances

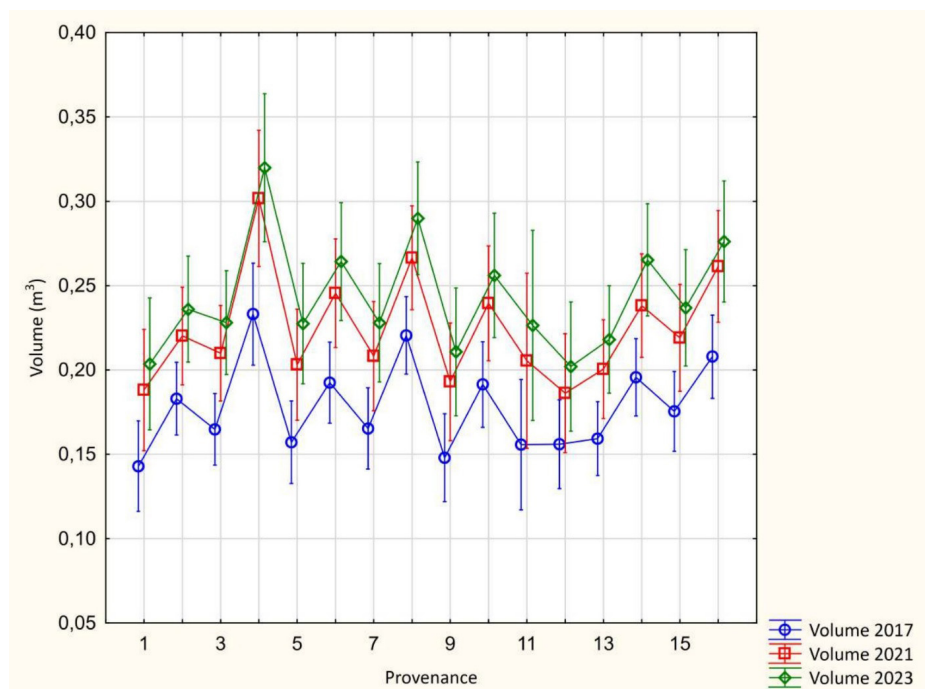
**Table 2** The Number of Living Trees (NLT) in 2023, Mean Volume Values (MVV), and Standard Deviation (SD) for 16 provenances across the studied years in the Gajno site.

		Descriptive statistics for the Gajno site						
Provenance	NLT 2023	MVV and SD (m <sup>3</sup> ) across the studied years						
		MVV 2017	SD	MVV 2021	SD	MVV 2023	SD	
1	Motovun	77	0.11796	0.10195	0.18252	0.15171	0.20359	0.15982
2	Skakavac	119	0.15756	0.13358	0.21454	0.16107	0.23603	0.17386
3	Orlovac	124	0.14017	0.10552	0.20993	0.14807	0.22811	0.16533
4	Velika Gorica	61	0.19618	0.14445	0.29064	0.19832	0.31992	0.19578
5	Novska	92	0.13684	0.09813	0.19893	0.13891	0.22746	0.15868
6	Lipovljani	96	0.16188	0.14258	0.24199	0.20646	0.26424	0.21428
7	Okučani	95	0.13456	0.09264	0.19677	0.12747	0.22796	0.14309
8	Đurđenovac	105	0.19533	0.14962	0.25360	0.17793	0.28992	0.19878
9	Guševac	82	0.12831	0.08753	0.18877	0.12878	0.21073	0.13961
10	Spačva	86	0.15816	0.11247	0.23527	0.15861	0.25607	0.17684
11	Gunja	37	0.12475	0.09002	0.19456	0.13503	0.22640	0.15084
12	Morović	80	0.13168	0.12155	0.18626	0.16159	0.20199	0.17030
13	Dubica	116	0.12887	0.11129	0.19715	0.14910	0.21808	0.16700
14	Zdenački gaj	107	0.17127	0.11858	0.22908	0.15878	0.26698	0.18397
15	Ključevi	99	0.15084	0.11873	0.21182	0.16434	0.23682	0.18323
16	Vrbanja	91	0.16979	0.12901	0.25925	0.18231	0.27617	0.18085
	All groups	1467	0.15077	0.11993	0.21827	0.16248	0.24283	0.17627

Motovun, Orlovac, Novska, Guševac, Morović, and Dubica ( $p < 0.05$ ). The other provenances did not show statistically significant differences in volume.

