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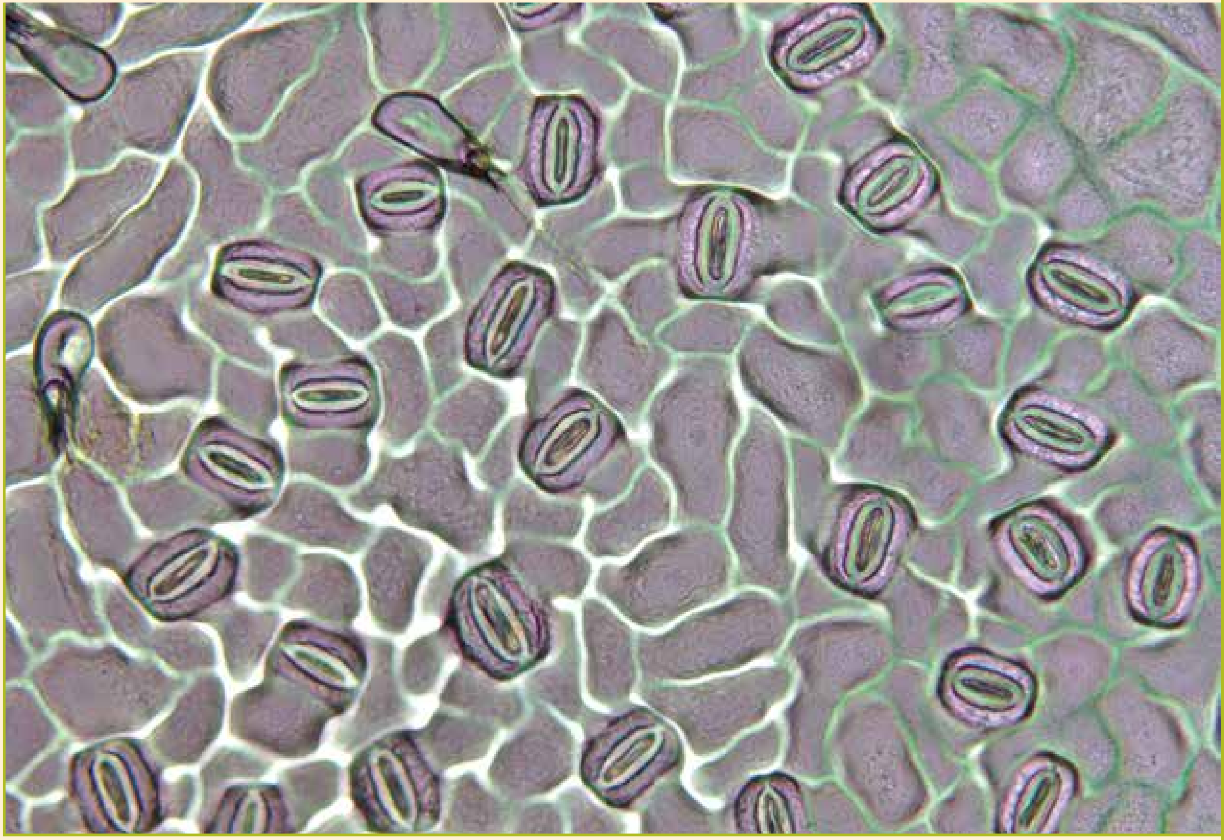

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GROWING STOCK OF TREE AND SHRUB SPECIES ACROSS ELEVATION ZONES IN SLOVENIA: COMPARATIVE ANALYSIS AND DEVELOPMENTAL CHARACTERISTICS

Anže Martin PINTAR,[1] Andreja FERREIRA,[1] Gal KUŠAR,[1] Mitja SKUDNIK,[1, 2] Luka KRAJNC[1]

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IZVLEČEK

Slovenski gozdovi spadajo med vrstno pestrejše, saj v njih raste kar 71 avtohtonih drevesnih vrst. Navkljub veliki vrstni pestrosti slovenskih gozdov v lesni zalogi le teh s 60 % prevladujeta bukev (*Fagus sylvatica*) in navadna smreka (*Picea abies*). Lesna zaloga merskih dreves narašča z nadmorsko višino, tako ima zgornji višinski pas največjo lesno zalogo, in sicer 398 m^3/ha. Obratno od lesne zaloge merskih dreves in grmov se Shannon-Wienerjev indeks vrstne pestrosti z nadmorsko višino zmanjšuje. Podobno je tudi pri Shannon-Wienerjevem indeksu vrstne pestrosti podmerskih dreves, s tem da je v nižinskem pasu nekoliko manjši. Delež smreke v lesni zalogi merskih dreves se veča z nadmorsko višino. V nižinskem pasu (do 300 m) znaša 10,2 %, v najvišjem pa 49,4 %. Bukev je v zadnjem obdobju postala najpogostejša drevesna vrsta v deležu lesne zaloge merskih in podmerskih drevesnih vrst, kar nakazuje tudi na prihodnje večanje lesne zaloge deleža merskih dreves bukve. V nižinskem in spodnjem višinskem pasu (nižjem od 700 m) je delež lesne zaloge podmerskih dreves: termofilnih listavcev – predvsem malega jesena (*Fraxinus ornus*), črnega gabra (*Ostrya carpinifolia*), tujerodne robinije (*Robinia pseudoaccacia*) in sencozdržnega belega gabra (*Carpinus betulus*) precej večji od deleža lesne zaloge teh drevesnih vrst v lesni zalogi merskih dreves. V merski zalogi podmerskih grmovnih vrst tako v celotni Sloveniji kot tudi v vseh višinskih pasovih prevladuje navadna leska (*Corylus avellana*), ta prav tako močno prevladuje v vseh višinskih pasovih – največji delež ima v višinskem pasu od 700 do 1.000 m (91,3 %), najmanjšega pa v nižinskem pasu (61,9 %).

Ključne besede: Nacionalna gozdna inventura, Slovenija, gozdovi, višinski pasovi, raznolikost, drevesne vrste, grmovne vrste, lesna zaloga

ABSTRACT

Slovenian forests are among the most species-rich in Europe, with 71 native tree species recorded. Despite this high diversity, two species—European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*)—dominate the growing stock, together accounting for 60% of the total volume. The growing stock of trees and shrubs above the 10 cm DBH (diameter at breast height) threshold increases with elevation, with the highest elevation zone reaching 398 m^3/ha. In contrast, the Shannon–Wiener diversity index for trees and shrubs above 10 cm DBH decreases as elevation increases. A similar pattern is observed for the Shannon–Wiener index of small trees and shrubs (below the 10 cm DBH threshold), although values in the lowest elevation zone are slightly lower. The proportion of Norway spruce in the growing stock of trees above 10 cm DBH increases markedly with elevation, rising from 10.2% in the lowest elevation zone (<300 m) to 49.4% in the highest zone. In recent years, European beech has become the dominant species in the growing stock of both trees and shrubs above 10 cm DBH, as well as small trees and shrubs below 10 cm DBH, indicating a likely further increase in the proportion of beech in future growing stock development. In elevation zones below 700 m, the growing stock of small trees and shrubs contains a substantially higher proportion of thermophilous broadleaved species—particularly manna ash (*Fraxinus ornus*), hop hornbeam (*Ostrya carpinifolia*), the non-native black locust (*Robinia pseudoacacia*), and shade-tolerant hornbeam (*Carpinus betulus*)—compared to their proportion in the growing stock of trees and shrubs above 10 cm DBH. In the growing stock of small shrubs across Slovenia and within all elevation zones, common hazel (*Corylus avellana*) predominates. Its growing stock proportion is highest in the 700–1000 m elevation zone (91.3%) and lowest in the lowest elevation zone (61.9%).

Keywords: National Forest Inventory, Slovenia, forests, elevation zones, diversity, tree species, shrub species, growing stock

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1 UVOD

Slovenija se nahaja na območju stika Alp, Dinaridov, Sredozemlja in Panonske nižine. Velika razgibanost terena, raznoliko podnebje, pestre talne razmere in pestrost mnogoterih drugih okoljskih dejavnikov omogočajo veliko raznolikost gozdnih združb (Kutnar s sodelavci 2002) ter s tem veliko pestrost drevesnih in grmovnih vrst v gozdovih. V slovenskih gozdovih tako najdemo 71 različnih avtohtonih drevesnih vrst (Brus s sodelavci 2017). V Sloveniji raste še 230 avtohtonih lesnatih rastlinskih vrst (Brus 2008). Med njimi prevladujejo pravi grmi, le nekaj je polgrmov, ki jim oleseni le spodnji del poganjka. Raznolikost drevesnih in grmovnih vrst v slovenskih gozdovih potrjuje tudi analiza pojavljanja teh na ploskvah Nacionalne gozdne inventure (NGI) v obdobju od leta 2020 do leta 2023 (Pintar s sodelavci 2024).

Navkljub veliki vrstni pestrosti slovenskih gozdov v lesni zalogi le teh s 60-odstotnim deležem prevladujeta bukev (*Fagus sylvatica*) in navadna smreka (*Picea abies*) (Pintar s sodelavci 2024), ki sta tudi najpomembnejši drevesni vrsti submontanskih in montanskih regij Srednje Evrope (Leuschner & Ellenberg 2017). V Sloveniji se več kot 70 % gozdov nahaja na bukovih, jelovo-bukovih in bukovo-hrastovih rastiščih (Dakskobler 2008, Dakskobler 2012). Tako v Sloveniji bukev ni prisotna le na petini celotne površine slovenskih gozdov, in sicer na nižinskih hidromorfnih tleh, v alpskem pasu in mraziščih, na ekstremno suhih rastiščih in na območjih, kjer se jo je zaradi nasadov smreke ali kakšne druge ekonomsko zaželene drevesne vrste, z načinom gospodarjenja z gozdovi, povsem izločilo iz sestojev (Poljanec s sodelavci 2012). Le manjši delež gozdov v Sloveniji z visokim deležem smreke so naravni smrekovi gozdovi (Dakskobler 2008, Poljanec s sodelavci 2012).

Tako kot v gozdovih Srednje Evrope se je tudi v slovenskih gozdovih v preteklosti pospešeno sadilo smreko zunaj njenega naravnega areala. Ti gozdovi so sedaj v veliki meri podvrženi ujmam in napadom podlubnikov (Kutnar, Kermavnar & Pintar 2021), kar se v zadnjem obdobju že odraža v zmanjševanju lesne zaloge smreke na nacionalni ravni. V Sloveniji je bukev po letu 2020 po dolgem obdobju ponovno postala najpogostejša drevesna vrsta v lesni zalogi z 32 %, medtem ko delež smreke na drugem mestu znaša 28 % (Skudnik s sodelavci 2021, Pintar s sodelavci 2024). Na osnovi modela prostorskega širjenja bukve (Poljanec s sodelavci 2010) lahko v prihodnosti pričakujemo povečanje lesne zaloge bukve v zasmrečenih gozdovih, predvsem na podgorskih bukovih rastiščih (Poljanec s sodelavci 2012).

Nadmorska višina je eden od ključnih dejavnikov, ki posredno odraža spremembe v podnebnih in rastiščnih razmerah ter s tem vpliva na razširjenost in konkurenčne odnose med drevesnimi in grmovnimi vrstami (Körner 2007). Tako nadmorska višina ključno vpliva na vrstno sestavo gozdov (Lomolino 2001), kar je predstavljeno tudi v tipologiji slovenskih gozdnih rastiščnih tipov (Kutnar s sodelavci 2012, Bončina s sodelavci 2021). Trenutno so podatki o spreminjanju deleža posameznih drevesnih vrst v lesni zalogi med višinskimi pasovi v Sloveniji predstavljeni na podlagi podatkov gozdne inventure za potrebe gozdnogospodarskega načrtovanja, ki poteka v izbranih gozdnogospodarskih enotah v letu pred posodobitvijo gozdnogospodarskega načrta in jo izvaja Zavod za gozdove Slovenije (Poljanec s sodelavci 2023). V prispevku predstavljamo analizo spremenljivosti deleža drevesnih in grmovnih vrst v lesni zalogi slovenskih gozdov glede na višinske pasove na ploskvah NGI, ki so sistematično razporejene po celotni Sloveniji na vzorčni mreži 2 x 2 km.

Namen prispevka je analizirati, kako se delež drevesnih in grmovnih vrst v lesni zalogi slovenskih gozdov spreminja med višinskimi pasovi ter nakazati možne razvojne trende drevesne sestave na podlagi primerjave lesne zaloge merskih in podmerskih drevesnih vrst. S pričujočimi analizami dopolnjujemo obstoječe poznavanje stanja in spreminjanja vrstne sestave slovenskih gozdov vzdolž gradienta nadmorske višine ter prispevamo strokovno podlago za razmislek o gospodarjenju z gozdovi, ki je v luči podnebnih sprememb in ujm pred velikimi izzivi.

2 METODE

2.1 Opis terenskih meritev

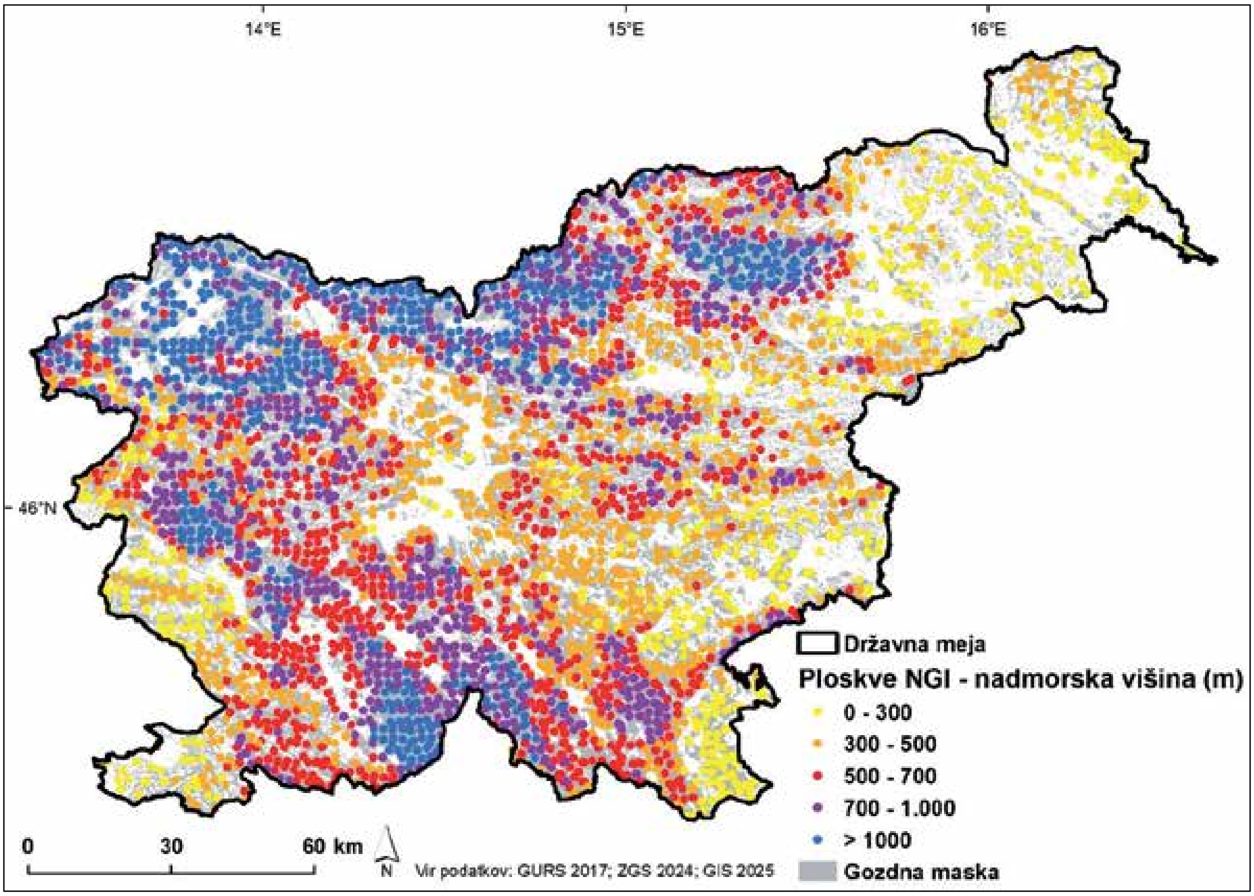
V okviru NGI se podatki o stanju in spremembah gozdov na reprezentativni mreži z gostoto 4 x 4 km, ki pokriva celotno Slovenijo, zberejo v enem letu (Skudnik s sodelavci 2021 a, Skudnik s sodelavci 2021 b). Letno se na terenu obišče in izmeri okvirno 750 gozdnih ploskev. Skupno NGI v celotni Sloveniji zajema okvirno 3.750 vzorčnih ploskev (Pintar s sodelavci 2024). Glavni namen NGI je nacionalno zbiranje podatkov za oceno trajnosti, podporo gozdarski politiki in njeno načrtovanje, spremljanje ekonomskega stanja ter strukturnih sprememb gozdov in gozdarstva, obdelavo statističnih podatkov ter pripravo drugih strokovnih analiz (ZoG 1993). V okviru izvajanja javne gozdarske službe NGI vodi Gozdarski inštitut Slovenije in jo izvaja skupaj z Zavodom za gozdove Slovenije (ZGS) (ZoG 1993). Leta 2020 je bil prvič izmerjen prvi, 2021 drugi, 2022 tretji in v 2023 četrti panel NGI, v letu 2024 pa petič peti panel NGI. Tako je bil leta 2024 zaključen prvi inventurni cikel NGI (2020-2024). V pričujočem delu smo analizirali podatke o lesni zalogi podmerskega in merskega drevja, izmerjenega na 3743 dostopnih ploskvah. Pri analizi nedostopne ploskve niso bile upoštevane.

Merska drevesa in grmi, se pravi drevesa in grmi, katerih prsni premer ($d_{1,3}$) je vsaj 10 cm, so popisana na krožnih ploskvah, velikosti 2 ara, drevesa in grmi s prsnim premerom vsaj 30 cm pa na 6-arskih ploskvah (Skudnik s sodelavci 2022). Drevesne vrste so bile v šifrant NGI uvrščene na podlagi Brus (2012), grmovne pa na podlagi Brus (2008) (Pintar s sodelavci 2020, Pintar s sodelavci 2024).

Podmersko živo drevje in grmovje se popisujeta na vzorčni ploskvi velikosti 30 m^2, ki se nahajajo 10 m severno od središča trajne vzorčne ploskve. Na teh ploskvah se popišejo vsi živi osebki drevesnih in grmovnih vrst, ki so visoki vsaj 1,3 m in imajo premer ($d_{1,3}$) do 10 cm (Skudnik s sodelavci 2022).

V prispevku smo raznolikost drevesnih in grmovnih vrst analizirali na podlagi lesne zaloge. Lesna zaloga merskega drevja in grmov se v okviru NGI izračuna na podlagi enovhodnih volumenskih funkcij – tarif, povzetih po bazi odsekov ZGS (ZGS 2021). Lesna zaloga podmerskega drevja in grmov pa se izračuna na podlagi izmerjenega premera na višini 1,3 m in višine. Za oceno povprečij se izračuna tudi vzorčna napaka na podlagi cenilke za naključno vzorčenje.