The RM ANOVA of volume across the researched years confirmed a significant difference in provenance volume ( $p < 0.05$ ), both between the values of individual years and between provenance and years. This indicates that the provenances displayed different growth dynamics throughout the study period. For example, the Vrbanja provenance recorded one of the highest annual volume increments during the period from 2017 to 2021. However, in the following period from 2021 to 2023, the provenance showed one of the lowest annual volume increments. A similar pattern was recorded in the Orlovac, Velika Gorica, Lipovljani, and Spačva provenances, which showed greater annual growth increments in the period from 2017 to 2021, followed by reduced annual growth in the period from 2021 to 2023. In contrast, the Zdenački gaj and

Đurđenovac provenances showed greater annual volume increments during the period from 2021 to 2023 compared with the preceding period. Figure 4 presents the 95% confidence interval for volume across the studied years.



**Figure 4** The 95% confidence intervals for mean volume values for 16 pedunculate oak provenances in the Gajno site.

## Slavir Site

Descriptive statistics of the Slavir site include the NLT in 2025, MVV, and SD for 16 provenances across the studied years (2023 and 2025), as presented in Table 3.

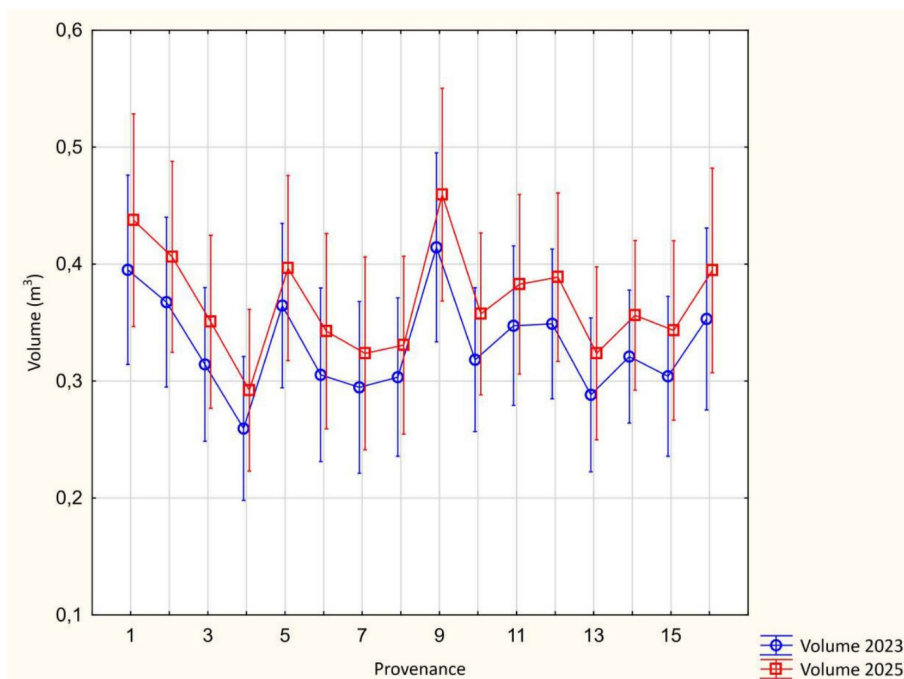
The lowest NLT was recorded in the Motovun and Guševac provenances. In contrast, the highest NLT was recorded in the Zdenački Gaj provenance. The highest MVV was recorded for the Guševac provenance, while the lowest

MVV was recorded for the Velika Gorica provenance, in both researched years. The Gunja provenance exhibited the largest SD, while the smallest SD was recorded for the Velika Gorica provenance, in both years.

The RM ANOVA conducted on the volume did not reveal any significant differences in the volume of the provenances ( $p > 0.05$ ). This finding applies to both comparisons between the individual years and the interaction between provenance and year (Figure 5).

**Table 3** The Number of Living Trees (NLT) in 2025, Mean Volume Values (MVV), and Standard Deviation (SD) for 16 provenances across the studied years in the Slavir site.

Descriptive statistics for the Slavir site						
Provenance	NLT 2025	MVV and SD (m <sup>3</sup> ) across the studied years				
		MVV 2023	SD	MVV 2025	SD	
1	Motovun	37	0.38168	0.30389	0.43751	0.33736
2	Skakavac	46	0.36001	0.26218	0.40624	0.29016
3	Orlovac	56	0.30979	0.25565	0.35075	0.28568
4	Velika Gorica	64	0.25159	0.18332	0.29217	0.21182
5	Novska	49	0.36462	0.24790	0.39662	0.27125
6	Lipovljani	44	0.28963	0.24295	0.34269	0.27247
7	Okučani	45	0.28373	0.24401	0.32370	0.27300
8	Đurđenovac	53	0.29243	0.27102	0.33074	0.30488
9	Guševac	37	0.39928	0.27085	0.45949	0.30690
10	Spačva	64	0.31098	0.25885	0.35751	0.29754
11	Gunja	52	0.31715	0.32248	0.38276	0.36794
12	Morović	59	0.32675	0.23486	0.38883	0.26195
13	Dubica	56	0.26860	0.22059	0.32373	0.26279
14	Zdenački gaj	75	0.31453	0.24763	0.35624	0.28525
15	Ključevi	52	0.27285	0.19399	0.34327	0.21695
16	Vrbanja	40	0.33914	0.22165	0.39465	0.25392
	All groups	829	0.31331	0.25037	0.36313	0.28233



**Figure 5** The 95% confidence intervals for mean volume values for 16 pedunculate oak provenances in the Slavir site.

### Multivariate Analysis of Variance (MANOVA) between Gajno and Slavir Sites

The MANOVA revealed a difference in volume by site and an interaction between site and provenance ( $p < 0.05$ ). A 95% confidence interval for the difference in overall provenance volume at the sites is shown in Figure 6. The MVV at the

Gajno site was  $0.25 \text{ m}^3$ , while at the Slavir site it was  $0.32 \text{ m}^3$ . A 95% confidence interval for the difference in provenance MVV at the sites is shown in Figure 7. The greatest volume differences in 2023 between the Gajno and Slavir sites were recorded for the Guševac provenance ( $0.18855 \text{ m}^3$ ), followed by provenances Motovun ( $0.17808 \text{ m}^3$ ), Novska ( $0.13715 \text{ m}^3$ ), Morović ( $0.12476 \text{ m}^3$ ), and Skakavac ( $0.12398 \text{ m}^3$ ).