Analizo raznolikosti drevesnih in grmovnih vrst na podlagi podatkov NGI smo opravili za celotno Slovenijo in po višinskih pasovih, povzetih po Kutnar s sodelav-



Vir podatkov: GURS 2017; ZGS 2024; GIS 2025

Slika 1: Trajne vzorčne ploskve, popisane v okviru NGI 2020–2024, stratificirane po višinskih pasovih
Figure 1: Permanent sample plots surveyed in the NFI 2020–2024, stratified by elevation zones

ci (2002), do 300 m nadmorske višine (nižinski pas), od 300 do 700 m nadmorske višine (spodnji višinski pas), od 700 m nadmorske višine (srednji višinski pas) in nad 1.000 m nadmorske višine (zgornji višinski pas) (slika 1). Ker je bila v spodnjem višinskem pasu (od 300 do 700 m nadmorske višine) skoraj polovica ploskev, smo v nadaljevanju predstavili še raznolikost drevesnih vrst za dva podpasova spodnjega višinskega pasu, in sicer od 300 do 500 m in od 500 do 700 m. Pri analizi števila ploskev smo predstavili tudi delež ploskev od vseh ploskev za celotno Slovenijo in po posameznih višinskih pasovih, uvrščenih v kategorijo gozdov, dostopnih za gospodarjenje (FAWS – forest available for wood supply) (Kušar & Pintar 2021, Skudnik s sodelavci 2022).

2.2 Raznolikost merskih drevesnih in grmovnih vrst po višinskih pasovih iz podatkov NGI 2020–2024

Na podlagi podatkovne baze o drevesih NGI 2020–2024 smo za vsako ploskev izračunali Shannon-Wienerjeva indeksa vrstne pestrosti (Pielou 1966) glede na lesno zalogo merskih dreves in grmov (*H1´*) ter glede na lesno zalogo dreves (*H2´*). Vrednost *pi* tako predstavlja delež lesne zaloge dreves in grmov (m^3/ha) posamezne drevesne in grmovne vrste (enačba 1) na ploskvi oziroma delež lesne zaloge dreves (m^3/ha) posamezne drevesne vrste (enačba 1) na ploskvi.

$$H' = -\sum p_i \ln(p_i) \qquad \text{enačba 1}$$

Predstavili smo tudi deleže prvih 15 drevesnih in grmovnih vrst v lesni zalogi po višinskih pasovih in za celotno Slovenijo. Nadalje smo predstavili še deleže lesne zaloge merskih drevesnih vrst v lesni zalogi merskih drevesnih in grmovnih vrst za celotno Slovenijo in po višinskih pasovih.

2.3 Raznolikost podmerskih drevesnih in grmovnih vrst po višinskih pasovih iz podatkov NGI 2020–2024

Na podlagi podatkovne baze o podmerskih drevesih in grmih NGI 2020–2024 smo analizirali prisotnost drevesnih in grmovnih vrst na ploskvah podmerskega drevja in grmov NGI, njihovo lesno zalogo in deleže posameznih drevesnih vrst v lesni zalogi drevesnih vrst ter deleže posameznih grmovnih vrst v lesni zalogi grmovnih vrst. Prikazali smo deleže prvih 15 drevesnih vrst in prvih 7 grmovnih vrst v lesni zalogi po višinskih pasovih in za raven celotne Slovenije.

Enako kot pri merskih drevesih in grmih smo tudi iz lesne zaloge podmerskih dreves in grmov za vsako vzorčno ploskev izračunali Shannon-Wienerjeva indeksa vrstne pestrosti (Pielou, 1966) (enačba 1) glede na lesno zalogo podmerskih dreves in grmov (*H3´*) ter glede na lesno zalogo podmerskih dreves (*H4´*). Predstavili smo tudi deleže lesne zaloge podmerskih drevesnih vrst v lesni zalogi podmerskih drevesnih in grmovnih vrst za celotno Slovenijo in po višinskih pasovih.

3 REZULTATI

3.1 Lesna zaloga in raznolikost lesne zaloge merskih in podmerskih drevesnih in grmovnih vrst

Skupna lesna zaloga merskih dreves in grmov v Sloveniji med leti 2020–2024 znaša 333,9 m^3/ha (± 1,9 %) (Preglednica 1), lesna zaloga podmerskih dreves pa 7,5 m^3/ha (± 5,8 %). Lesna zaloga merskih dreves se veča z nadmorsko višino, tako ima zgornji višinski pas največjo lesno zalogo, in sicer 398 m^3/ha. Lesna zaloga podmerskih dreves je v vseh višinskih pasovih približno enaka, nekoliko večja pa v pasu med 300 in 700 m.

Obratno od lesne zaloge merskih dreves in grmov se Shannon-Wienerjev indeks vrstne pestrosti z višanjem nadmorske višine zmanjšuje (Preglednica 1). Podobno je tudi pri Shannon-Wienerjevem indeksu vrstne pestrosti podmerskih dreves, s tem, da je v nižinskem pasu nekoliko manjši.

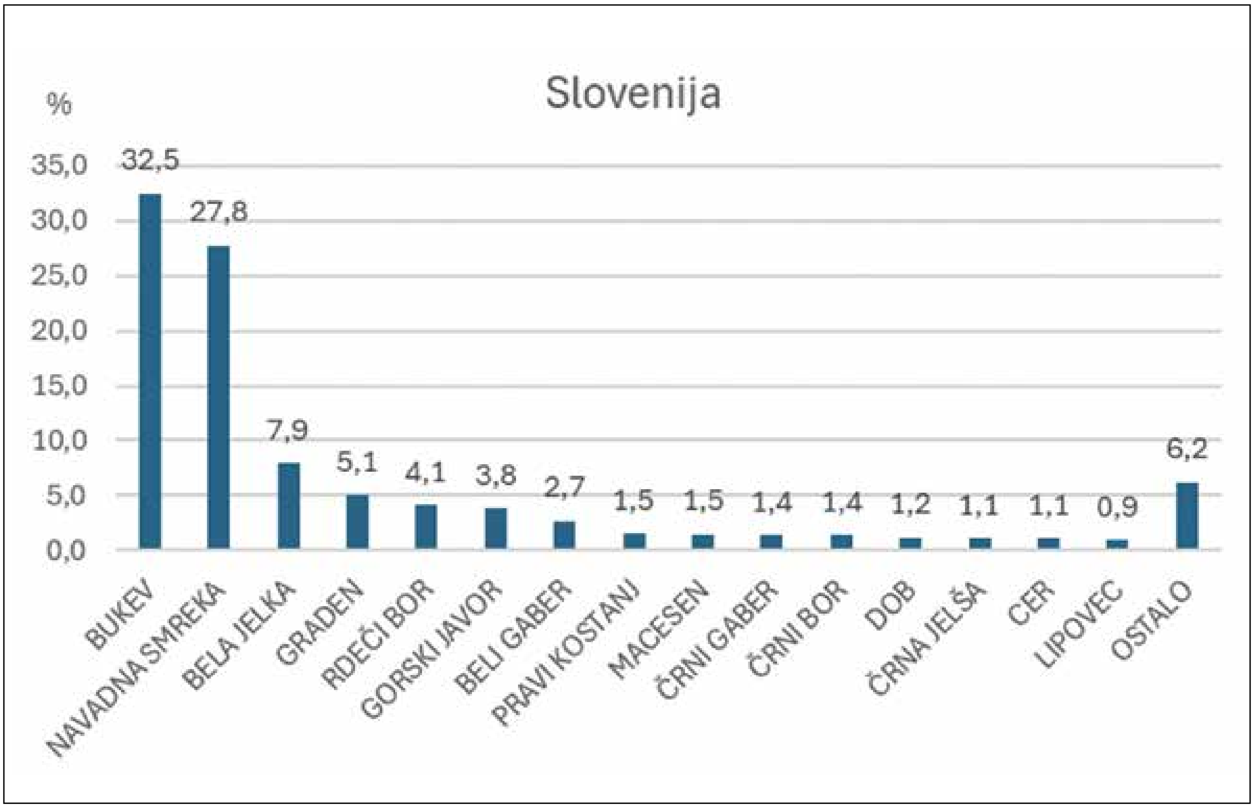
3.2 Raznolikost merskih drevesnih in grmovnih vrst

V celotni Sloveniji v lesni zalogi prevladujeta bukev (*Fagus sylvatica*) in navadna smreka (*Picea abies*), ki skupaj predstavljata več kot polovico lesne zaloge. Skupaj z belo jelko (*Abies alba*) in gradnom (*Quercus petraea*) najpogostejše štiri drevesne vrste predstavljalo skoraj tri četrtine lesne zaloge (Slika 2). Od merskih grmovnih vrst so bile popisane naslednje: navadna leska (*Corylus avellana*), črni bezeg (*Sambucus nigra*), rumeni dren (*Cornus mas*), čistilna kozja češnja (*Rhamnus fallax*), navadni ruj (*Cotinus coggygria*) in navadni bršljan (*Hedera helix*), ki predstavljajo manj kot 1 % lesne zaloge merskih drevesnih in grmovnih vrst (Preglednica 1).

Delež bukve je v lesni zalogi merskih dreves in grmov najmanjši v višinskem pasu do 300 m v primerjavi z ostalimi višinskimi pasovi (Slika 3). V ostalih višinskih pasovih je v istem velikostnem razredu. Bukev je v vseh

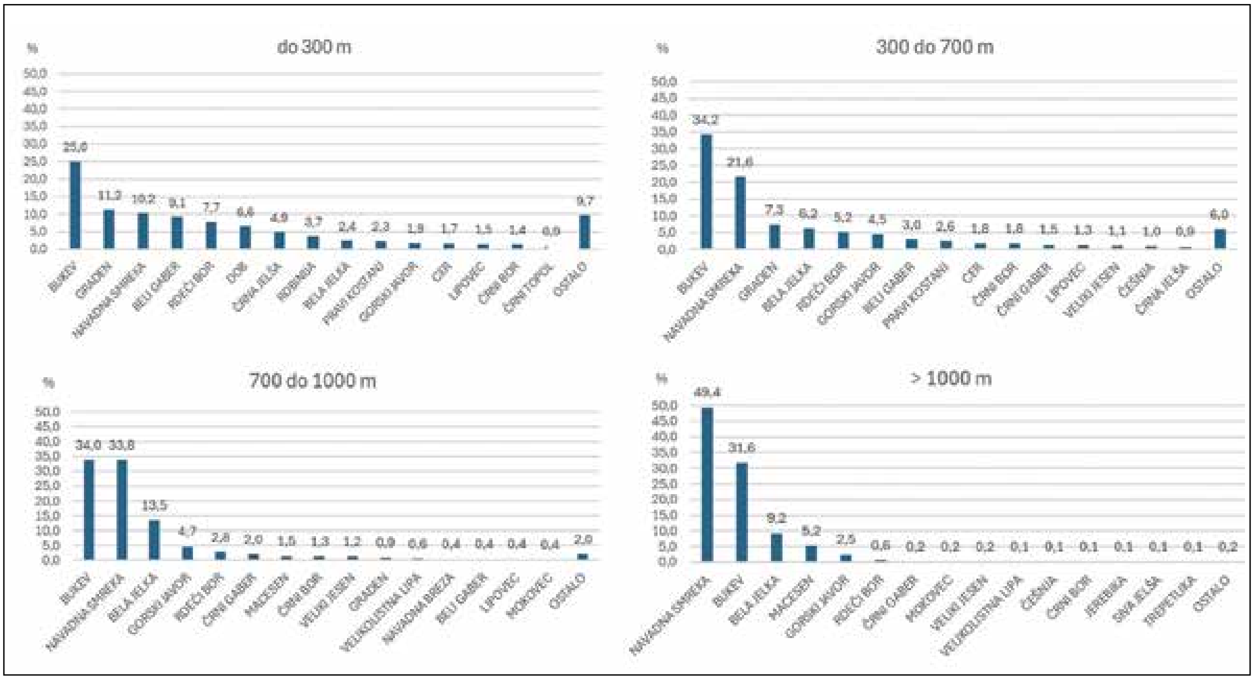
Preglednica 1: Skupno število ploskev, delež ploskev FAWS (%) od skupnega števila ploskev, lesna zaloga (LZ) merskih drevesnih in grmovnih ter delež lesne zaloge drevesnih vrst in Shannon-Wienerjev indeks vrstne pestrosti merskih drevesnih in grmovnih vrst (H_1') ter drevesnih vrst (H_2') in lesna zaloga podmerskih drevesnih in grmovnih ter delež lesne zaloge drevesnih vrst in Shannon-Wienerjev indeks vrstne pestrosti podmerskih merskih drevesnih in grmovnih (H_3') vrst ter drevesnih vrst (H_4') po višinskih pasovih in za celotno Slovenijo
Table 1: Total number of sample plots, share of FAWS plots (%), growing stock (LZ) of trees and shrubs above the 10 cm DBH threshold, proportion of growing stock by tree species, and the Shannon–Wiener diversity index for trees and shrubs above 10 cm DBH (H_1') and for tree species only (H_2'). Growing stock of small trees and shrubs (trees and shrubs below the 10 cm DBH threshold), proportion of growing stock by tree species, and the Shannon–Wiener diversity index for small trees and shrubs (H_3') and for tree species only (H_4'), by elevation zones and for Slovenia as a whole.

Višinski pas	**Število ploskev**	**Delež ploskev FAWS (%)**	**LZ merskih drevesnih in grmovnih vrst (m^3/ha)**	**Delež LZ merskih drevesnih vrst (%)**	**H_1'**	**H_2'**	**LZ podmerskih drevesnih in grmovnih vrst (m^3/ha)**	**Delež LZ podmerskih drevesnih vrst (%)**	**H_3'**	**H_4'**
do 300 m	567	98,8	298,4	99,8	0,81	0,81	9,3	75,5	0,34	0,20
300 do 700 m	1838	96,5	310,6	99,9	0,78	0,77	11,0	76,1	0,34	0,25
700 do 1.000 m	774	92,5	369,4	99,9	0,69	0,68	9,0	76,6	0,25	0,17
od 1.000 m	564	78,0	398,2	100,0	0,49	0,49	6,3	98,3	0,13	0,11
Skupaj	**3743**	**93,2**	**335,4**	**99,9**	**0,72**	**0,72**	**9,6**	**78,3**	**0,29**	**0,20**

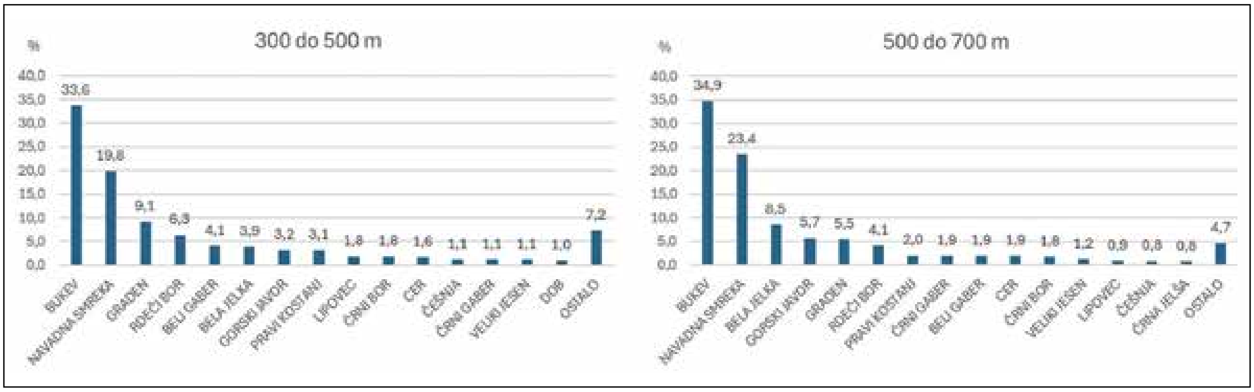


Slika 2: Deleži prvih 15 merskih drevesnih vrst v lesni zalogi v celotni Sloveniji. Ostale drevesne in grmovne vrste so uvrščene v skupino ostalo.
Figure 2: Share of the 15 most abundant tree species in the growing stock of trees and shrubs above the 10 cm DBH threshold in Slovenia. All other tree and shrub species are classified as "other" (ostalo).

višinskih pasovih na prvem mestu z zgornjega višinskega pasu (nad 1.000 m). V slednjem z 49,4 % močno prevladuje navadna smreka v primerjavi z bukvijo, ki je na drugem mestu z 31,6 %. Bukev in navadna smreka sta v vseh višinskih pasovih na prvem oziroma drugem mestu z izjemo nižinskega, kjer je navadna smreka na tretjem mestu in je na drugem graden z 11,2 %. Gradna je več kot 5 % še v višinskem pasu od 300 do 700 m. Macesna (*Larix decidua*) je več kot 1 % zgolj v višinskem pasu nad 1.000 m, in sicer 5,2 %. Bela jelka je na tretjem mestu v deležu lesne zaloge merskih drevesnih in grmovnih vrst v višinskem pasu od 700 do 1.000 m in nad 1000 m. Več kot 5 % jo je v lesni zalogi tudi v višinskem pasu od 300 do 700 m, kjer so na četrtem mestu deleži lesne zaloge.

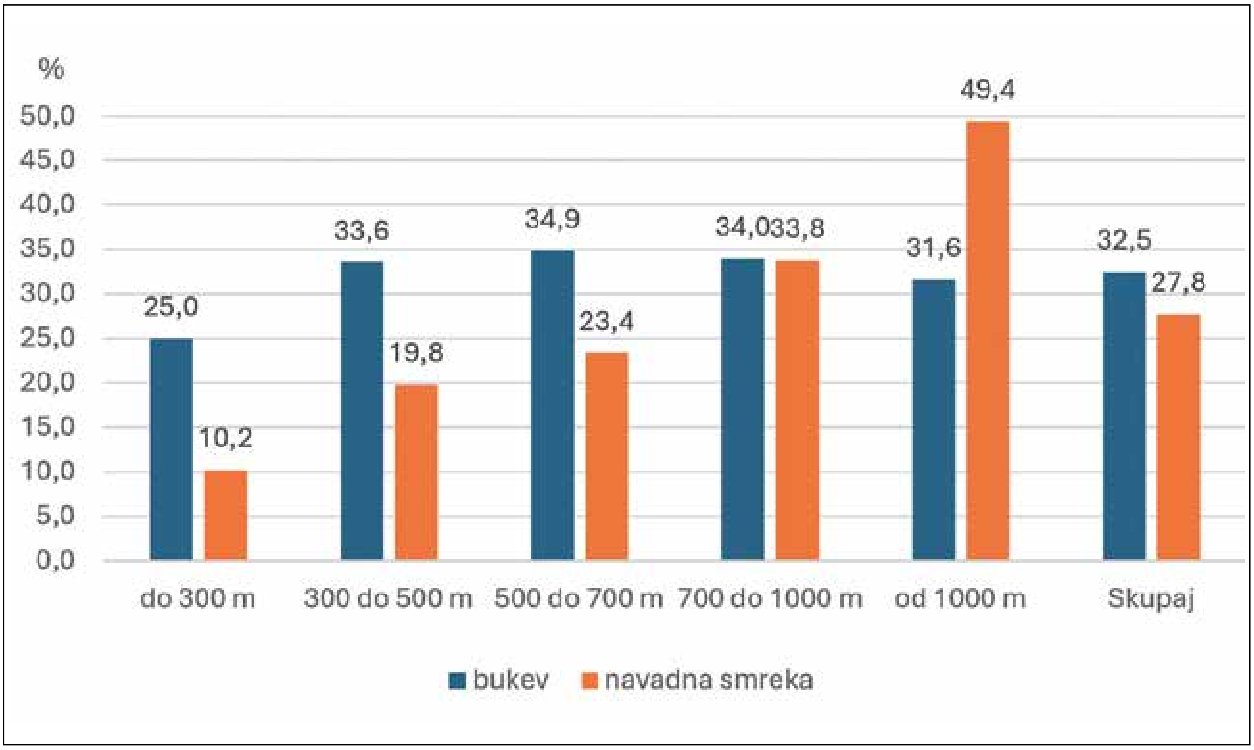


Slika 3: Deleži prvih 15 merskih drevesnih vrst v lesni zalogi po višinskih pasovih. Ostale drevesne in grmovne vrste so uvrščene v skupino ostalo.
Figure 3: Share of the 15 most abundant tree species in the growing stock of trees and shrubs above the 10 cm DBH threshold across elevation zones. All other tree and shrub species are classified as "other" (ostalo).