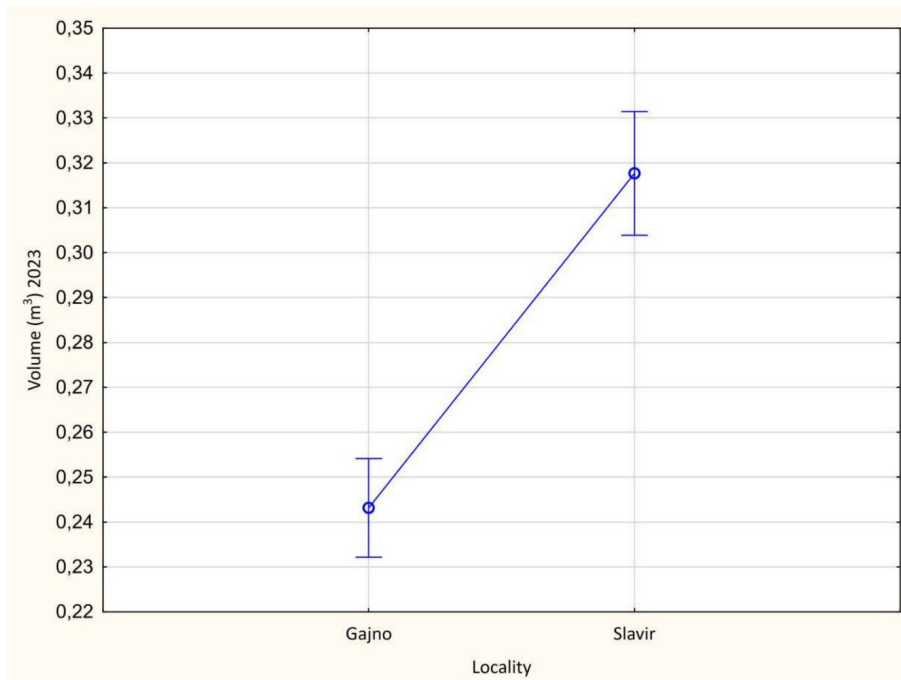


Figure 6 The 95% confidence intervals for the overall mean volume values in 2023 of the Gajno and Slavir sites.

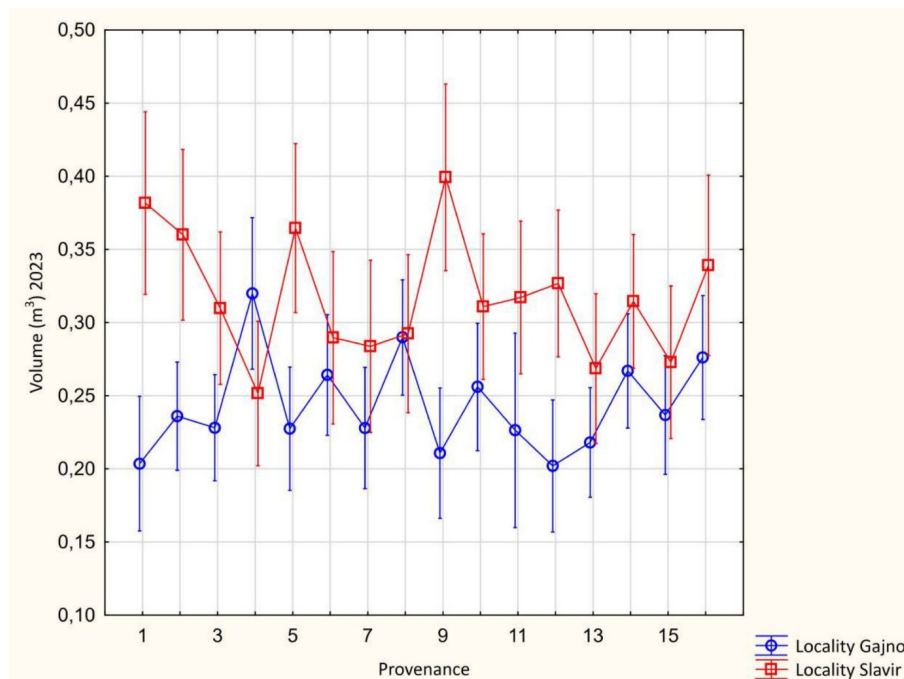


Figure 7 The 95% confidence intervals for the mean volume values in 2023 of 16 pedunculate oak provenances in the Gajno and Slavir sites.

## DISCUSSION

Regional variation and clinal patterns in European oaks have been described in earlier literature (Kleinschmit 1993), but statistical results have rarely been reported. In the Croatian lowland forests, the pedunculate oak differs very clearly, both morphologically and ecologically, from other oak species, as it occupies floodplains and, in contrast to other oaks, very selective sites (Franjić et al. 2000). The provenance that demonstrates the best growth performance can be considered the best adapted to the given site conditions and is thus recommended for restoration in similar environments (Balian and Memišević Hodžić 2022). In our research, the Vrbanja provenance demonstrates above-average production at both studied sites, indicating its adaptability to various site conditions. Such provenances may be of particular interest to actors in restoration actions and beyond, especially if they exhibit traits associated with high-quality timber, such as a well-developed wood structure and stem straightness (Kranenborg and de Vries 1999). Previous studies showed that some provenances in the Gajno site were more similar and more closely related to each other than others, and this relatedness depended on microsite conditions, which were crucial for their similarity and mutual association (Franjić et al. 2000). Jensen (2000) conducted a study of 33 provenances in Danish field trials with pedunculate oak. The trials included provenances from Denmark, the Netherlands, Germany, Norway, and Sweden, established between 1900 and 1988. The results revealed significant differences in volume among provenances and strong geographical patterns in growth, although considerable variation was also evident within regions. Buras et al. (2020) investigated how soil properties impact the growth and productivity of pedunculate oak. Ten Dutch provenances were planted across three trials located on soils with differing characteristics. The study found significant variation in productivity among provenances, with growth patterns closely linked to soil type. In the Gajno site, the Velika Gorica provenance showcased the highest volume, where soil conditions closely match its native habitat. Conversely, in the Slavir site, where the soil types are moister, the Velika Gorica provenance recorded the lowest volume. The Guševac provenance demonstrated the highest tree volume on soil typical of its native habitat at the Slavir site, while it ranked among the lowest in volume at the Gajno site. Overall, tree volume was generally greater at Slavir, suggesting that soil composition and water availability may influence growth parameters. For instance, Klein et al. (2015) reported that sites with higher groundwater levels had an increased average tree height. Neyko et al. (2023) evaluated 65 pedunculate oak provenances from Central Ukraine and, in line with the present study, found that local populations generally exhibited the highest growth values. Fober (1998) noted in a 28-year-old provenance test that Polish pedunculate oak populations differ in growth, with these differences persisting over time, suggesting that the suitable selection of provenances may be essential for the economic success of plantations. This is partly confirmed by Perić (2001), who reported that 12 years after the establishment of the trial in Gajno, the Đurđenovac provenance had the greatest timber volume (14.38 m<sup>3</sup>/ha) per hectare, followed by the Spačva (13.75 m<sup>3</sup>/ha) and Orlovac (12.41 m<sup>3</sup>/ha) provenances. The lowest results were shown by the

Motovun (4.81 m<sup>3</sup>/ha), Skakavac (7.18 m<sup>3</sup>/ha), and Dubica (7.72 m<sup>3</sup>/ha) provenances. Even 38 years after the trial establishment, the Motovun provenance continues to show the lowest volume, while the Đurđenovac provenance remains the second most productive. Regarding the Slavir site, Perić (2001) recorded greatest timber volume per hectare for the Gunja (9.88 m<sup>3</sup>/ha), Zdenački gaj (9.41 m<sup>3</sup>/ha), and Đurđenovac (9.63 m<sup>3</sup>/ha) provenances, while the lowest values were recorded for the Skakavac (4.11 m<sup>3</sup>/ha), Velika Gorica (4.61 m<sup>3</sup>/ha), and Motovun (4.73 m<sup>3</sup>/ha) provenances. Although the experiment in Slavir did not identify a statistically significant difference in provenance volume, the Velika Gorica provenance still had the lowest recorded volume.