Slika 4: Deleži prvih 15 merskih drevesnih vrst v lesni zalogi po višinskih podpasovih višinskega pasu (300 do 700 m). Ostale drevesne in grmovne vrste so uvrščene v skupino ostalo.
Figure 4: Share of the 15 most abundant tree species in the growing stock of trees and shrubs above the 10 cm DBH threshold across elevation sub-zones within the 300–700 m elevation range. All other tree and shrub species are classified as "other" (ostalo).

Ker je višinski pas od 300 do 700 m zajemal več kot polovico vzorčnih ploskev, smo analizo opravili še posebej za višinska pasova od 300 do 500 m in od 500 do 700 m. V prvem (nižjem) se je nahajalo 905 ploskev, lesna zaloga je znašala 315,7 m^3/ha, Shannon-Wienerjev indeks 0,82, v drugem (višjem) pa se je nahajalo 933 ploskev, povprečna lesna zaloga je znašala 302,2 m^3/ha, Shannon-Wienerjev indeks pa 0,73. V obeh pasovih prevladujeta bukev in navadna smreka, s tem, da je v višjem delež navadne smreke nekoliko višji (23,4 v primerjavi z 19,8 %) (Sliki 4 in 5).



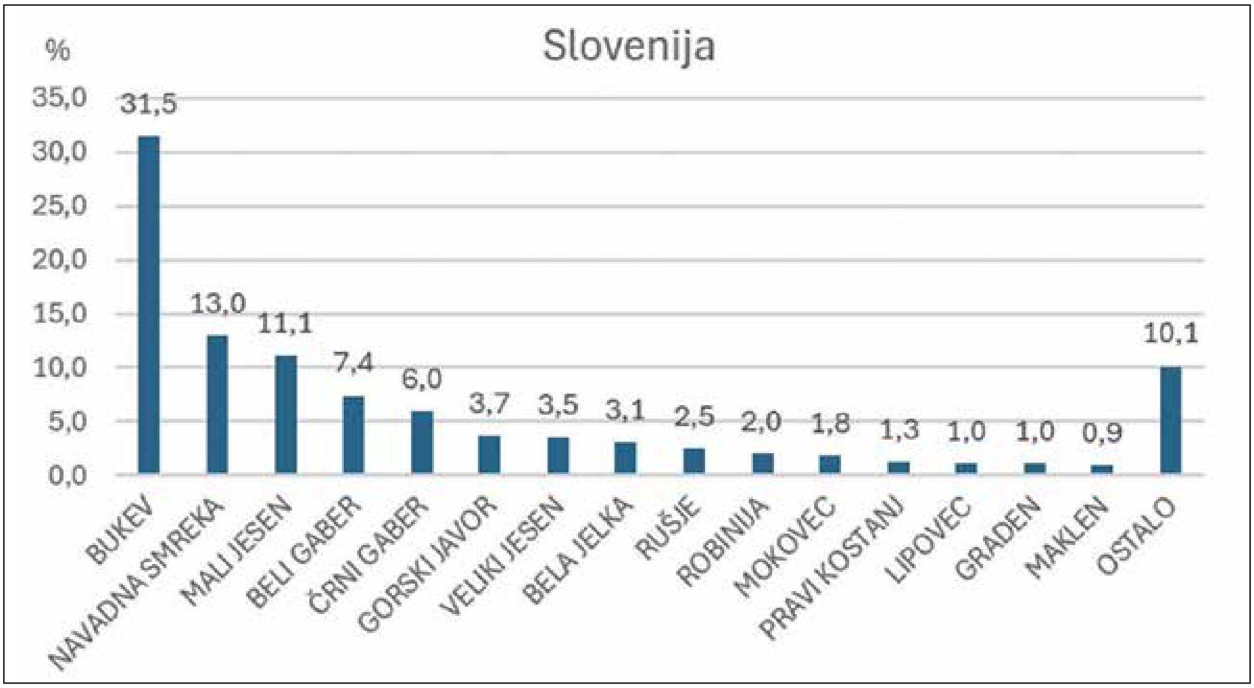
Slika 5: Izpostavljen prikaz deležev drevesnih vrst z najvišjim deležem v lesni zalogi merskih dreves v celotni Sloveniji – bukve in navadne smreke v lesni zalogi merskih dreves in grmov po višinskih pasovih.
Figure 5: Highlighted shares of the tree species with the highest proportion in the growing stock of trees and shrubs above the 10 cm DBH threshold in Slovenia—European beech and Norway spruce—across elevation zones.

3.3 Raznolikost podmerskih drevesnih vrst

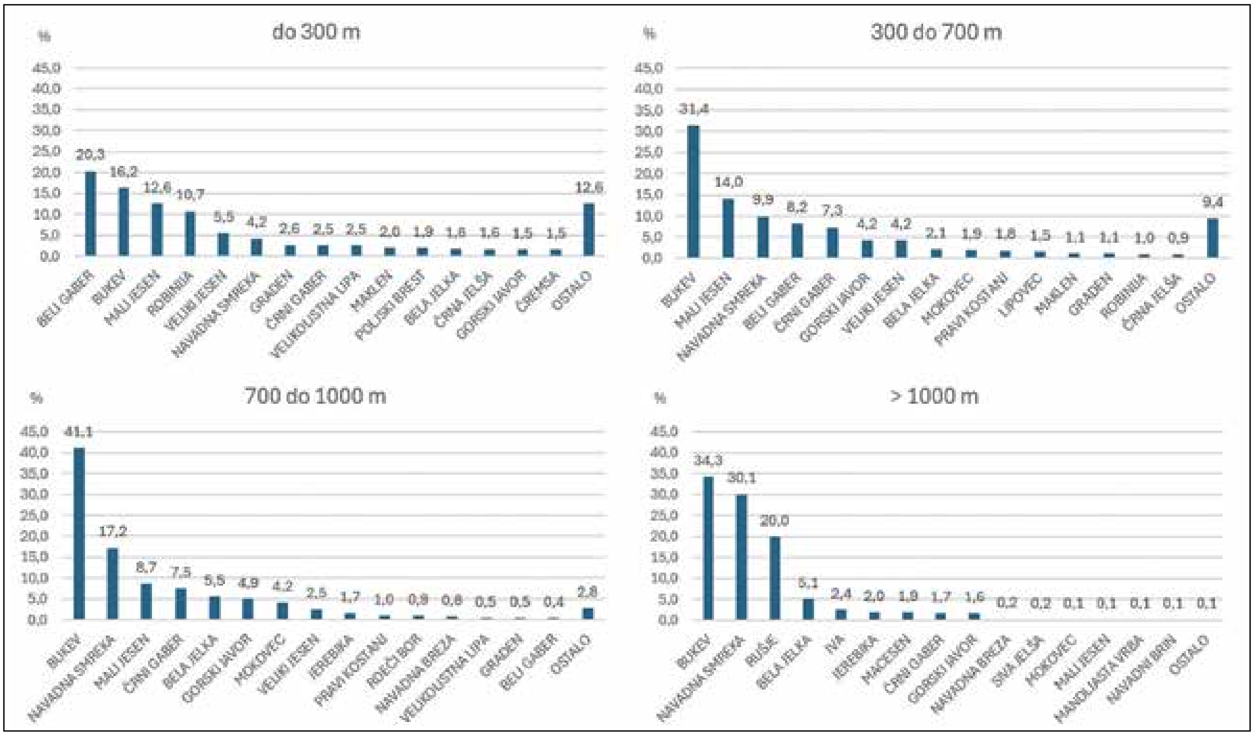
V celotni Sloveniji v lesni zalogi podmerskega drevja prevladuje bukev z 31,5 % (Slika 6). Več kot 10 % predstavljata še navadna smreka in mali jesen (*Fraxinus ornus*), več kot 5 % in manj kot 10 % pa beli gaber (*Carpinus betulus*) in črni gaber (*Ostrya carpinifolia*).

V deležu lesne zaloge podmerskega drevja je bukev na prvem mestu v vseh višinskih pasovih z izjemo nižinskega pasu (Slika 7). V slednjem je na prvem mestu beli gaber (20,3 %), sledi mu bukev, več je še malega jesena in robinije (*Robinia pseudoaccacia*). Bukev v pasovih od 300 do 700 in od 700 do 1.000 m močno prevladuje – več kot dvakratnik deleža druge drevesne vrste (malega jesena (14,0 %) v nižjem pasu in navadne smreke (17,2 %) v višjem). V zgornjem višinskem pasu sta deleža prvih dveh drevesnih vrst (bukve in smrke) v istem velikostnem razredu (34,3 oziroma 30,1 %). V slednjem bela jelka predstavlja 5,1 % lesne zaloge in rušje (*Pinus mugo*) 20,0 % lesne zaloge podmerskega drevja.

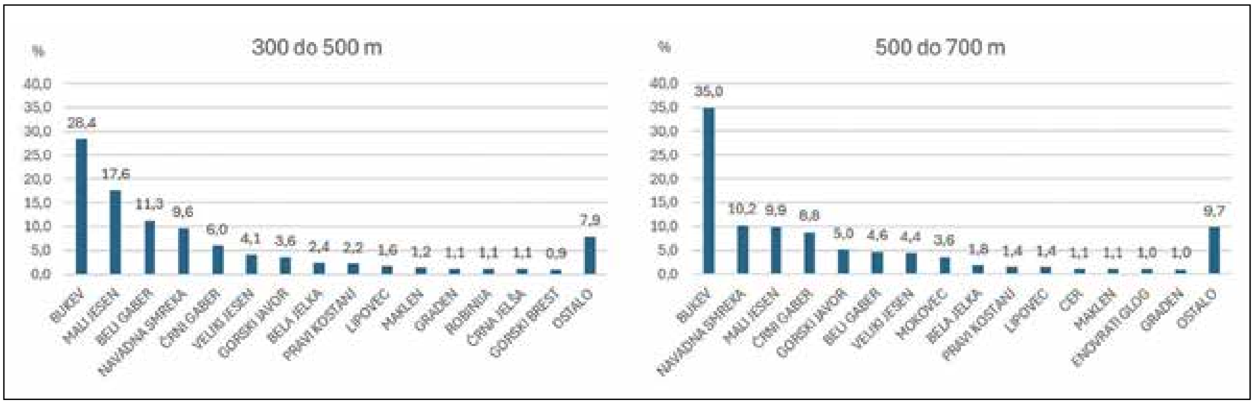
V obeh podpasovih višinskega pasu od 300 do 700 m v deležu prevladuje bukev, s tem, da v višjem veliko izraziteje (Sliki 8 in 9). V nižjem podpasu je na drugem mestu mali jesen (17,6 %), sledi mu beli gaber (11,3 %), šele na četrtem mestu je navadna smreka (9,6 %). V višjem pasu je na drugem mestu navadna smreka z 10,2 %, sledita ji mali jesen (9,9 %) in črni gaber (8,8 %).



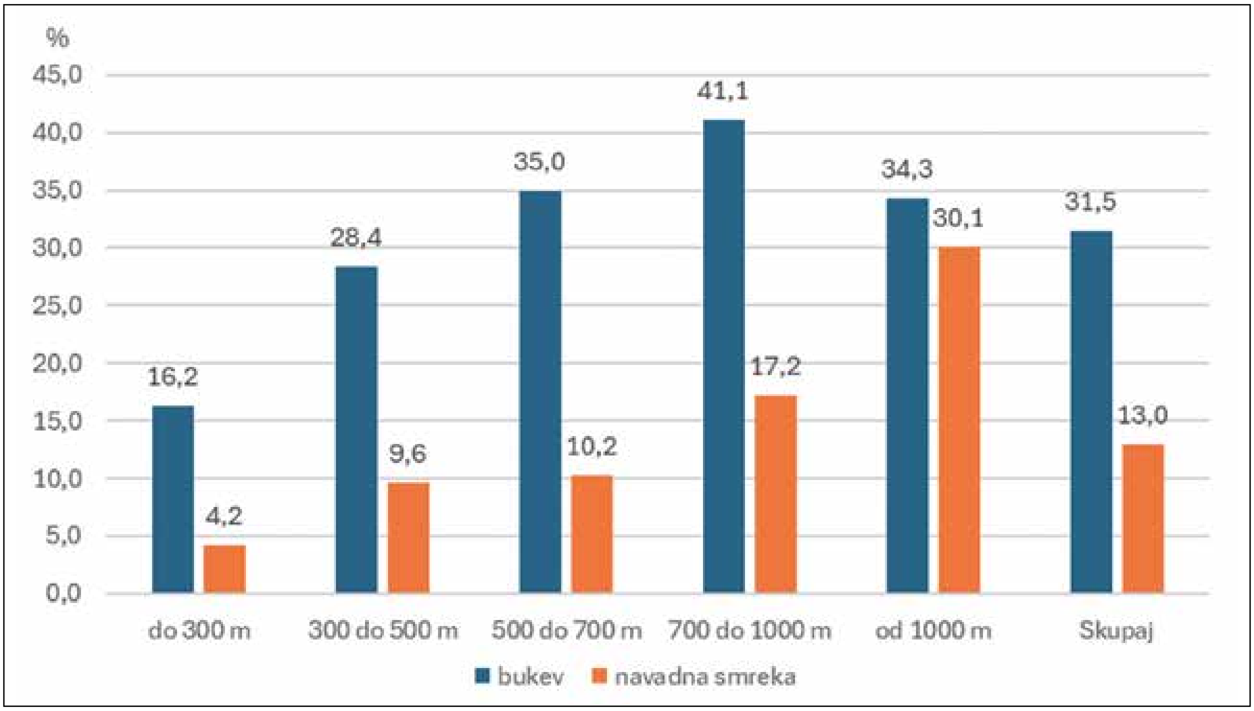
Slika 6: Deleži prvih 15 podmerskih drevesnih vrst v lesni zalogi po višinskih pasovih. Ostale drevesne vrste so uvrščene v skupino ostalo.
Figure 6: Share of the 15 most abundant small tree species (trees below the 10 cm DBH threshold) in the growing stock across elevation zones. All other tree species are classified as “other” (ostalo).



Slika 7: Deleži prvih 15 podmerskih drevesnih vrst v lesni zalogi po višinskih pasovih. Ostale drevesne vrste so uvrščene v skupino ostalo.
Figure 7: Share of the 15 most abundant small tree species (trees below the 10 cm DBH threshold) in the growing stock across elevation zones, based on NFI 2020–2024 data. All other tree species are classified as “other” (ostalo).



Slika 8: Delež prvih 15 podmerskih drevesnih vrst v lesni zalogi po višinskih podpasovih pasu 300 do 700 m. Ostale drevesne vrste so uvrščene v skupino ostalo.
Figure 8: Share of the 15 most abundant small tree species (trees below the 10 cm DBH threshold) in the growing stock across elevation sub-zones within the 300–700 m elevation range. All other tree species are classified as "other" (ostalo).

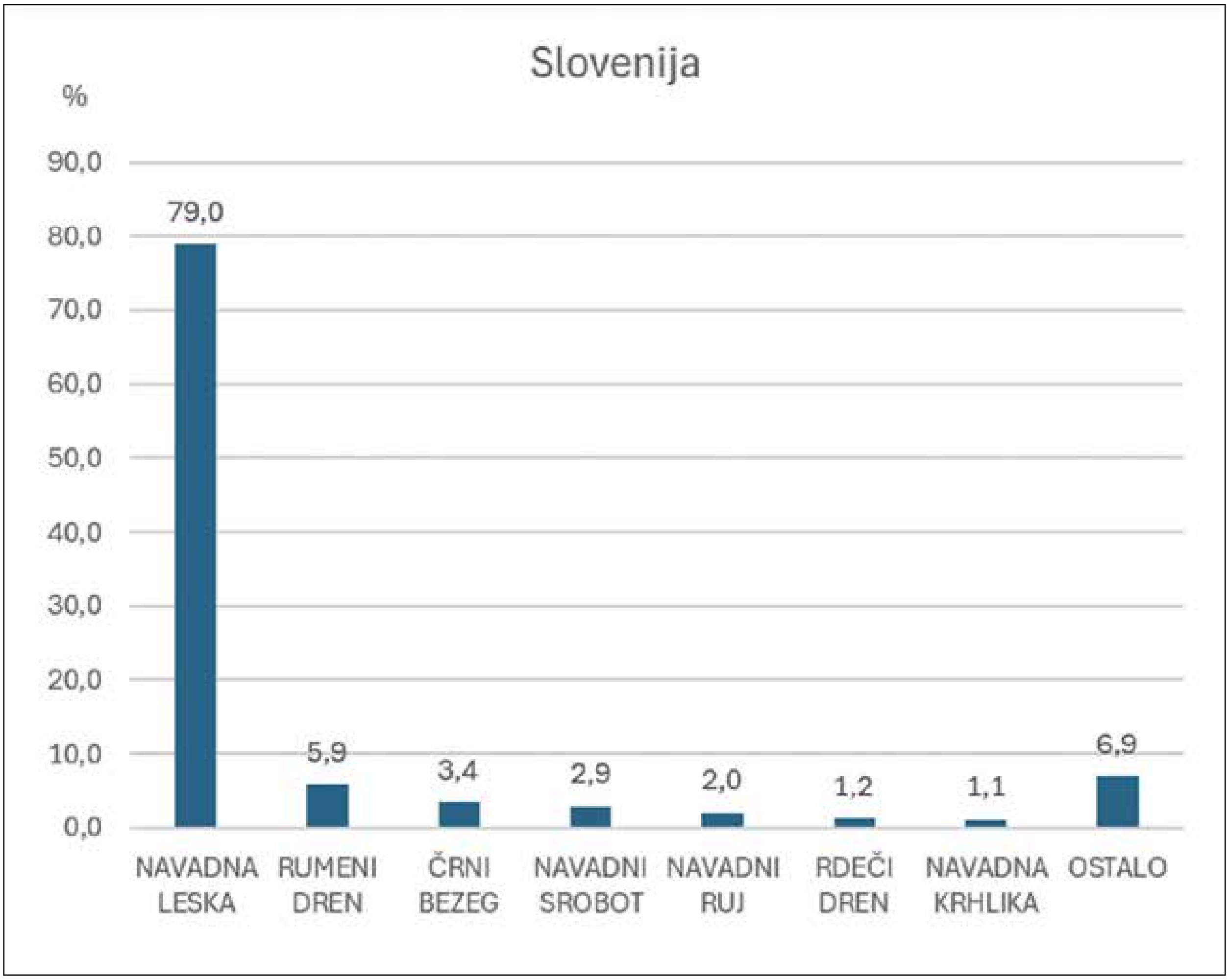


Slika 9: Izpostavljen prikaz deleža drevesnih vrst z najvišjim deležem v lesni zalogi merskih dreves v celotni Sloveniji – bukve in navadne smreke v lesni zalogi podmerskih dreves po višinskih pasovih.
Figure 9: Highlighted shares of European beech and Norway spruce—the two tree species with the highest proportions in the growing stock of trees above the 10 cm DBH threshold in Slovenia—in the growing stock of small trees (trees below the 10 cm DBH threshold) across elevation zones.

3.4 Raznolikost podmerskih grmovnih vrst

Lesna zaloga podmerskih grmovnih vrst na podlagi vseh petih panelov 2020–2024 NGI v celotni Sloveniji znaša 2,1 m^3/ha (± 12,2 %). V celotni Sloveniji lesni zalogi podmerskih grmovnih vrst prevladuje navadna leska (Slika 10). Več kot 5 % lesne zaloge podmerskih grmovnih vrst predstavlja še rumeni dren (5,9 %) (Slika 10). Navadna leska prav tako močno prevladuje v vseh višinskih pasovih – največji delež ima v višinskem pasu od

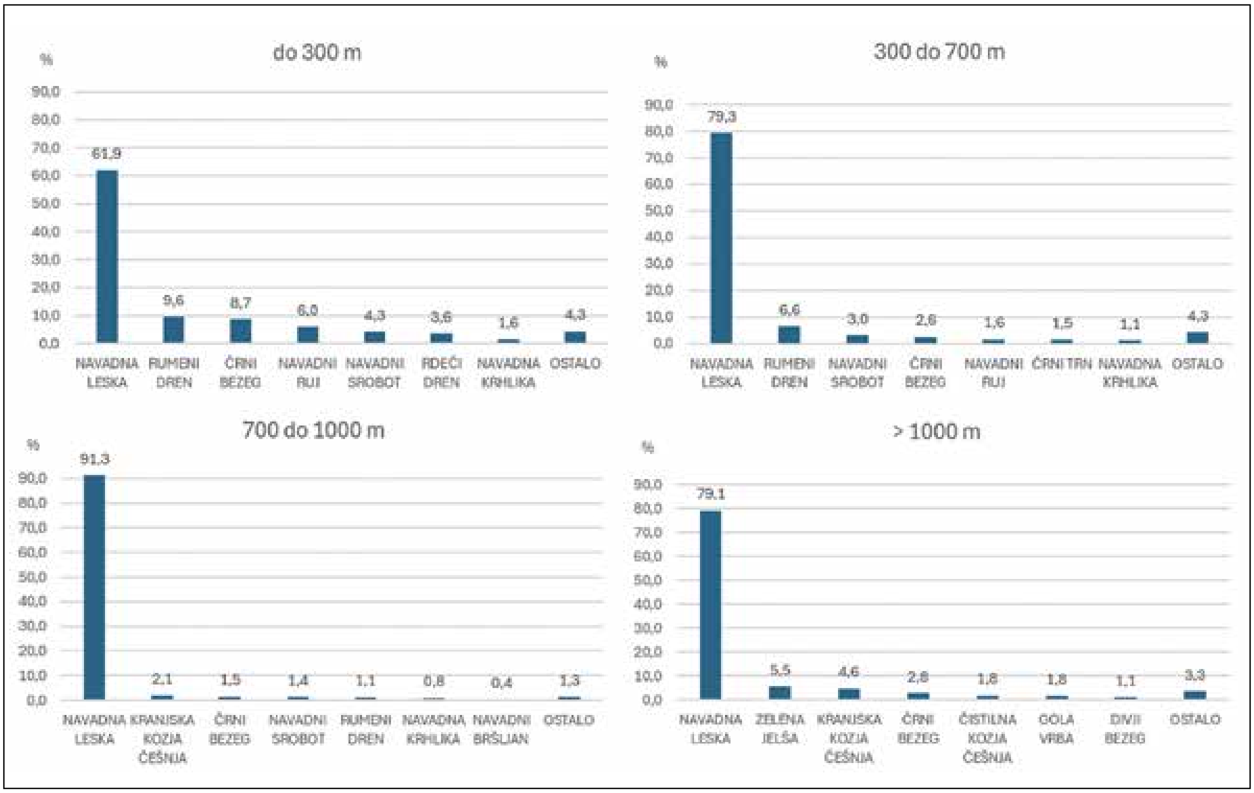
700 do 1.000 m (91,3 %), najmanjšega pa v nižinskem pasu (61,9 %) (Slika 11). V nižinskem in spodnjem višinskem pasu je na drugem mestu rumeni dren (9,6 in 6,6 %). V zgornjem višinskem pasu je na drugem mestu s 5,5 % zelena jelša (*Alnus viridis*).



Slika 10: Deleži prvih 7 podmerskih grmovnih vrst v lesni zalogi po višinskih pasovih. Ostale grmovne vrste so uvrščene v skupino ostalo.
Figure 10: Share of the seven most abundant small shrub species (shrubs below the 10 cm DBH threshold) in the growing stock across elevation zones. All other shrub species are classified as "other" (ostalo).

4 RAZPRAVA

Slovenski gozdovi spadajo med vrstno pestrejše po številu drevesnih vrst, saj je bilo v okviru NGI med merskimi drevesi zaznanih vsaj 71 avtohtonih drevesnih vrst, skupaj s tujerodnimi in z udomačenimi pa vsaj 73, medtem ko jih je bilo v švicarskih gozdovih, kjer prevladuje vpliv Alp, zaznanih manj – 59 in v španskih, kjer prevladuje vpliv Mediterana, precej več – 126 (Portier s sodelavci 2022). Če pogledamo raznolikost slovenskih gozdov z vidika zastopanosti drevesnih vrst v lesni zalogi, so slovenski gozdovi precej manj raznoliki kot po absolutnem številu drevesnih vrst. V celotni Sloveniji v lesni zalogi merskih dreves prevladujeta bukev in navadna smreka, ki skupaj predstavljata več kot 60 % lesne zaloge. Skupaj z belo jelko in gradnom najpogostejše štiri



Slika 11: Deleži prvih 7 podmerskih grmovnih vrst v lesni zalogi po višinskih pasovih. Ostale grmovne vrste so uvrščene v skupino ostalo.
Figure 11: Share of the seven most abundant small shrub species (shrubs below the 10 cm DBH threshold) in the growing stock across elevation zones. All other shrub species are classified as "other" (ostalo).

drevesne vrste predstavljalo skoraj tri četrtine lesne zaloge. Najpogostejših 10 drevesnih vrst z največjimi deleži v lesni zalogi predstavlja 88 % lesne zaloge merskih drevesnih in grmovnih vrst. Vse ostale tako avtohtone kot tudi tujerodne vrste tako predstavljajo le 12 % lesne zaloge. Največjo lesno zalogo (398,2 m^3/ha) smo ugotovili v zgornjem višinskem pasu (nad 1.000 m). V tem pasu se nahajajo smrekovo-bukovi-jelovi gozdovi Snežniškega pogorja, dela Kočevske, Trnovskega gozda, Jelovice, Pokljuke in Pohorja, ki spadajo med najproduktivnejše slovenske gozdove (Kotar 2011). To potrjuje tudi velik delež teh vrst v lesni zalogi, in sicer smreke 49,4, bukve 31,6 in bele jelke 9,2 %. Skupaj tako prve tri drevesne vrste predstavljajo 90,2 % lesne zaloge. Je pa v tem višinskem pasu najmanjši delež ploskev uvrščen v kategorijo gozdov, dostopnih za gospodarjenje (78,0 %). To pripisujemo večjim površinam varovalnih gozdov in drugih gozdnih zemljišč v Alpah (Kušar & Pintar 2021), slednje so predvsem površine, porasle z ruševjem, kar potrjuje tudi velik delež ruševja (20 %) v lesni zalogi podmerskih dreves. Zaradi velike prevlade prvih treh drevesnih vrst imajo gozdovi v zgornjem višinskem pasu nizko pestrost drevesnih vrst, kar potrjuje tudi najmanjši izračunani Shannon-Wienerjev indeks (0,49) med vsemi višinski pasovi. Ta višinski pas je močno zastopan v Alpski, Pohorski in Dinarski ekološki regiji, v katerih je bil Shannon-Wienerjev indeks med najmanjšimi med slovenskimi ekološkimi regijami (od 0,58 do 0,68) (Pintar s sodelavci 2024). Indeks je bil vseeno nekoliko večji od indeksa v tem višinskem pasu, saj so v ekoloških regijah zajeti tudi gozdovi nižin v teh regijah, kjer je vrstna pestrost drevesnih in grmovnih vrst v gozdovih večja. Tako v zgornjem višinskem pasu kot tudi v ostalih je v podmerskem drevju Shannonov indeks bistveno manjši kot v merskem, kar nakazuje na manjšo vrstno pestrost podmerskega drevja v primerjavi z vrstno pestrejšimi merskimi drevesi. To lahko pojasnimo z razlikami v ekoloških lastnostih različnih drevesnih vrst med podmerskimi in merskimi drevesi, saj se odziv na omejene svetlobne razmere in konkurenčna sposobnost med juvenilnimi in odraslimi osebki iste vrste lahko razlikujeta (Kobe s sodelavci 1995, Valladares

& Niinemets 2008). To nakazuje, da bo potrebna velika pozornost pri negi mladih sestojev, če bomo v prihodnosti želeli stremeti k vrstno pestrim gozdnim sestojem, ki so veliko odpornejši proti ujmam in posledicam podnebnih sprememb.

Čeprav smo zaznali večanje lesne zaloga merskih dreves z višanjem višinskih pasov, smo ugotovili večjo lesno zalogo merskih dreves v višinskem podpasu od 500 do 700 m (302 m^3/ha) kot v podpasu 300 do 500 m (316 m^3/ha). To pojasnjujemo predvsem z večjim vplivom poškodb zaradi naravnih motenj v zadnjem obdobju (Kutnar, Kermavnar & Pintar 2021) v podpasu od 500 do 700 m kot v podpasu od 300 do 500 m. Razlike med višinskima podpasovoma so vidne tudi pri podmerskem drevju. Bukev v višjem podpasu 500–700 m dosega večji delež v lesni zalogi podmerskih dreves (35,0 %) kot v pasu 300–500 m (28,4 %). Tudi to bi lahko pripisali posledicam naravnih motenj, ki so vodile v osnovanje večjih površin mladovij bukve. V istem višinskem pasu dosega večji delež v lesni zalogi podmerskih dreves tudi črni gaber (8,8 % v primerjavi s 6,0 %). To je skladno z njegovimi ekološkimi značilnostmi, saj je izrazito termofilna vrsta, ki uspeva na toplih, suhih, svetlih prisojnih legah (Brus 2012), ki so pogostejše v višinskem podpasu 500–700 m.

Delež smreke v lesni zalogi se veča z višanjem nadmorske višine. V nižinskem pasu (do 300 m) znaša 10,2 %, v najvišjem pa 49,4 %. Večanje deleža smreke glede na višanje nadmorske višine in velikost gozdne posesti so v Sloveniji predstavili tudi Krajnc s sodelavci (2022). Delež smreke v zgornjem višinskem pasu je primerljiv z deležem smreke v avstrijskih gozdovih (46,2 %), v bližini katerih ta pas prevladuje (Lackner, Schreck & Walli 2023). Na začetku tretjega tisočletja je v Sloveniji prišlo do največjega zmanjšanja deleža lesne zaloge smreke predvsem zaradi ujm in gradacij podlubnikov v višinskem pasu do 500 m (mediana = 20 %), najmanjše pa je bilo v višinskem pasu nad 1.000 m (Kutnar, Kermavnar & Pintar 2021). Manjši delež v lesni zalogi podmerskega drevja predvsem v nižjih višinskih pasovih nakazuje počasno umikanje smreke v višje nadmorske višine. V prihodnosti je treba v luči podnebnih sprememb posvetiti veliko pozornost debeljakom smreke, osnovanih na rastiščnih tipih alpsko bukovje s črnim telohom in predalpsko jelovo bukovje na karbonatnih in mešanih kamninah (Kutnar s sodelavci 2012, Bončina s sodelavci 2021) tudi na nadmorskih višinah, višjih od 1.000 m, kjer navadna smreka v lesni zalogi prevladuje, sanitarni posek smreke zaradi ujm in podlubnikov pa se v zadnjem obdobju povečuje (Pintar s sodelavci 2025).

Od leta 1970 do leta 2020 se je lesna zaloga bukve podvojila (Poljanec & Bončina 2020, Poljanec s sodelavci 2023) in je v zadnjem obdobju postala prva drevesna vrsta v deležu lesne zaloge merskih in podmerskih drevesnih vrst, kar nakazuje tudi na prihodnje večanje lesne zaloge deleža merske lesne zaloge merskih dreves bukve. Vendar bo potrebna velika pazljivost pri gospodarjenju z bukovimi gozdovi, saj se že zaznava proces večanja osutosti krošenj dreves bukev oziroma hiranja bukve predvsem v južni in jugovzhodni Sloveniji (Ogris & Skudnik 2021, Pintar & Skudnik 2024) ter tudi npr. na lokacijah v Nemčiji in Franciji (Michel s sodelavci 2024).

Bela jelka, ki je po pogostosti tretja drevesna vrsta v lesni zalogi merskih dreves v Sloveniji (7,9 %), ima večjo prisotnost v deležu lesne zaloge merskih dreves nad 500 m nadmorske višine, z največjo v višinskem pasu od 700 do 1.000 m – 13,5 %. Lesna zaloga bele jelke se je od leta 1970 zmanjšala s 17,5 % v letu na 7,4 % v letu 2018 (Ficko s sodelavci 2011, Poljanec & Bončina 2020). V prihodnje lahko pričakujemo zmanjšanje lesne zaloge bele jelke v Sloveniji, saj jo je v lesni zalogi podmerskega drevja zgolj 3,1, zmanjšanje lahko pričakujemo v vseh višinskih pasovih. Prihodnost bele jelke v celotni Sloveniji ni tako neugodna, saj so Pintar s sodelavci (2024) ugotovili zadovoljiv delež bele jelke v lesni zalogi podmerskega drevja v Pohorski in Alpski ekološki regiji, kjer se v prihodnosti, v nasprotju z Dinarsko ekološko regijo, ne pričakuje bistveno zmanjšanje bele jelke v lesni zalogi merskih dreves.

V nižinskem in spodnjem višinskem pasu (nižjih od 700 m) je delež lesne zaloge podmerskih dreves: termofilnih – predvsem malega jesena, črnega gabra, tujerodne robinije in sencozdržnega belega gabra – precej večji od deleža lesne zaloge in drevesnih vrst v lesni zalogi merskih dreves. Lesna zaloga merskih tako avtohtonih termofilnih vrst kot tudi robinije se bo tako, predvsem zaradi posledic ujm in podnebnih sprememb na podlagi modela razvoja gozdov (Kutnar, Kobler & Bergant 2009, Kutnar & Kobler 2013), povečevala. To se izraža tudi v večji termofilnosti razgalelih površin, kjer te vrste odigrajo pionirsko vlogo. Povečevanje lesne zaloge merskih dreves belega gabra je pričakovano in je že bilo potrjeno v naravi (Hladnik & Pintar 2017), trend pa se bo verjetno nadaljeval tudi v prihodnosti predvsem v gradnovo-belogabrovih sestojih in tudi v dobovo-belogabrovih. V teh sestojih je že sedaj delež doba in gradna v lesni zalogi podmerskih dreves veliko manjši od deleža v lesni zalogi merskih dreves.

Z vzpostavitvijo NGI v letu 2020 se je v Sloveniji začelo sistematično popisovati tudi podmerske grmovne vrste. V vseh višinskih pasovih v lesni zalogi podmerskih grmovnih vrst močno prevladuje navadna leska, kar potrjuje dejstvo, da je ena od najpogostejših grmovnih vrst v Sloveniji (Brus, 2008). Rumeni dren je na drugem mestu v deležu lesne zaloge podmerskih grmovnih vrst v celotni Sloveniji ter tudi v nižinskem in spodnjem višinskem pasu. Zaradi njegove toploljubnosti (Brus 2008) ga lahko v prihodnosti pričakujemo tudi z večjim deležem v višjih višinskih pasovih. Kranjska kozja češnja, ki je najpogostejša v alpskem in dinarskem svetu, je na drugem (2,1 %) oziroma tretjem mestu (4,1 %) v srednjem in zgornjem višinskem pasu, kar potrjuje ugotovitev Brus (2008), da je najpogostejša v gorskem pasu v jelovo-bukovih in bukovih gozdovih.

Na nadmorskih višinah, višjih od 500 m, bi bilo treba nameniti posebno pozornost dopolnilni sadnji bele jelke, katere delež v podmerskem drevju (3,1 %) je bistveno manjši od deleža v lesni zalogi merskih dreves (7,9 %), kar nakazuje na prihodnje zmanjševanje njene prisotnosti v vseh višinskih pasovih, razen v Pohorski ekološki regiji. Alternativa sta pospeševanje naravne obnove jelke neposredno preko višanja intenzitete odstrela divjadi, ki je njen največji naravni sovražnik, in upoštevanje drugih smernic in usmeritve za gospodarjenje z jelovo-bukovimi gozdovi v Sloveniji (Lipužič 2025).