## CONCLUSIONS

Given the significant variability in the morphological and physiological properties of pedunculate oak, research into provenance productivity plays an important role for the forestry sector. The study results support the hypothesis that selecting the appropriate provenance for a specific site is important, as the volume of provenances varies among both provenances and sites. Volume in the Slavir site was 28% greater than productivity in the Gajno site in 2023. Thus, the observed values are higher at the Slavir site, which also suggests that higher productivity of provenances can be expected at this site in the future. Provenances Motovun, Skakavac, Novska, Guševac, and Morović showed the largest differences in volume between sites. The same was noted for the Velika Gorica provenance, which recorded the lowest volume at the Slavir site, but the highest volume at the Gajno site. The local provenances demonstrated the highest volume in all provenance tests. The restoration recommendations are that areas with climatic conditions like those in Gajno should be restored with the Velika Gorica provenance, while areas with climate conditions like those in Slavir should be restored with the Guševac provenance. Attention should be paid to provenances that exhibited high volume performance at both sites, such as Vrbanja, as this suggests good adaptability to a broader range of site conditions. At the Gajno site, a statistically significant interaction between provenance and year of measurement was detected, indicating that the provenances exhibited different patterns of volume growth over the study period. However, at the Slavir site, no statistically significant interaction between provenance and year of measurement was observed, suggesting that the provenances showed similar patterns of volume growth over the study period. These provenance tests were originally established to identify the most productive provenances for forest restoration in the Republic of Croatia. Beyond high productivity, recent findings also highlight the potential adaptive capacity of this species to climate change. Provenance trials are also of great importance for identifying forest reproductive material that is best adapted to future restoration efforts under changing site conditions. The selection of forest reproductive material from appropriate provenances is one of the essential components for establishing more resilient and stable pedunculate oak forests. Therefore, new scientific insights not only justify the original rationale for establishing these trials but also underscore the importance of setting up additional trials to gain further knowledge for future forest restoration and conservation strategies.

## ACKNOWLEDGEMENTS

This work was partially funded by the project Conservation of pedunculate oak (*Quercus robur* L.) stands in the Republic of Croatia with emphasis on biotic harmful factors (*Očuvanje sastojina hrasta lužnjaka (Quercus robur L.) u Republici Hrvatskoj s naglaskom na biotske štetne čimbenike*), and partially funded by the European Union – NextGenerationEU, project Establishment and development of LABORatory for ADAPTEd forest reproductive material (LABADAPT) (*Uspostava i razvoj LABORatorija za ADAPTirani šumski reprodukcijski materijal (LABADAPT)*). The views and opinions expressed are solely those of the author and do not necessarily reflect the official views of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

## REFERENCES

- Anić, I., 2025: Povijest obnove šuma hrasta lužnjaka u Hrvatskoj. Šumarski list 149 (5–6): 279–290. <https://doi.org/10.31298/sl.149.5-6.6>
- Ballian, D., M. Memišević Hodžić, 2022: Varijabilnost hrasta lužnjaka (*Quercus robur* L.) u bosanskohercegovačkom testu provenijencija: korelacije između svojstava rasta i morfologije lista. Šumarski list 146 (1–2): 41–49. <https://doi.org/10.31298/sl.146.1-2.4>
- Buras, A., U. Sass-Klaassen, I. Verbeek, P. Copini, 2020: Provenance selection and site conditions determine growth performance of pedunculate oak. *Dendrochronologia* 61: 125705. <https://doi.org/10.1016/j.dendro.2020.125705>
- Ceccherini, G., G. Duveiller, G. Grassi, G. Lemoine, V. Avitabile, R. Pilli, A. Cescatti 2020: Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583 (7814): 72–77. doi: 10.1038/s41586-020-2438-y
- Cloud Software Group, Inc., 2023: Data Science Workbench, version 14. <https://www.spotfire.com/>
- Đodan, M., S. Perić, 2022: Stručni nadzor i pregled rasadničke proizvodnje šumskog sadnog materijala u Republici Hrvatskoj tijekom 2021. godine. Radovi – Šumarski institut Jastrebarsko 48 (1): 48–56. <https://hrcak.srce.hr/306997>
- Dolos, K., A. Bauer, S. Albrecht, 2015: Site suitability for tree species: Is there a positive relation between a tree species' occurrence and its growth? *European Journal of Forest Research* 134: 609–621. <https://doi.org/10.1007/s10342-015-0876-0>
- Eaton, E., G. Caudullo, S. Oliveira, D. de Rigo, 2016: *Quercus robur* and *Quercus petraea* in Europe: Distribution, habitat, usage and threats. In (San-Miguel-Ayanz, D. de Rigo, G. Caudullo, T. Houston Durrant, A. Mauri, eds.): *European Atlas of Forest Tree Species*. Publication Office of the European Union: Luxembourg, pp. 160–163.
- Fady, B., F.A. Aravanopoulos, P. Alizoti, C. Matyas, G. von Wühlisch, M. Westergren, P. Belletti, B. Cvjetković, F. Ducci, G. Huber, C.T. Kelleher, A. Khaldi, M. Bou Dagher Kharrat, H. Kraigher, K. Kramer, U. Mühlethaler, S. Perić, A. Perry, M. Rousi, H. Sbay, S. Stojnić, M. Tijardović, I. Tsvetkov, M.C. Varela, G.G. Vendramin, T. Zlatanov, 2016: Evolution-based approach needed for the conservation and silviculture of peripheral forest tree populations. *Forest Ecology and Management* 375: 66–75. <https://doi.org/10.1016/j.foreco.2016.05.01>
- Fober, H., 1998: Provenance experiment with pedunculate (*Quercus robur* L.) and sessile (*Q. petraea* [Matt.] Liebl.) oaks established in 1968. *Arboretum Kórníckie* 43: 67–78.
- Franjić, J., J. Gračan, D. Kajba, Ž. Škvorc, B. Dalbelo-Bašić, 2000: Multivariate analysis of leaf shape of the common oak (*Quercus robur* L.) in the Gajno provenance test (Croatia). *Glasnik za šumske pokuse* 37: 469–479.
- Gračan, J., 1986: Program znanstvenoistraživačkog rada za razdoblje 1986. do 1990. Poslovna zajednica „Exportdrvo“, Zagreb.
- Gračan, J., 1993: Preliminary results of common oak (*Quercus robur* L.) provenance experiments in Croatia. *Annals of Forest Science* 50 (1): 215–221. <https://doi.org/10.1051/forest:19930720>
- Gračan, J., N. Komlenović, P. Rastovski, 1991: Pokus provenijencija hrasta lužnjaka (*Quercus robur* L.). Šumarski list 115 (6–9): 245–260.
- Gračan, J., Z. Perić, 1993: Pokus provenijencija hrasta lužnjaka (*Quercus robur* L.) u Hrvatskoj. Radovi – Šumarski institut Jastrebarsko 28 (1–2): 25–36.
- IPCC, 2021: *Climate Change 2021: The Physical Science Basis*. Cambridge University Press, Cambridge, UK. [www.ipcc.ch](http://www.ipcc.ch)
- Jensen, J.S., 2000: Provenance variation in phenotypic traits in *Quercus robur* and *Quercus petraea* in Danish provenance trials. *Scandinavian Journal of Forest Research* 15 (3): 297–308. <https://doi.org/10.1080/028275800447922>