Od leta 1970 do leta 2018 se je delež smreke v rastiščnih tipih, kjer ni naravno prisotna, zmanjšal, njen delež pa se je povečal v gorskem vegetacijskem pasu, zlasti v alpskih gozdovih iglavcev (Poljanec & Bončina 2020). Navadna smreka v lesni zalogi močno prevladuje (49,4 %) v višinskem pasu nad 1.000 m. V sestojih na rastiščnih tipih bukovij in jelovih bukovij (npr. predalpsko jelovo bukovje, dinarsko jelovo bukovje, alpsko bukovje s črnim telohom, gorsko-zgornjegorsko bukovje na silikatnih kamninah (Kutnar s sodelavci 2012, Bončina s sodelavci 2021)), kjer je bila navadna smreka v preteklosti pospeševana, bi bilo za povečanje odpornosti sestojev na ujme in podnebne spremembe smiselno spodbujati večjo vrstno pestrost z dopolnilnimi saditvami različnih drevesnih vrst ter s tem zmanjšati delež lesne zaloge smreke v teh sestojih. Smiselno bi bilo pospeševati bukev, macesen, plemenite listavce (gorski javor, ostrolistni javor), belo jelko, mestoma tudi jerebiko, zeleno in sivo jelšo (Bončina s sodelavci 2021, Poljanec s sodelavci 2023). Se pa v tem višinskem pasu nahajajo tudi naravna smrekovja (skupine rastiščnih tipov: gorsko-zgornjegorsko smrekovje na karbonatnem skalovju in grušču, zgornjegorsko-podvisokogorsko smrekovje na karbonatnih in mešanih kamninah, gorsko-zgornjegorsko smrekovje na silikatnih kamninah), kjer smreka naravno prevladuje (Kutnar s sodelavci 2012, Bončina s sodelavci 2021). V teh sestojih bi se v prihodnosti velik delež smreke v lesni zalogi lahko ohranjal, saj je tu tveganje za smreko nižje. Bi pa vseeno bilo treba v teh sestojih stremeti k ohranjanju in osnovanju raznomerne zgradbe, ki povečuje odpornost proti ujmam (Bončina s sodelavci 2021).

V nižinskem in spodnjem višinskem pasu (pod 700 m), kjer je lesna zaloga podmerskega drevja termofilnih vrst (mali jesen, črni gaber) že precej višja od njihovega deleža v merskih drevesih, je smiselna predvsem dopolnilna sadnja gradna. To velja predvsem za sestoje na gozdnih rastiščnih, kjer je graden naravno prisoten v večjem deležu (Bončina s sodelavci 2021). Delež tega v podmerskem drevju je bistveno manjši od deleža v merskem drevju, kar nakazuje na prihodnje umikanje te ekološko pomembne vrste.

5 SUMMARY

Slovenia is situated at the intersection of the Alps, the Dinaric Mountains, the Mediterranean, and the Pannonian Plain. High terrain heterogeneity, diverse climatic conditions, varied soil properties, and numerous other environmental factors support a high diversity of forest communities (Kutnar et al. 2002) and, consequently, a high diversity of tree and shrub species in forests. Slovenian forests contain 71 native tree species (Brus et al. 2017). Despite this high species diversity, European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) together account for 60% of the growing stock in Slovenian forests (Pintar et al. 2024) and are also the most important tree species in the submontane and montane regions of Central Europe (Leuschner & Ellenberg 2017). The diversity of tree and shrub species across ecological regions (Kutnar et al. 2002), based on data from the National Forest Inventory (NFI) 2020–2023, was presented by Pintar et al. (2024). The aim of this study is to present the variability in the proportion of tree and shrub species in the growing stock of Slovenian forests based on NFI 2020–2024 data across elevation zones.

The highest growing stock of trees and shrubs above 10 cm DBH (398.2 m^3/ha) was recorded in the highest elevation zone, above 1000 m. This elevation zone includes spruce–beech–fir forests of the Snežnik Mountains, parts of the Kočevje region, the Trnovo Forest Plateau, Jelovica, Pokljuka, and Pohorje, which are among the most productive forests in Slovenia (Kotar 2011). This is also confirmed by the high proportion of these species in the growing stock: Norway spruce (49.4%), European beech (31.6%), and silver fir (*Abies alba*) (9.2%). Together, these three leading tree species account for 90.2% of the growing stock. However, this elevation zone also has the lowest proportion of plots classified as forests available for wood supply (78.0%). This is attributed to the larger extent of protective forests and other forest land in the Alpine region (Kušar & Pintar 2021), the latter mainly comprising areas covered by dwarf pine (*Pinus mugo*), which is also reflected in the high proportion of dwarf pine (20%) in the growing stock of small trees (trees below the 10 cm DBH threshold). Due to the strong dominance of the three leading tree species, forests in the highest elevation zone exhibit low tree species diversity, as indicated by the lowest calculated Shannon–Wiener index (0.49) among all elevation zones. In the highest elevation zone, as in the other elevation zones, the Shannon–Wiener index for small trees is substantially lower than that for trees and shrubs above the 10 cm DBH threshold, indicating lower species diversity among small trees compared to the more species-diverse trees and shrubs above 10 cm DBH. This suggests that considerable attention will be required in tending young stands if species-rich forest stands, which are more resistant to disturbances and the impacts of climate change, are to be promoted in the future.

The proportion of Norway spruce in the growing stock increases with elevation. In the lowest elevation zone (up to 300 m), it accounts for 10.2%, while in the highest elevation zone it reaches 49.4%. The lower proportion of spruce in the growing stock of small trees, particularly in lower elevation zones, indicates a gradual retreat of spruce at lower elevations. In the future, in the context of climate change, considerable attention will be needed for mature spruce stands established on beech and fir–beech sites at higher elevations, where spruce dominates the growing stock, as sanitary felling of spruce—primarily due to disturbances and bark beetle outbreaks—has increased in recent years (Pintar et al. 2025). In recent years, European beech has become the leading tree species in terms of its share of the growing stock of both trees and shrubs above the 10 cm DBH threshold and small trees and shrubs below the 10 cm DBH threshold, indicating a further increase in the proportion of beech in the growing stock of trees and shrubs above 10 cm DBH in the future. However, great caution will be needed in the management of beech forests, as increasing crown defoliation and beech decline have already been detected, particularly in southern and southeastern Slovenia (Ogris & Skudnik 2021; Pintar & Skudnik 2024).

Silver fir, the third most abundant tree species in the growing stock of trees and shrubs above the 10 cm DBH threshold in Slovenia (7.9%), shows a higher proportion in elevation zones above 500 m, with the highest share recorded in the 700–1000 m elevation zone (13.5%). In the future, a decline in the growing stock of silver fir in Slovenia can be expected, as its share in the growing stock of small trees amounts to only 3.1%, and a decrease can be anticipated across all elevation zones. However, the future of silver fir across Slovenia is not entirely pessimistic, as Pintar et al. (2024) reported a satisfactory share of silver fir in the growing stock of small trees in the Pohorje and Alpine ecological regions, where—unlike in the Dinaric ecological region—a substantial decline in the growing stock of trees and shrubs above 10 cm DBH is not expected. In lower elevation zones (below 700 m), the proportion of the growing stock of small trees belonging to thermophilous species—primarily manna ash (*Fraxinus ornus*), hop hornbeam (*Ostrya carpinifolia*), the non-native black locust (*Robinia pseudoacacia*), and the shade-tolerant hornbeam (*Carpinus betulus*)—is considerably higher than the proportion of these species in the growing stock of trees and shrubs above the 10 cm DBH threshold. Consequently, the growing stock of native thermophilous tree species, as well as black locust, is expected to increase, mainly due to the effects of climate change (Kutnar, Kobler & Bergant 2009; Kutnar & Kobler 2013). An increase in the growing stock of trees and shrubs above 10 cm DBH of hornbeam is therefore expected and has already been confirmed in the field (Hladnik & Pintar 2017), and this trend is likely to continue in the future, particularly in oak–hornbeam and sessile oak–hornbeam stands. In these stands, the current share of pedunculate oak and sessile oak in the growing stock of small trees is already substantially lower than their share in the growing stock of trees and shrubs above the 10 cm DBH threshold.

6 ZAHVALA

Prispevek je nastal v okviru naloge 4 Javne gozdarske službe (razvijanje in strokovno usmerjanje informacijskega sistema za gozdove) na Gozdarskem inštitutu Slovenije, ki jo financira Ministrstvo za kmetijstvo, gozdarstvo in prehrano Republike Slovenije, ter v okviru Raziskovalnih programov Gozdna biologija, ekologija in tehnologija (P4-0107) ter Gozdno-lesna veriga in podnebne spremembe: prehod v krožno biogospodarstvo (P4-0430), ki ju financira Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije. Delo avtorja L. Krajnca je bilo financirano s strani Evropske unije, pogodba št. 0005-404, Mehanizem za okrevanje in odpornost (NOO). Za delo pri terenskem zbiranju podatkov in pripravi podatkovne baze NGI se zahvaljujemo vsem sodelavcem Gozdarskega inštituta Slovenije in Zavoda za gozdove Slovenije, ki so sodelovali pri NGI 2020–2024. Zahvala velja tudi anonimnima recenzentoma za koristne predloge, ki so izboljšali prvotno različico članka.

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PRIMERJAVA DVEH METOD ZA MERJENJE LISTNIH REŽ PRI DOBU IN GRADNU

COMPARISON OF TWO METHODS FOR MEASUREMENT OF STOMATA IN PEDUNCULATE AND SESSILE OAK

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IZVLEČEK

Lastnosti listnih rež, kot sta gostota in velikost, pomembno vplivajo na izmenjavo plinov, zato je njihova analiza ključna za razumevanje fiziologije rastlin, njihove prilagodljivosti na okoljske razmere ter odzivov na podnebne spremembe. Z našo raziskavo smo želeli ugotoviti, ali ročne meritve listnih rež pri drevesnih sadikah lahko nadomestimo z avtomatiziranimi meritvami, kar bi zaradi prihranka časa močno povečalo število vzorcev, ki jih lahko analiziramo. Pripravili smo odtise spodnje povrhnjice z listnimi režami pri sadikah doba in gradna z istega rastišča. Na desetih naključno izbranih posnetkih preparatov pod 200 x in 400 x povečavo mikroskopa za vsako vrsto smo merili število režnih kompleksov ter dolžino in širino celic zapiralk ter porusa z ročnimi meritvami v programu Image J ter z avtomatiziranimi meritvami v programu StoManager1. Rezultate smo statistično ovrednotili. Pri meritvah števila režnih kompleksov nismo zasledili statistično značilnih razlik med obema metodama. Bland-Altmanova analiza je pokazala dobro ujemanje med ročnimi in avtomatiziranimi meritvami. Avtomatizirane meritve so sicer rahlo precenile število režnih kompleksov, vendar je bila napaka majhna. Pri meritvah velikosti so bile razlike med obema metodama meritev statistično značilne, Bland-Altmanova analiza pa je pokazala odstopanja med obema metodama pri večjih razponih velikosti merjenih struktur. Z regresijsko analizo smo ugotovili, da je ujemanje med ročnimi in avtomatiziranimi meritvami v velikostnem razredu 20-25 µm (večjih struktur nismo merili) dokaj zanesljivo, z manjšanjem velikosti struktur pa upade, najverjetneje zaradi segmentacije slike pri avtomatizirani metodi, pri kateri je zaznavanje robov manj natančno. Pri majhnih strukturah že majhne razlike v segmentaciji privedejo do večjih napak. Po drugi strani pa lahko tudi ročne meritve na mikroskopskih slikah postanejo vse bolj subjektivne, ko se velikost struktur zmanjšuje. Naši rezultati nakazujejo, da so avtomatizirane meritve s programom StoManager1 ustrezna nadomestitev

ABSTRACT

Stomatal traits, such as density and size, significantly influence gas exchange; therefore, their analysis is essential for understanding plant physiology, their adaptation to environmental conditions, and their responses to climate change. The aim of this study was to determine whether manual measurements of stomata in tree seedlings could be replaced by automated measurements, which would substantially increase the number of samples that can be analysed due to time savings. Epidermal imprints of stomata were prepared from seedlings of pedunculate oak and sessile oak growing at the same site. Ten randomly selected micrographs of the preparations at 200 × and 400 × magnification per species were used to analyse the number of stomata as well as the length and width of guard cells and stomatal pore, using both manual measurements in ImageJ and automated measurements in StoManager1. The results were statistically evaluated. No statistically significant differences between the two methods were found for measurements of stomatal number. Bland–Altman analysis showed good agreement between manual and automated measurements. Although the automated method slightly overestimated the number of stomata, the error was small. For size measurements, statistically significant differences between the two methods were observed, and Bland–Altman analysis revealed deviations between the methods at larger size ranges of the measured structures. Regression analysis indicated that agreement between manual and automated measurements was reasonably reliable within the size range of 20–25 µm (larger structures were not measured), but decreased with decreasing structure size, most likely due to image segmentation in the automated method and the associated less precise edge detection. In small structures, even minor segmentation differences can lead to larger errors. On the other hand, manual measurements in microscopy images can also become increasingly subjective as the size of structures decreases. Our results suggest that automated measurements using StoManager1 represent a

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ročnih meritev števila oz. gostote režnih kompleksov ter velikosti večjih struktur znotraj režnega kompleksa za izbrane drevesne vrste.

Ključne besede: število listnih rež, oblika listnih rež, orodja za analizo slike, avtomatizirane meritve, sadike, hrasti, *Quercus robur, Quercus petraea*

suitable alternative to manual measurements of stomatal number/ density and dimensions of larger structures within the stomatal complex for the selected tree species.

Key words: number of leaf stomata, leaf stomata shape, image analysis tools, automated measurements, seedlings, oaks, *Quercus robur, Quercus petraea*

1 UVOD

Stomatarni aparat oz. režni kompleks so strukture v površnjici listov in stebel in iz njih nastalih struktur, zgrajene navadno iz dveh celic zapiralk in različnega števila celic spremljevalk. Med celicama zapiralkama je shizogena intercelularna stomatarna odprtina ali porus (listna reža v ožjem pomenu besede) (Batič et al. 2011). Listne reže predstavljajo ključno mesto izmenjave plinov med rastlino in ozračjem. Skozi listne reže v list vstopa ogljikov dioksid, potreben za fotosintezo, medtem ko prek njih s transpiracijo izhaja vodna para (Yan et al. 2017). Velikost odprtine listne reže, porusa, določajo spremembe turgorja celic zapiralk, s čimer rastlina uravnava difuzijo plinov in vzdržuje stabilno notranje okolje lista (Lawson 2009). Regulacija listnih rež je bistvena za prilagoditev rastlin na okoljske razmere. Vključuje kratkoročne spremembe odprtosti rež, ki omogočajo odzive na razpoložljivost vode, svetlobo, temperaturo, hitrost vetra in koncentracijo ogljikovega dioksida ter dolgoročnejše prilagoditve, kot so spremembe v gostoti listnih rež (Hetherington & Woodward 2003, Gong et al. 2025). Te prilagoditve določajo največjo prevodnost listnih rež ter s tem omejujejo izmenjavo plinov glede na razmere v okolju ter signale med koreninami in nadzemnimi deli rastline (Gong et al. 2025). Prevodnost listnih rež neposredno vpliva na fotosintezo, rast in učinkovitost izrabe vode (Bertolino et al. 2019). Omejitve v prevodnosti listnih rež lahko zmanjšajo fotosintetsko aktivnost tudi za več kot 50 %, hkrati pa predstavljajo prvo linijo obrambe pred izsušitvijo (Jezek & Blatt 2017). S pripiranjem oz. z zapiranjem listnih rež rastline zmanjšujejo tveganje za nastanek embolije v ksilemu in poškodbe zaradi sušnega stresa (Jones & Sutherland 1991). Poleg tega listne reže vplivajo na temperaturo lista, odpornost na temperaturne ekstreme (Urban et al. 2017) in vstop patogenih organizmov (Melotto et al. 2006). Na ravni ekosistema imajo listne reže ključno vlogo pri kroženju ogljika in vode, saj uravnavajo privzem CO_2, t.j. bruto primarno proizvodnjo (GPP), in evapotranspiracijo (Haworth et al. 2021). Njihove morfološke in funkcionalne značilnosti odražajo evolucijske prilagoditve na pretekle okoljske razmere in koncentracije CO_2 v ozračju, zato se pogosto uporabljajo tudi pri rekonstrukciji preteklih okoljskih razmer (Haworth et al. 2021).

Preučevanje lastnosti listnih rež, kot so velikost, gostota in razporeditev, pomembno prispeva k razumevanju fiziologije rastlin, njihovega prilagajanja okoljskim razmeram ter odzivov na podnebne spremembe (Yan et al. 2017, Thai et al. 2025). Večinoma analize teh lastnosti temeljijo na mikroskopskih metodah oz. njihovih izpeljankah (npr. prenosni mikroskopi, 3D zajem intaktnih listov) (Eisele et al. 2016, Matthaeus et al. 2020, Liang et al. 2022, Pathoumthong et al. 2023). Klasične mikroskopske metode temeljijo na izdelavi odtisa listnih rež (Wu & Zhao 2017) oz. preiskavi vzorca površnjice (Ibata et al. 2013). Temu sledi ročno ali polavtomatizirano vrednotenje s pomočjo programske opreme, kot je npr. Image J (Jayakody et al. 2017), kar pa je zamudno delo. Poleg tega metoda ročnega štetja ni povsem ponovljiva, saj se je vedno potrebno subjektivno odločiti, kako šteti reže na robu, ki niso v celoti zajete na posnetku (Fetter et al. 2019). Z metodami strojnega učenja, kot je globoko učenje, v zadnjem času prihaja do velikega napredka v pospešitvi procesa vrednotenja z avtomatiziranim zaznavanjem in meritvami, kar je še posebej dobrodošlo pri fenotipizaciji (Gibbs & Burgess 2024, Thai et al. 2025). Modeli globokega učenja delujejo na treh ravneh. Prva raven je zaznavanje struktur, pri kateri program zazna listne reže in jih obkroži z okvirjem. Ta raven omogoča ugotavljanje števila oz. gostote listnih rež. Druga raven je semantična segmentacija, kjer pride do klasifikacije posameznih slikovnih točk, kar omogoča določitev robov režnega kompleksa, celic zapiralk, porusa,…, ter meritve dimenzij. Tretja raven je instančna segmentacija, kjer pride do identifikacije posameznega režnega kompleksa in struktur povezanih z njim ter izvajanje meritev, povezanih s točno določeno strukturo (Gibbs & Burgess 2024). Avtomatizirano zaznavanje ima prednost pred ročnim štetjem tudi v ponovljivosti, saj imajo algoritmi točno določena vnaprej postavljena pravila, na podlagi katerih določeno strukturo opredelijo kot listno režo, vključno s štetjem rež ob robovih (Fetter et al. 2019). Razvoj novih aplikacij je pogosto usmerjen v določeno taksonomsko skupino (npr. koruza (Zhang et al. 2022, Yang et al. 2025), soja (Sultana et al. 2021)) in za točno določen namen, tako da ta orodja večinoma niso ovrednotena za širšo rabo oz. bi potrebovala ustrezne prilagoditve (Gibbs & Burgess 2024). Poleg tega je napredek omejen s pomanjkanjem oz. prostim dostopom do ročno označenih posnetkov (Gibbs et al. 2021, Gibbs & Burgess 2024), ki se uporabljajo za strojno učenje ter z nestandardiziranimi postopki v različnih fazah priprave slike (Gibbs & Burgess 2024). Večina modelov je še vedno omejenih zgolj na zaznavanje struktur, se pravi meritve gostote in števila listnih rež (Gibbs & Burgess 2024).