- Kesić, L., K. Cseke, S. Orlović, D.B. Stojanović, S. Kostić, A. Benke, A. Borovics, S. Stojnić, E.V. Avramidou, 2021: Genetic diversity and differentiation of pedunculate oak (*Quercus robur* L.) populations at the southern margin of its distribution range—implications for conservation. *Diversity* 13 (8): 371. <https://doi.org/10.3390/d13080371>
- Klein, T., C. Randin, C. Körner, 2015: Water availability predicts forest canopy height at the global scale. *Ecology Letters* 18 (12): 1311–1320. <https://doi.org/10.1111/ele.12525>
- Kleinschmit, J. 1993: Intraspecific variation of growth and adaptive traits in European oak species. *Annals of Forest Science* 50 (1): 166–185. <https://doi.org/10.1051/forest:19930716>
- Klepac, D., 2000: Najveća cjelovita šuma hrasta lužnjaka u Hrvatskoj – Spačva. Hrvatska akademija znanosti i umjetnosti i Centar za znanstveni rad Vinkovci, Zagreb.
- Komlenović, N., J. Gračan, P. Rastovski, 1988: Istraživanja rasta i ishrane biljaka hrasta lužnjaka (*Quercus robur* L.), kitnjaka (*Quercus petraea* Matt. Lieb), medunca (*Quercus pubescens* Willd.) i crnike (*Quercus ilex* L.). Radovi – Šumarski institut Jastrebarsko 75: 211–223.
- Kramer, K., 2016: Guidelines for the choice of forest reproductive material in the face of climate change. EU. <https://edepot.wur.nl/384587>
- Kranenborg, K.G., S.M.G. de Vries, 1999: Provenance research *Quercus robur* in de rips (No. 99/4). IBN-DLO.
- Krutovsky K.V., A.A. Popova, I.A. Yakovlev, Y.A. Yanbaev, S.M. Matveev, 2025: Response of pedunculate oak (*Quercus robur* L.) to adverse environmental conditions in genetic and dendrochronological studies. *Plants* 14: 109. <https://doi.org/10.3390/plants14010109>
- Mikac, S., D. Trlin, A. Žmegač, S. Dekanić, B. Miklič, I. Anić, 2020: Impact of recent climate change on the lowland forest ecosystems of pedunculate oak (*Quercus robur* L.) in Croatia. In (Anić, I., ed.): *Zbornik radova – Gospodarenje šumama u uvjetima klimatskih promjena i prirodnih nepogoda*. Zagreb, pp. 1–15.
- Neyko, I., M. Matusyak, O. Neyko, O. Tsyhanska, 2023: Variability of pedunculate oak (*Quercus robur* L.) provenances in Central Ukraine. *Bulletin of the Transilvania University of Brasov, series II: Forestry, Wood Industry, Agricultural Food Engineering* 16 (65): 1–16. <https://doi.org/10.31926/but.fwi.2023.16.65.2.1>
- Ortmann-Ajkai, A., G. Csicssek, M. Lukács, F. Horváth, 2017: Regeneration patterns in a pedunculate oak (*Quercus robur* L.) Strict Forest reserve in Southern Hungary. Šumarski list 141 (1–2): 39–46. <https://doi.org/10.31298/sl.141.1-2.4>
- Perić, S., 2001: Šumsko-uzgojna svojstva različitih provenijencija hrasta lužnjaka (*Quercus robur* L.) u Hrvatskoj. Doktorski rad, Sveučilište u Zagrebu Fakultet šumarstva i drvne tehnologije, Zagreb.
- Špiranec, M., 1975: Prirasno-prihodne tablice za hrastove, bukvu, obični grab i pitomi kesten. Radovi – Šumarski institut Jastrebarsko 25: 1–103.
- Teslak, K., J. Čavlović, M. Božić, K. Beljan, 2013: Kvalitativna struktura stabala hrasta lužnjaka (*Quercus robur* L.) kao kriterij planiranja sastojina za obnovu. Šumarski list 137 (7–8): 367–377. <https://hrcak.srce.hr/109439>
- Thomas, F.M., R. Blank, G. Hartmann, 2002: Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. *Forest Pathology* 32: 277–307. <https://doi.org/10.1046/j.1439-0329.2002.00291.x>
- Tikvić, I., Ž. Žečić, D. Ugarković, D. Posarić, 2009: Oštećenost stabala i kakvoća drvnih sortimenata hrasta lužnjaka na spačvanskom području. Šumarski list 135 (5–6): 237–248.
- Zaninović, K., M. Gajić-Čapka, M. Prečec Tadić, M. Vučetić, J. Milković, A. Bajić, K. Cindrić, L. Cvitan, Z. Katušin, D. Kaučić, T. Lisko, E. Lončar, N. Strelec Mahović, V. Vučetić, M. Orlić, 2008: *Klimatski atlas Hrvatske 1961–1990., 1971–2000*. Državni hidrometeorološki zavod, Zagreb.