Za vrednotenje listnih rež v ekologiji oz. ekofiziologiji gozdnega drevja je obetaven program StoManager1, saj je bil v procesu razvoja validiran na obsežnem številu listavcev (Wang et al. 2024a). StoManager1 je program, ki so ga razvili Wang et al. (2024a, b) in je prosto dostopen v repozitoriju Zenodo na povezavi https://doi.org/10.5281/zenodo.17856516 (Wang et al. 2023). StoManager1 deluje po načelu segmentacije slike, s pomočjo katere pridobi koordinate robov strukture, te pa zabeleži v pravilnem vrstnem redu v smeri urinega kazalca oz. v njegovi nasprotni smeri. Okrog oblike nariše ustrezno zasukan okvir z najmanjšo možno površino, čemur sledi določitev kota, pod katerim je okvir zasukan. Potem program poišče centroida režnega kompleksa in porusa ter ju uskladi. Porus je v tem primeru definiran kot območje znotraj notranjih sten celic zapiralk (Wang et al. 2023). Iz dolžine večjega okvira izračuna dolžino celic zapiralk, iz dolžine manjšega okvirja dolžino porusa, iz najkrajše dolžine med robom večjega okvirja in robom manjšega okvirja širino celic zapiralk, iz razdalje med obema daljšima robovoma manjšega okvirja pa širino porusa. Program StoManager1 podpira formate slik 'jpg', 'png', 'tif', in 'jpeg' (Wang et al. 2023).

Z našo raziskavo smo želeli ovrednotiti program StoManager1 (Wang et al. 2023, Wang et al. 2024a, b) za uporabo pri avtomatiziranih meritvah listnih rež drevesnih sadik doba in gradna in primerjati pridobljene rezultate z ročnimi meritvami v programu Image J (Schneider et al. 2012). Vrednotenje programa za avtomatizirane meritve listnih rež je bilo del širše raziskave v okviru temeljnega projekta ARIS J4-4541, kjer smo analizirali funkcionalno-strukturni odziv sadik doba in gradna na identične naravne okoljske razmere v nižinskem hrastovem sestoju v Krakovskem gozdu med obnavljanjem, tj. kritično fazo vzpostavljanja novega gozda. Čeprav je Krakovski gozd tipično rastišče doba, v zadnjih letih tam redno prihaja do propadanja in odmiranja te vrste hrasta (Gričar et al. 2013, 2014), zato sta vrednotenje in primerjava uspevanja doba in gradna na tem rastišču ključna za napovedi rastnega potenciala in razširjenosti obeh vrst hrasta v prihodnosti. V projektu smo primerjali višino, priraščanje, anatomske lastnosti lesa in skorje ter lastnosti listnih rež sadik doba in gradna na istem rastišču (Gričar et al., v pripravi).

2 MATERIAL IN METODE

V začetku decembra 2023 smo v nižinskem Krakovskem gozdu (45°54'N, 15°25'E, 150 m n.m) posadili sto dvo oz. triletnih sadik doba (*Quercus robur* L.) in gradna (*Quercus petraea* (Matt.) Liebl.). Od stotih sadik posamezne vrste smo za podrobnejše analize naključno izbrali po deset sadik.

Vzorčenje listov in priprava preparatov

V juniju 2025, ko so bili listi popolnoma razviti, smo z desetih sadik, pri katerih smo podrobneje spremljali višinsko in debelinsko priraščanje (Gričar et al., v pripravi), odvzeli pet listov in jih shranili v 70 % etanolu. Za pripravo odtisa spodnje povrhnjice z listnimi režami (Meister & Bolhàr Nordenkampf 2001) smo liste vzeli iz etanola in njihovo površino osušili s papirnato brisačo. Na spodnjo povrhnjico smo nanesli tanko plast prozornega laka za nohte na sredinskem delu vsakega lista med glavnimi listnimi žilami. Ko se je lak posušil, smo nanj nalepili prozoren lepilni trak (Scotch) ter trak z odtisom nalepili na objektno steklo. Odtise smo fotografirali pri 200 x in 400 x povečavi mikroskopa Leica DM 4000 (Leica Microsystems) pod presevno svetlobo. Posnetke pod 200 x povečavo smo uporabili za vrednotenje števila listnih rež, posnetke pod 400 x povečavo pa za natančnejše meritve režnega kompleksa.

Vrednotenje listnih rež ter primerjava rezultatov

Izmed vseh posnetkov smo s pomočjo "rand" funkcije v programu Excel naključno izbrali po deset posnetkov spodnje povrhnjice za obe vrsti hrastov pod 200 x povečavo. Na teh posnetkih smo prešteli število režnih kompleksov z orodjem "Multi-point tool" v programu Image J (Schneider et al. 2012). Šteli smo samo režne komplekse, ki so bili v celoti na posnetku.

V naslednji fazi smo po enakem postopku naključno izbrali po deset fotografij spodnje povrhnjice doba in gradna pod 400 x povečavo. Na teh posnetkih smo izvedli ročne meritve dolžine celic zapiralk, širine celic zapiralk ter dolžino in širino porusa v programu ImageJ (Schneider et al. 2012). Širino celic zapiralk smo merili od zunanjega roba do pričetka odebeljene notranje celične stene, saj smo ocenili, da bi bil ta način najbolj primerljiv s StoManager1.

Iste fotografije smo ovrednotili tudi s programom StoManager1 v različici za namestitev na sistem Windows. Pri posnetkih, narejenih pod 200 x povečavo, ki so bili namenjeni meritvam števila oz. gostote listnih rež, nismo obkljukali možnosti »*Segment model using trained YOLOv8-seg-x*«, ki se uporablja samo v primeru, če potrebujemo podrobne meritve velikosti struktur režnega kompleksa. Pri obeh meritvah smo uporabili privzeto nastavitev praga zaznavanja (angl. *confidence treshold for detection*), ki znaša 0,25. Pri nižjem pragu zaznavanja program zazna več listnih rež, pri višjem pragu zaznavanja pa manj rež, saj se izločijo zaznave z manjšo stopnjo zaupanja (Wang et al. 2024b).

Statistika

Statistične analize smo opravili v programu Statistica (1984-2023, Cloud Software Group, Inc.). Najprej smo preverili, ali med vrstama obstajajo statistično značilne razlike v številu rež pri obeh metodah. Za to smo uporabili enosmerno analizo variance (ANOVA). Enakost varianc smo preverili z Levenovim testom ($p > 0.05$). Normalnost porazdelitve razlik med obema metodama meritve smo testirali s Shapiro-Wilkovim testom. Naredili smo t-test za odvisne vzorce, s katerim smo preverili, ali so rezultati obeh metod primerljivi. Za natančnejše ovrednotenje, ali lahko ročno štetje oz. meritve režnega kompleksa nadomestimo z avtomatiziranim zaznavanjem, pa smo naredili Bland-Altmanovo analizo (Bland & Altman 1986).

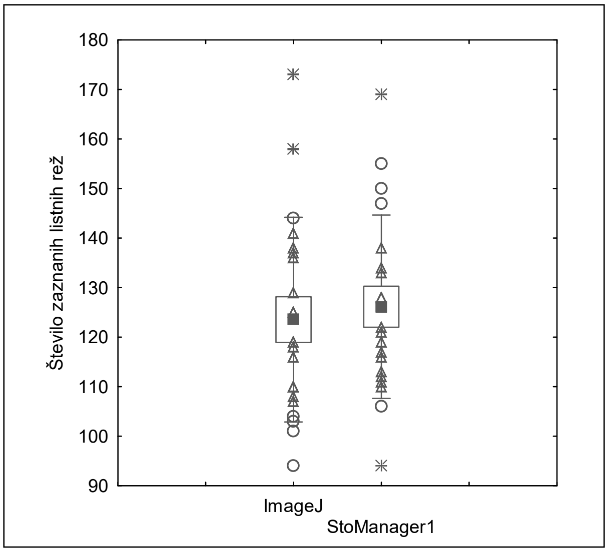
3 REZULTATI IN RAZPRAVA

Število zaznanih režnih kompleksov

Med vrstama ni bilo statistično značilnih razlik v številu zaznanih režnih kompleksov, ne z ročnim štetjem (F = 0,4815, p = 0,496616) in ne s programom StoManager1 (F = 0,7247, p = 0,405794), zato smo za primerjavo med obema metodama uporabili cel podatkovni niz. Shapiro-Wilkov test je pokazal, da vrednosti razlik med obema metodama statistično značilno ne odstopajo od normalne porazdelitve (W = 0,97015, p = 0,75801). T-test za odvisne vzorce je pokazal, da med obema metodama meritev števila režnih kompleksov ni bilo statistično značilnih razlik (t = -1,22537, p = 0,235411) (Slika 1).

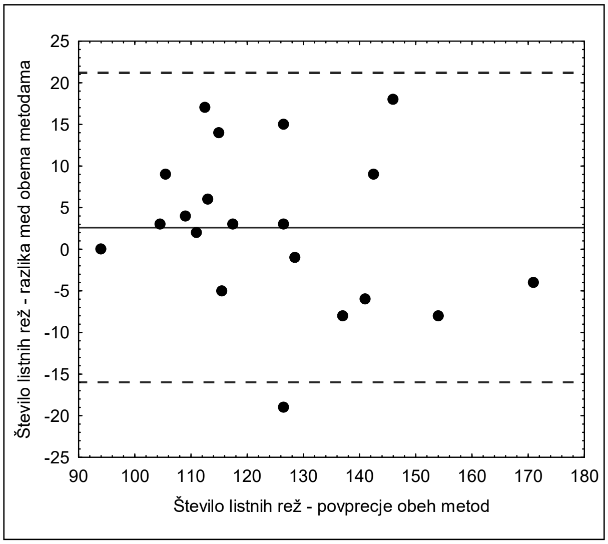
Bland-Altmanova analiza (Slika 2) je pokazala povprečno razliko med obema metodama 2,60 režnih kompleksov v korist StoManager1, kar kaže na manjše sistemsko odstopanje med obema metodama. Večina vrednosti razlik med obema metodama (19 od 20 vrednosti) se je nahajala med obema mejama strinjanja (angl. limits of agreement), vrednosti pa so bile enakomerno razpršene.

StoManager1 je v povprečju zaznal večje število celih režnih kompleksov na posnetkih (126 ± 19) v primerjavi z ročnim štetjem v ImageJ (124 ± 21), Slika 1. Pregled posnetkov z označenimi režnimi kompleksi v StoManager1 je pokazal, da StoManager1 kot režni kom-

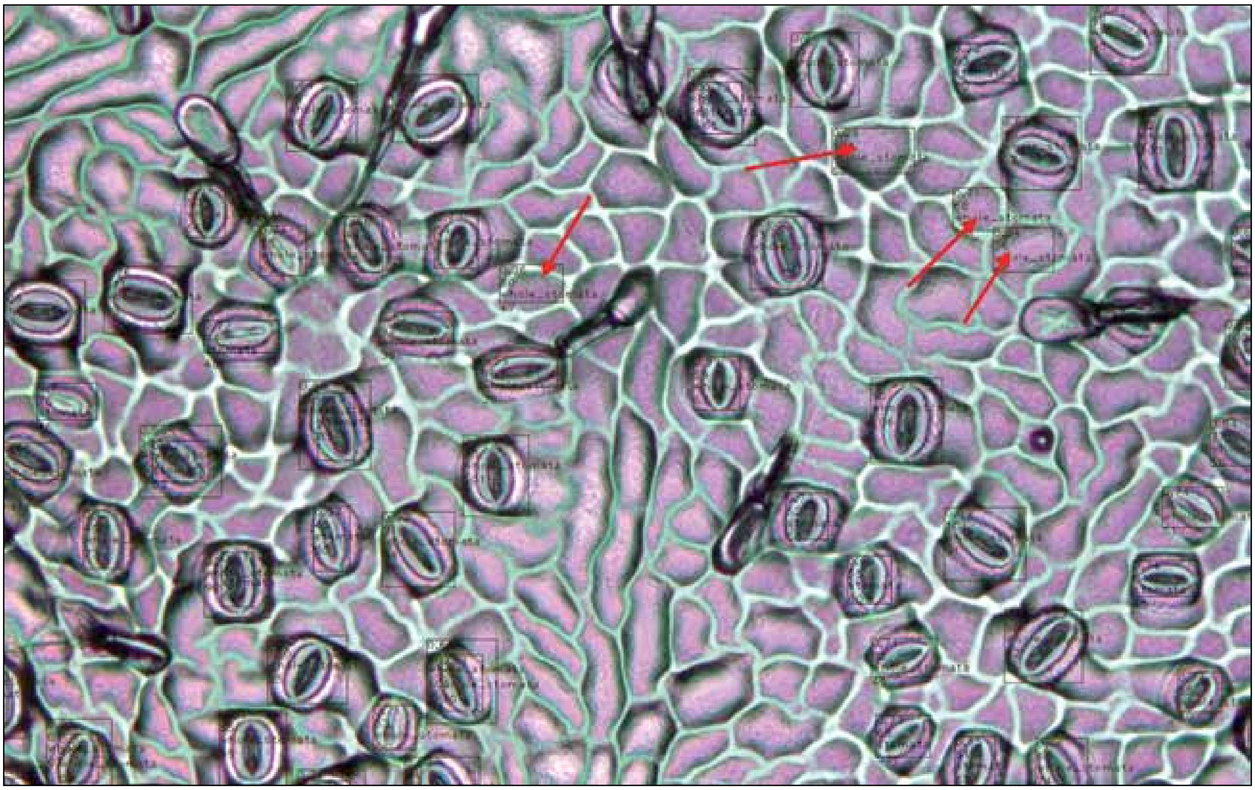


Slika 1: Primerjava ročnih meritev števila režnih kompleksov v programu ImageJ z avtomatiziranimi meritvami v StoManager1 pri dobu in gradnu. Statistično značilnih razlik med obema metodama ni bilo (t-test, p > 0,05). Povprečje je prikazano s polnim kvadratkom, okvir prikazuje standardno napako, ročaji standardno deviacijo, krogci pa osamelce, križci pa ekstreme. Posamezne meritve so prikazane s trikotniki.
Figure 1: Comparison of manual measurements of stomatal number in ImageJ with automated measurements in StoManager1 for pedunculate and sessile oak. No statistically significant differences were found between the two methods (t-test, p > 0.05). The mean is shown by a filled square, the box represents the standard error, the whiskers indicate the standard deviation, circles denote outliers, and crosses indicate extreme values. Individual measurements are shown as triangles.

pleks zazna tudi nekatere celice povrhnjice, ki so ovalne oblike, na robovih posnetkov pa označi več režnih kompleksov kot celih, čeprav so na posnetku samo deloma, kar razloži manjše sistemsko odstopanje te metode od ročnih meritev v programu ImageJ (Slika 3). Posamezni trihomi niso bili moteči za avtomatizirano analizo.



Slika 2: Bland-Altmanov diagram za ovrednotenje primerljivosti metod zaznavanja režnih kompleksov pri dobu in gradnu. Sredinska referenčna črta predstavlja povprečje razlik med obema metodama, spodnja in zgornja črtkana črta pa predstavljata meji strinjanja (angl. limits of agreement) in sta izračunani kot povprečje razlik med obema metodama ± 1,96 x SD.
Figure 2: Bland–Altman plot for evaluating the agreement between methods for stomatal detection in pedunculate and sessile oak. The central reference line represents the mean difference between the two methods, while the lower and upper dashed lines indicate the limits of agreement, calculated as the mean difference ± 1.96 × SD.

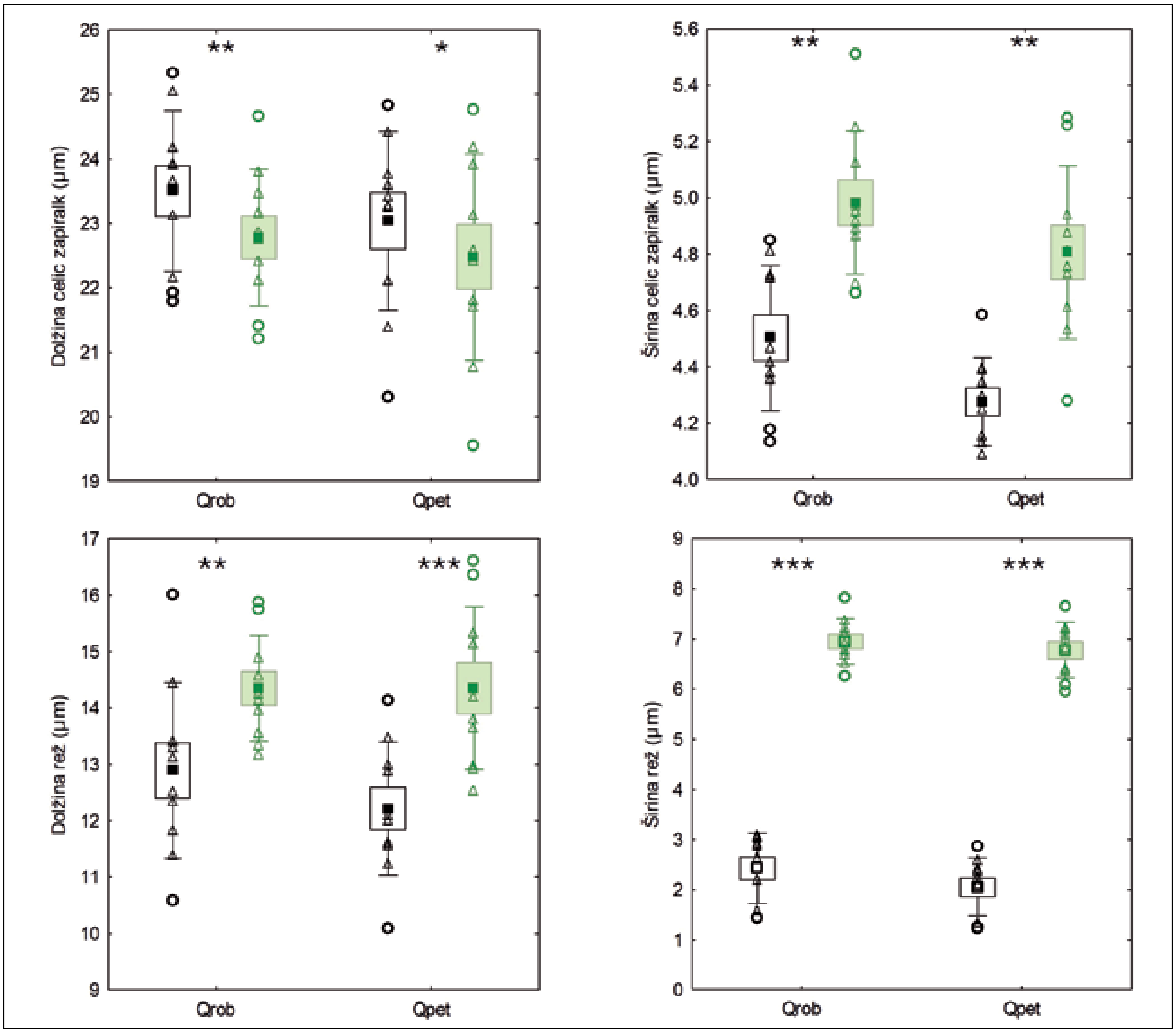


Slika 3: Detajl iz posnetka odtisa povrhnjice hrasta z označenimi režnimi kompleksi pri dobu v programu StoManager1 pod 200 x povečavo mikroskopa. Napačno identificirane celice so označene z rdečo puščico.
Figure 3: Detail from an image of an epidermal imprint of pedunculate oak under 200 x magnification with stomata marked in the StoManager1 software. Incorrectly identified cells are indicated by a red arrow.

Glede na povprečno število preštetih režnih kompleksov v programu ImageJ predstavlja navedeno odstopanje v programu StoManager1 zgolj 2,1 % napako, kar pomeni, da lahko ročno štetje pri dobu in gradnu nadomestimo z avtomatiziranim zaznavanjem v programu StoManager1. To manjše odstopanje bi najverjetneje lahko odpravili s povišanjem nastavitve praga zaznavanja, ki je bil v našem primeru nastavljen na privzeto vrednost 0,25.

Velikost celic zapiralk in porusa

Najprej smo preverili, ali med vrstama obstajajo statistično značilne razlike v dolžini in širini celic zapiralk ter v dolžini in širini porusa pri obeh metodah. ANOVA je pokazala statistično značilno razliko med vrstama samo za širino celic zapiralk merjeno v Image J (F = 5,684, $p = 0{,}0283$). Zaradi tega smo vse spremenljiv-



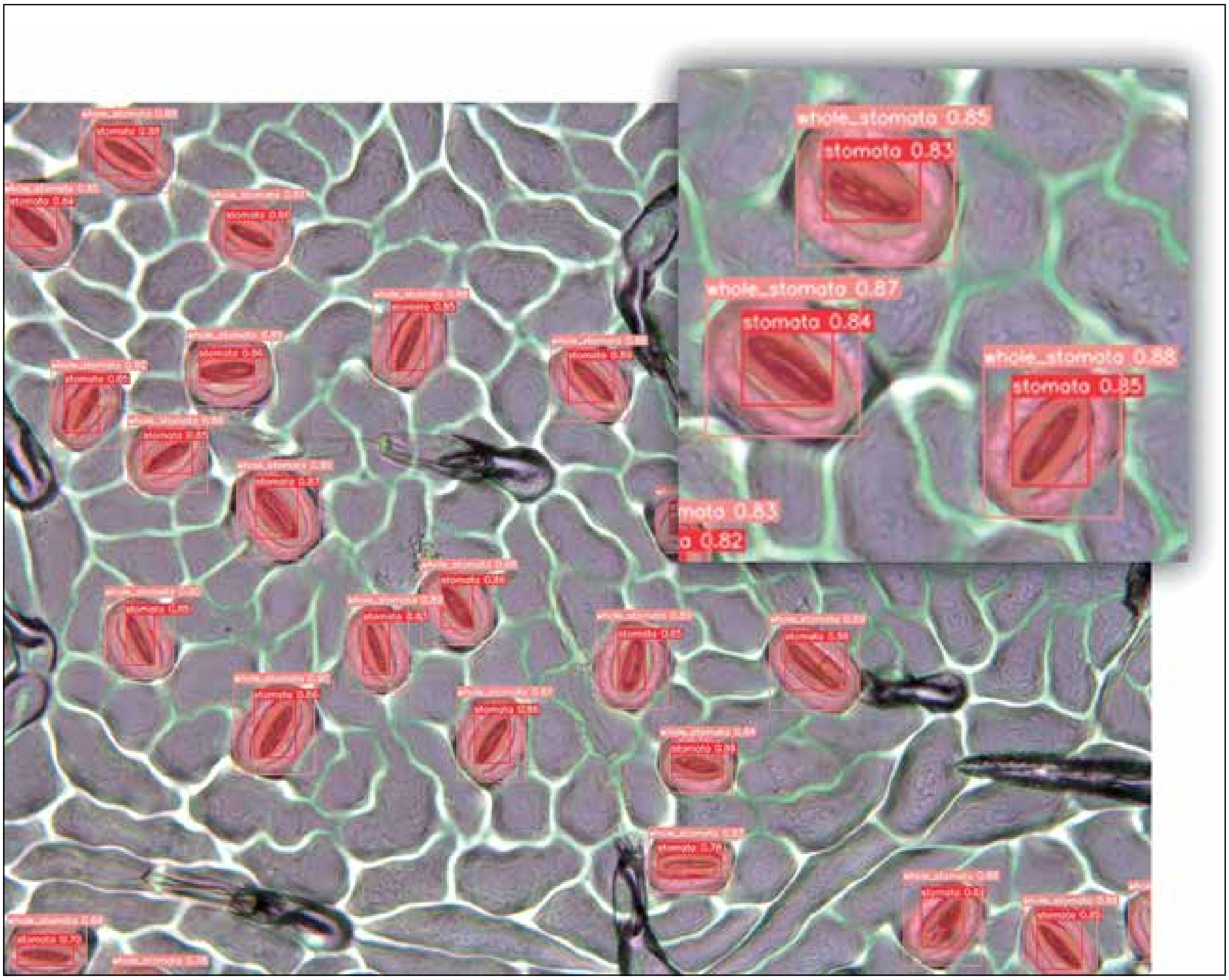
Slika 4: Primerjava ročnih meritev celic zapiralk in porusa v programu ImageJ (črna barva) z avtomatiziranimi meritvami v StoManager1 (zelena barva) pri dobu in gradnu. Statistično značilne razlike (t-test za odvisne vzorce) med obema metodama so označene z * $p < 0{,}05$, ** $p < 0{,}01$, ***$p < 0{,}0001$. Povprečje je prikazano s polnim kvadratkom, okvir prikazuje standardno napako, ročaji standardno deviacijo, krogci pa osamelce. Posamezne meritve so prikazane s trikotniki.

Figure 4: Comparison of manual measurements of guard cells and stomatal pore in the ImageJ program (black) with automated measurements in StoManager1 (green) for pedunculate and sessile oak. Statistically significant differences (paired t-test) between the two methods are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$. The mean is shown by a filled square, the box represents the standard error, the whiskers indicate the standard deviation, and circles denote outliers. Individual measurements are shown as triangles.

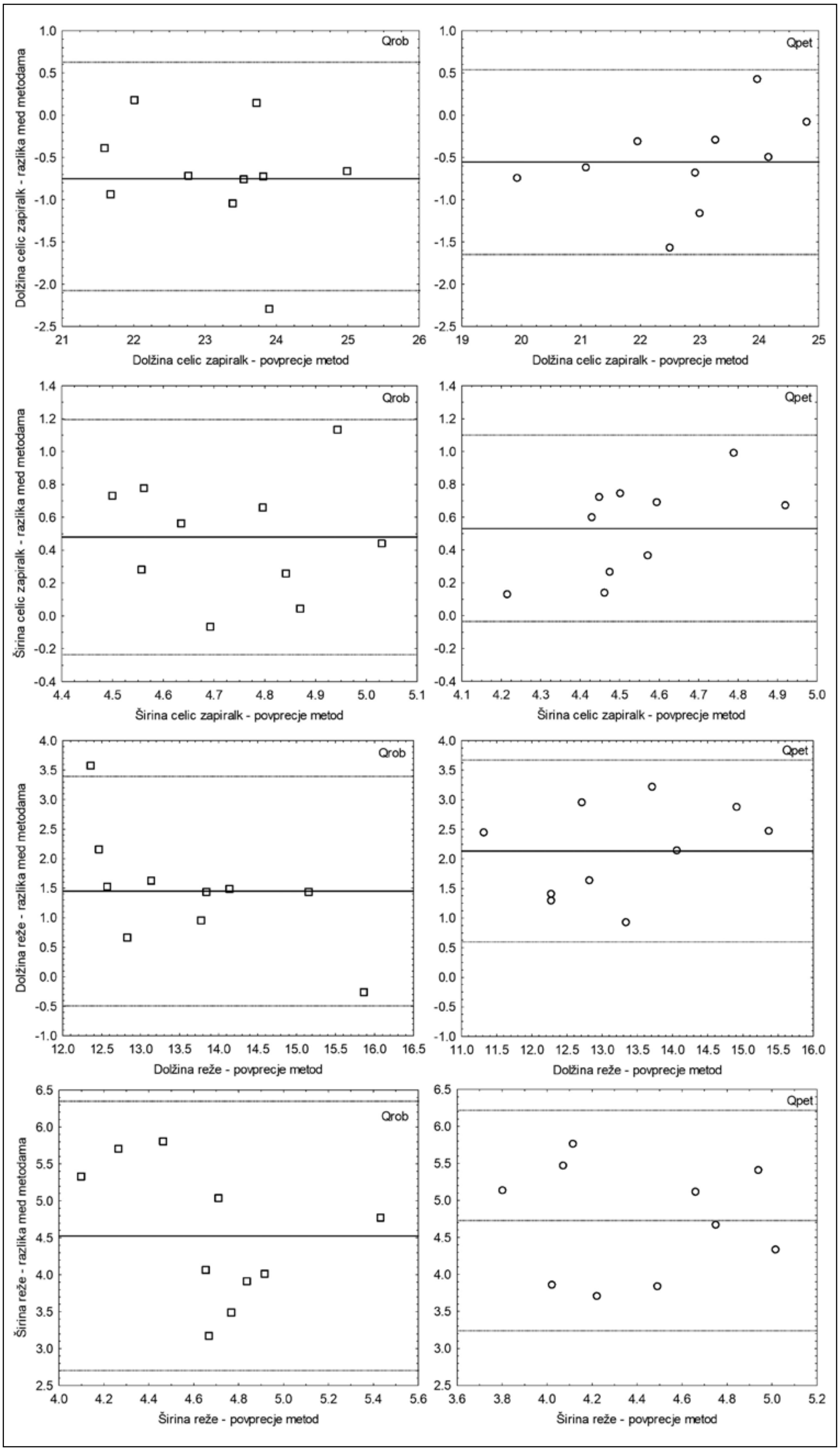
ke za nadaljnje analize ohranili ločene po vrstah. T-testi za odvisne vzorce so pokazali, da so rezultati obeh metod statistično značilno različni za vse spremenljivke in obe vrsti (Slika 4).

Največji razkorak med rezultati obeh meritev smo ugotovili za širino porusa (Slika 4), kar je bilo povezano s tem, da je program StoManager1 v širino porusa vštel tudi notranje odebeljene stene celic zapiralk (Slika 5). Na to težavo pri izračunu površine porusa opozarjajo tudi Gibbs et al. (2021).

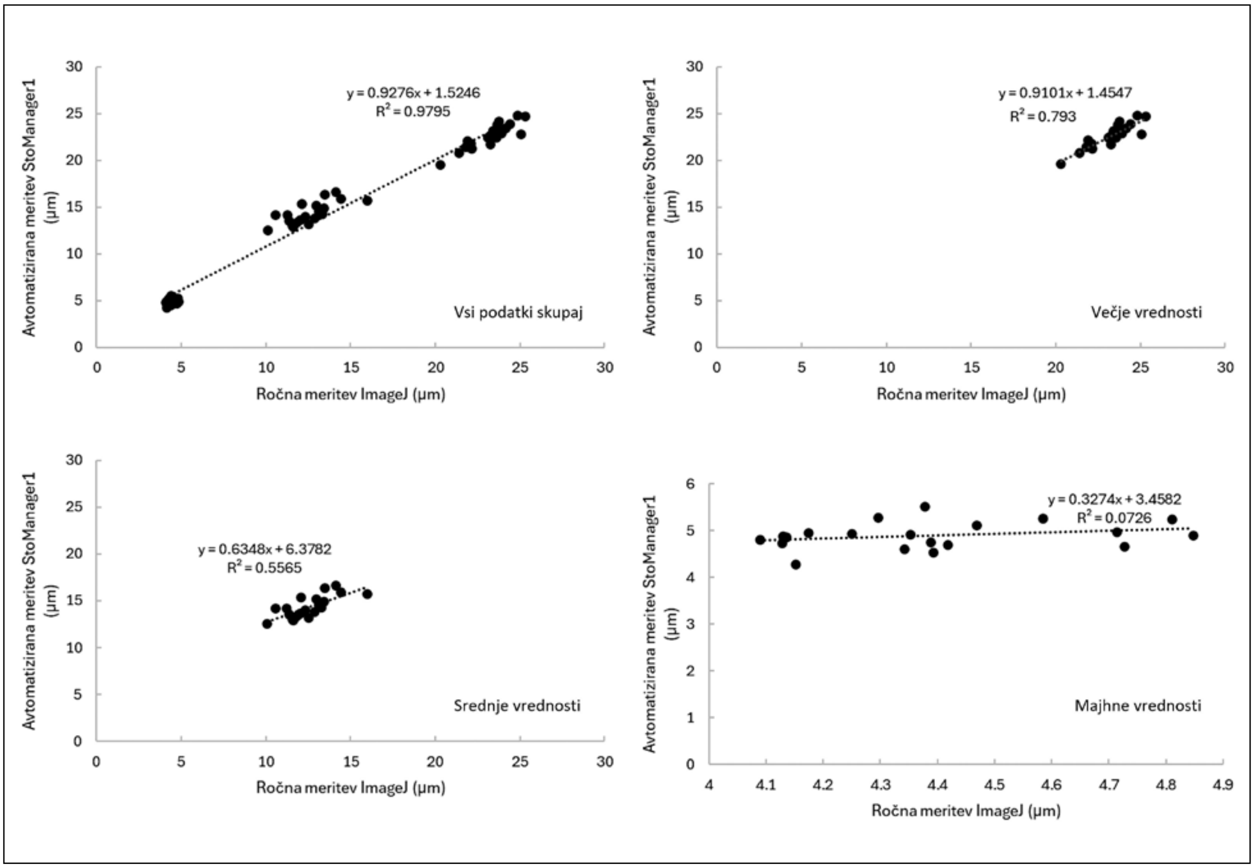
Čeprav so bile absolutne vrednosti med obema metodama različne, so avtomatizirane meritve večinoma ohranjale razmerja med vrstama, pri čemer pa je potrebno poudariti, da je avtomatizirana metoda zmanjševala razlike med vrstama (Slika 4). Iz Slike 4 je razvidno tudi, zakaj smo z ročnimi meritvami zasledili statistično značilno razliko v širini celic zapiralk, z avtomatiziranimi meritvami pa ne. Raztros avtomatiziranih meritev je bil v primeru gradna večji, kar je verjetno povezano s tem, da je širina celic zapiralk relativno majhna. V takih primerih lahko pride do tega, da je zaznavanje robov struktur manj natančno, že majhne razlike v segmentaciji pa privedejo do večjih napak. To nakazuje na to, da bi lahko bila avtomatizirana metoda manj natančna za manjše strukture. Bland-Altmanov diagram (Slika 6) je v tem primeru pokazal, da so bile majhne strukture z avtomatizirano metodo nekoliko podcenjene, večje pa nekoliko precenjene. Ta trend se je pri gradnu pokazal tudi pri meritvah dolžine celic zapiralk (Slika 6), kjer je bil razpon izmerjenih vrednosti večji kot pri dobu, kar nakazuje na



Slika 5: Primer posnetka odtisa površnjice gradna z označenimi porusi in celicami zapiralkami v programu StoManager1 pod 400 x povečavo mikroskopa. Podrobnejši izsek iz slike prikazuje način segmentacije, ki ga uporablja StoManager1.
Figure 5: Example image of an epidermal imprint of sessile oak with stomatal pores and guard cells marked in the StoManager1 program at 400× microscope magnification. A detailed inset from the image shows the segmentation method used by StoManager1.



Slika 6: Bland-Altmanovi diagrami za ovrednotenje primerljivosti metod merjenja dimenzij režnega kompleksa pri dobu in gradnu. Sredinska referenčna črta predstavlja povprečje razlik med obema metodama, spodnja in zgornja črtkana črta pa predstavljata meji strinjanja (angl. limits of agreement) in sta izračunani kot povprečje razlik med obema metodama +/- 1,96 x SD.
Figure 6: Bland–Altman plots for evaluating the agreement between methods for stomatal measurements in pedunculate and sessile oak. The central reference line represents the mean difference between the two methods, while the lower and upper dashed lines indicate the limits of agreement, calculated as the mean difference ± 1.96 × SD.



Slika 7: Primerjava med ročnimi meritvami v ImageJ in avtomatiziranimi meritvami v StoManager1. Za prikaz so bili uporabljeni podatki za obe vrsti hrasta skupaj, izločili pa smo podatke, za katere smo ugotovili, da merjena struktura ni primerljiva (širina porusa izmerjena z avtomatizirano meritvijo zajema precej večje območje – med obema celicama zapiralkama – kot pa ročna meritev).
Figure 7: Comparison between manual measurements in ImageJ and automated measurements in StoManager1. Data from both oak species were combined for the analysis, while measurements in which the evaluated structures were not comparable were excluded (i.e., the stomatal pore width measured automatically covered a substantially larger area—between the two guard cells—than the manual measurement).

to, da bi lahko bila ta merilna napaka prisotna na celotnem merilnem območju, vendar pa se razkrije le, kadar zajamemo zadostno variabilnost v velikosti struktur.

Da bi lažje ugotovili, ali je natančnost zaznavanja struktur z avtomatizirano metodo enaka po celotnem merilnem razponu, smo naredili regresijsko analizo (Slika 7) med podatki, pridobljenimi z ročnimi meritvami in podatki, pridobljenimi z avtomatiziranimi meritvami za različne dimenzijske parametre. Regresijska premica, ki je upoštevala vse podatke za meritve istih struktur, je pokazala dokaj dobro ujemanje med ročnimi in avtomatiziranimi meritvami. Pri ločeni obravnavi posameznih merilnih območij se je izkazalo, da je bilo ujemanje med obema metodama v velikostnem razredu struktur 20-25 µm razmeroma dobro, vendar so se pri večjih vrednostih znotraj tega območja pojavljale večje absolutne in relativne napake. V velikostnem razredu 10-15 µm sta metodi močno odstopali od razmerja 1:1, pri majhnih strukturah pa korelacije med ročnimi meritvami in meritvami, pridobljenimi z avtomatizirano metodo, sploh ni bilo več (Slika 7). To je lahko posledica tako razlik v zaznavanju robov majhnih struktur pri avtomatizirani metodi kot tudi dejstva, da je pri ročnih meritvah teh struktur težko objektivno določiti skrajni točki, med katerima želimo izvesti meritev zaradi omejitev v ločljivosti slike.

Vsi ti rezultati nakazujejo, da je bila merilna napaka pri avtomatizirani metodi odvisna od velikosti merjene strukture. Zaradi tega ocenjujemo, da je metoda primerna nadomestitev ročnih meritev pri večjih strukturah (20-25 µm, kar je razpon dolžine celic zapiralk pri obeh vrstah hrastov), kjer lahko reproducira trende, ki jih opazimo s pomočjo ročnih meritev. Ker so naše meritve zajele samo območje do 25 µm, bi bilo potrebno za večje strukture ujemanje med obema načinoma meritev dodatno preveriti.

Iz naših rezultatov lahko povzamemo, da je StoManager1 ustrezna nadomestitev ročnih meritev števila oz. gostote režnih kompleksov ter večjih struktur znotraj režnega kompleksa, kot je npr. dolžina celic zapiralk za izbrane drevesne vrste. Kot opozarjajo avtorji tega orodja, ima StoManager1 omejitve in potencialne vire napak, zato priporočajo njegovo testiranje in primerjavo z ročnimi meritvami (Wang et al. 2024). Poleg tega lahko viri napak izhajajo tudi iz postopkov zajema posnetkov, npr. različnih jakosti osvetlitve, neostrih območij na sliki ter prisotnosti artefaktov (Gibbs et al. 2021, Wang et al. 2024, Gibbs & Burgess 2024). Četudi modeli na slikah natančno zaznajo in izmerijo listne reže, je potrebno rezultate biološko ovrednotiti ter preveriti, ali dejansko odražajo fiziološko delovanje rastline (Gibbs & Burgess 2024).

4 SUMMARY

Analyses of stomatal traits, such as density and size, are essential for understanding plant physiology, their adaptability to environmental conditions, and their responses to climate change. Such analyses are predominantly based on microscopy techniques and their derivatives, which can be very time consuming. The aim of this study was to determine whether manual measurements of stomata in tree seedlings can be replaced by automated measurements, which would substantially increase the number of samples that can be analysed due to time savings. Leaves of pedunculate and sessile oaks growing at the same site were preserved in 70 % ethanol. Imprints of lower epidermis were prepared by nail polish method and imaged under 200 x and 400 x magnification of the microscope. Ten randomly selected micrographs per each species were used to analyse the number of stomata as well as the length and width of guard cells and stomata, using both manual measurements in ImageJ (Schneider et al. 2012) and automated measurements in StoManager1 (Wang et al. 2023, Wang et al. 2024a, b). The results were statistically evaluated by paired t-tests and Bland-Altman analysis, a statistical method to compare two quantitative measurement methods. No statistically significant differences between the two methods were found for the measurements of stomatal number. Bland–Altman analysis showed good agreement between manual and automated measurements. Although the automated method slightly overestimated the number of stomata, the error was small (2.1 %) and could be possibly reduced by decreasing of sensitivity of the automated method. For size measurements, statistically significant differences were observed between the two methods. Mean guard cell lengths were lower when measured using the automated method compared to manual measurements, whereas guard cell widths, as well as stomatal widths and lengths, were higher with the automated method. Bland–Altman analysis revealed deviations between the methods at larger size ranges of the measured structures. Regression analysis indicated that agreement between manual and automated measurements was reasonably reliable within the size range of 20–25 µm (larger structures were not measured), but decreased with decreasing structure size, most likely due to image segmentation in the automated method and the associated less precise edge detection. In small structures, even minor segmentation differences can lead to larger errors. On the other hand, manual measurements in microscopy images can also become increasingly subjective as the size of structures decreases, due to the difficulty of consistently identifying precise boundaries at or near the resolution limit. Our results thus indicate that StoManager1 is a suitable alternative to manual measurements of stomatal density and larger stomatal traits in the selected tree species, although its outputs should still be validated against manual measurements and biological function due to potential methodological and image-acquisition related sources of error.

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MORPHOLOGICAL VARIATION OF *BETULA PENDULA* AND *BETULA PUBESCENS* LEAVES IN SOUTH-EASTERN EUROPE

MORFOLOŠKA VARIABILNOST LISTOV NAVADNE IN PUHASTE BREZE V JUGOVZHODNI EVROPI

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IZVLEČEK

Navadna (*Betula pendula* Roth) in puhasta (*Betula pubescens* Ehrh.) breza sta ekološko pomembni v zmernih in borealnih gozdovih, in imata veliko morfološko variabilnost v okviru svojih arealov razširjenosti. V tej študiji smo želeli oceniti morfološko variabilnost listov med naravnimi populacijami breze v Bosni in Hercegovini (BiH) in v Sloveniji (SI) in raziskati odvisnost te variabilnosti od okoljskih in podnebnih dejavnikov.

Liste smo pridobili v 39 populacijah (31 v BiH in 8 v SI) v letih 2020–2022. Vzorčili smo 10 dreves na populacijo, z vsakega drevesa 30 listov. Skupno smo analizirali 11.700 listov. Morfometrične analize so vključevale izmerjene, ocenjene, preštete in izvedene znake. Uporabili smo opisno statistiko, gnezdeno analizo variance, koeficiente diferenciacije populacij, Pearsonovo korelacijo, analizo glavnih komponent (PCA) in analizo grozdov (UPGMA). Odnose med morfološkimi znaki in podnebnimi spremenljivkami smo ocenili z uporabo bioklimatskih podatkov iz baze WorldClim.

Rezultati so pokazali znatno fenotipsko variabilnost v morfologiji listov med preučevanimi populacijami. Prvi dve glavni komponenti sta pojasnili 73,2 % celotne variabilnosti, pri čemer parametri velikosti listov predstavljajo dominantno os diferenciacije. Analize grozdov in PCA so pokazale jasno regionalno strukturiranje, pri čemer so se slovenske populacije razlikovale od večine populacij v BiH. Kvalitativne lastnosti, kot so oblika listov, rob, dlakavost in tekstura, so pokazale znatno heterogenost med populacijami. Pri dveh populacijah, ki sta bili predhodno identificirani kot *B. pube-*

ABSTRACT

Birch species (*Betula pendula* Roth and *Betula pubescens* Ehrh.) are ecologically important components of temperate and boreal forests, exhibiting considerable morphological variability across their distribution ranges. This study aimed to assess leaf morphological variation among natural *Betula* populations in Bosnia and Herzegovina and Slovenia and to examine its relationship with environmental and climatic factors.

Leaves were collected from 39 populations (31 in Bosnia and Herzegovina and eight in Slovenia) during 2020–2022. Ten trees per population were sampled, with 30 leaves collected from each tree. In total, 11,700 leaves were analyzed. Morphometric analyses included measured, assessed, counted, and derived leaf traits. Descriptive statistics, nested analysis of variance, population differentiation coefficients, Pearson correlations, principal component analysis (PCA), and cluster analysis (UPGMA) were applied. Relationships between morphological traits and climatic variables were evaluated using bioclimatic data from the WorldClim database.

The results revealed substantial phenotypic variability in leaf morphology among the studied populations. The first two principal components explained 73.2% of the total variation, with leaf size parameters representing the dominant axis of differentiation. Cluster and PCA analyses indicated clear regional structuring, with Slovenian populations forming a distinct group from most populations in Bosnia and Herzegovina. Qualitative traits such as leaf shape, margin, pubescence, and texture showed significant heterogeneity among populations. Leaf pubescence was confirmed in two populations previously

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scens (Han Kram in Mokro 2), smo potrdili dlakavost listov. Ugotovili smo močne korelacije med morfološkimi lastnostmi listov in podnebnimi spremenljivkami, zlasti povprečno letno temperaturo, ki je pokazala močan vpliv na dimenzije listov.

Na splošno smo ugotovili izrazito morfološko raznolikost med populacijami brez v JV Evropi, pri kateri imajo ključno vlogo okoljski gradienti, zlasti temperatura.

Ključne besede: breza, morfologija listov, fenotipska variabilnost, diferenciacija populacij, klimatski gradienti, analiza glavnih komponent, gozdni genski viri

identified as *B. pubescens* (Han Kram and Mokro 2). Strong correlations were observed between leaf morphological traits and climatic variables, particularly mean annual temperature, which showed a strong influence on leaf dimensions.

Overall, the findings highlight pronounced morphological diversity in *Betula* populations and suggest that environmental gradients, particularly temperature, play a key role in shaping leaf morphological variation in south-eastern Europe.

Keywords: birch, leaf morphology, phenotypic variability, population differentiation, climatic gradients, principal component analysis, forest genetic resources

INTRODUCTION

Trees of the genus *Betula* (birches) play important ecological, economic and cultural roles across Europe's temperate and boreal forests. *Betula pendula* Roth (silver birch) and *Betula pubescens* Ehrh. (downy birch) are two widely distributed species in the region, each with distinct ecological niches but also overlapping habitats. *B. pendula* is a fast growing, light demanding pioneer species found from the Mediterranean up to central Siberia, and is considered as an essential component of temperate and boreal forests due to its role as a pioneer, its associations with fungi and insects, and its broad ecological amplitude (Vakkari 2009). *B. pubescens* is a fast-growing, light-demanding pioneer species found throughout northern and north-western Europe and extending into parts of Asia, and is considered an important component of boreal and temperate ecosystems due to its role as a pioneer species, its tolerance of cold and wet conditions, and its broad ecological amplitude (Atkinson, 1992). Despite their broad distributions and occasional habitat overlap, the two species differ in their ecological preferences. *Betula pubescens* is typically associated with acidic, peaty, or waterlogged soils, whereas *B. pendula* most commonly occurs on well-drained, neutral to slightly acidic soils (Atkinson 1992). These ecological differences contribute to their contrasting distribution patterns and may influence morphological variation among populations. *Betula pendula* exhibits strong environmental adaptability, colonising nutrient-poor, disturbed or early-successional sites, and thereby contributing to ecosystem regeneration and succession. For example, the species has been described as a pioneer anemochorous species with a significant role in river-valley forests of the Irtysh basin, demonstrating rapid growth rate and strong environmental adaptability (Li et al. 2024). In boreal/temperate forestry contexts, birches (including *B. pendula* and *B. pubescens*) are major components of forests, thus their management and conservation is relevant for climate change adaptation and multifunctional forestry (Vakkari 2009, Slepetiene et al. 2025). Additionally, many insect herbivore and simbiont communities are tightly associated with birch species. For example, in a *B. pendula* population the genotype of the tree explained substantial variation in the insect herbivore community structure (Silfver et al. 2014). These observations highlight that the species are not just woody biomass carriers, but keystone components in forest biodiversity, nutrient cycling and ecosystem functioning.

Leaves serve as the primary interface between plants and their environment, playing essential roles in light capture, gas exchange, water regulation, and the integration of various developmental and physiological processes. Morphological variation in leaf traits reflects not only responses to environmental gradients but also developmental constraints, genetic variation, and evolutionary adaptations. For example, natural populations of *Quercus petraea* showed substantial variation in leaf morphological traits, with several traits significantly correlating with temperature- and precipitation-related climatic variables, suggesting patterns of local adaptation (Memišević Hodžić et al. 2024, 2025). Such variation in leaf morphology can therefore serve as a reliable proxy for adaptive differentiation, phenotypic plasticity, and functional trait diversity within and among populations. Additionally, because leaf morphology is easier to quantify than many physiological traits, it provides a practical and accessible tool for studies of intraspecific variation and ecological adaptation.

Investigating morphological variation within species is increasingly recognized as essential for understanding how forest trees respond to environmental changes such as climate shifts, land-use transformation, and habitat fragmentation. This variation is particularly relevant for identifying adaptive traits, guiding the selection of suitable seed resources for ecological restoration, and conserving both functional and genetic diversity. Examining morphological traits across natural populations of *B. pendula* and *B. pubescens* in diverse environments, such as those found in the south-eastern Europe, provides an opportunity to assess how environmental heterogeneity (e.g. differences in altitude, soil characteristics, moisture availability, and light conditions), along with possible genetic differentiation, influences leaf trait variation. Such insights are crucial for developing evidence-based conservation strategies, managing forest genetic resources, and selecting locally adapted material for future restoration efforts.

Although birch species are broadly distributed, there are relatively few detailed studies of morphological trait variation of birches in south-eastern Europe (the Balkans and adjoining Alpine/Pre-Alpine areas) (Kovačić and Nikolić 2005). By focusing on natural populations of *B. pendula* and *B. pubescens* in south-eastern Europe, the present study contributes novel data from this biogeographically interesting region characterised by complex topography, varied soils, and climatic gradients. The morphological variation documented may reflect unique local adaptation or plastic responses, which have implications for both local ecosystem function and regional forest genetic resource management.

The present study aims to examine morphological variation of leaves in *B. pendula* and *B. pubescens* across natural populations in Bosnia and Herzegovina and Slovenia. Specifically, the objectives of this study were to:

1) quantify the morphological variation of key leaf traits within and among birch populations in Bosnia and Herzegovina and Slovenia
2) assess the extent to which observed varriation corresponds to environmental and climatic gradients
3) discuss the implications of leaf morphological variation for functional ecology, forest management and conservation of birch genetic/trait diversity in the region.

By addressing these objectives, the study contributes to the trait based ecology of forest trees, enhances understanding of intraspecific variation in *Betula* species, and provides baseline information relevant for future provenance-based work and resource management of birches in south-eastern Europe.

MATERIAL AND METHODS

During 2020-22, leaves of *Betula* sp. were collected from 31 locations (populations) in Bosnia and Herzegovina and eight locations (populations) in Slovenia (Figure 1, Table 1).

Figure 1. Researched populations of Betula sp.

Four populations of birch in Bosnia and Herzegovina (Han Kram, Mokro 1, Mokro 2 - Triješanj, Sokolac, and Mrkonjić Grad) were previously described as *Betula pubescens* (Fukarek 1957; Stefanović 1961).

Table 1. Information on researched populations of Betula sp.

No	Population	Locality	Label	Altitude	Latitude	Longitude
1	BiH Bihać	Gata	BiH Bi	369	44.96308	15.83031
2	BiH Borike	Borike	BiH Bo	991	43.97831	19.22678
3	BiH Bosanski Petrovac	Šekovac	BiH BP	697	44.57231	16.51908
4	BiH Bosansko Grahovo	Resanovci	BiH BG	890	44.42389	16.37678
5	BiH Bužim	Baštra	BiH Bu	485	45.02912	16.08979
6	BiH Goražde	Hranjen	BiH Go	759	43.74917	19.03306
7	BiH Han Kram*	-	BiH HK	1095	44.09864	18.91961
8	BiH Jajce	Bavar	BiH Ja	935	44.37064	17.4375
9	BiH Kakanj	-	BiH Ka	798	44.19964	18.18628
10	BiH Kladanj	Budin potok	BiH Kld	764	44.37039	18.68597
11	BiH Ključ	Krasulje	BiH Klj	454	44.62947	16.76764
12	BiH Komar	Komar	BiH Ko	881	44.31747	17.61258
13	BiH Konjic	Jasenik	BiH Knj	1160	43.8375	17.83565
14	BiH Kreševo 1	Jelačke	BiH Kr 1	797	43.98411	18.05747
15	BiH Kreševo 2	Radava	BiH Kr 2	1308	43.89147	18.05928
16	BiH Kupres	Kupres	BiH Ku	1140	44.06372	17.26808
17	BiH Livno	Sajkovački lug	BiH Li	705	44.11075	16.72722
18	BiH Miljevina	Dobro polje	BiH Mi	951	43.58861	18.54606
19	BiH Mokro 1*	-	BiH Mo 1	991	43.99214	18.70242
20	BiH Mokro 2*	Triješanj	BiH Mo 2	986	43.91901	18.62189
21	BiH Mrkonjić grad*		BiH MG	865	44,41424	16.99704
22	BiH Novi Travnik	Gornje Trenice	BiH NT 2	580	44.26094	17.7675
23	BiH Olovo	Bakići	BiH Ol	828	44.19872	18.65542
24	BiH Sanski Most 1	Dabar	BiH SM1	415	44.76014	16.61425
25	BiH Sanski Most 2	Hrustovo	BiH SM2	228	44.76206	16.84036
26	BiH Sokolac*		BiH So	872	43,92092	18.80037
27	BiH Srebrenik	Štalija	BiH Sr	427	44.75856	18.70758
28	BiH Tarčin	Osenik	BiH Ta	812	43.86367	18.25381
29	BiH Trnovo	Dejčići	BiH Tr	1001	43.71089	18.46456
30	BiH Žepa	Luka	BiH Že	1114	44.14378	19.31814
31	BiH Žepče	Donja Golubinja	BiH Žč	265	44.38827	17.98268
32	SLO Begunje	-	SLO Be	772	46.38163	14.21433
33	SLO Črnomelj	Semič	SLO Čr	203	45.70278	15.21667
34	SLO Ljubljansko Barje	Kozlerjeva Gošča	SLO LjB	278	46.08889	14.56944
35	SLO Novo Mesto	Koroška vas	SLO NM	334	45.79167	15.23889
36	SLO Pongrac	-	SLO Po	424	46.20183	15.15502
37	SLO Ponikva	Zagaj pri Ponikvi	SLO Pnk	405	46.27749	15.44412
38	SLO Šenčur	-	SLO Še	356	46.21111	14.45556
39	SLO Zgornje Gorje	-	SLO ZG	912	46.39444	14.05833

The geographic locations of the sampled populations were determined using GPS and consist of latitude, longitude, and altitude. The study used bioclimatic data obtained from the WorldClim portal (https://www.worldclim.org/data/bioclim.html). The names of the bioclimatic variables are shown in Table 1.1.

Table 1.1. List of bioclimatic variables (WorldClim database)

Bioclimatic variable	Variable Description
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Ten trees per population were sampled, and a total of 30 leaves collected per tree. Birch leaves were collected from fertile shoots (short shoots) in the south-exposed parts of the crowns of adult trees growing in open areas or forest edges. Trees were selected based on standard functional trait sampling criteria, i.e., well-developed, healthy individuals growing in well-lit conditions to minimize the effects of shade-induced plasticity on leaf traits (Cornelissen et al. 2003). The leaves were then pressed, dried, and measured.

Morphometric Analysis

The dried leaves were measured using a digital caliper (in mm) and a protractor. Six phenotypic traits were measured on each leaf (Table 2, Figure 2). Four traits

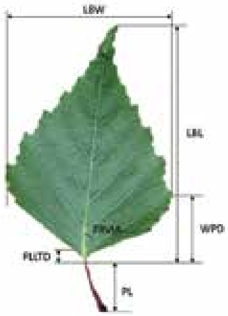

Figure 2: Measured traits of the leaf

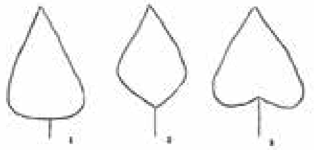

Figure 3: Leaf shape categories

Figure 4: Leaf margin categories

Table 2. Measured, assessed, counted, and derived traits of the birch leaf

No	Trait	Unit	Label	Trait type	Note
1.	Leaf blade length	mm	LBL	Measured	-
2.	Petiole length	mm	PL	Measured	-
3.	Leaf blade width at the widest point	mm	LBW	Measured	-
4.	Distance from leaf widest point to leaf base	mm	WPD	Measured	-
5.	Distance from petiole to first left leaf tooth	mm	FLLTD	Measured	-
6.	Angle of insertion of the first right vein	°	FRVIA	Measured	-
7.	Number of teeth between 2nd and 3rd vein		NT2-3	Counted	-
8.	Number of teeth between 3rd and 4th vein		NT3-4	Counted	-
9.	Leaf shape	-	LS	Assessed	Categories 1-3 (Fig. 3)
10.	Leaf margin	-	LM	Assessed	1 = coarsely serrate 2 = doubly serrate 3 = irregularly serrate 4 = entire margin (Fig. 4)
11.	Leaf pubescence on the abaxial side	-	LP	Assessed	1 = yes, 2 = no
12.	Leaf texture	-	LSR	Assessed	1 = smooth 2 = rough-textured leaf
13.	Total leaf length (blade + petiole)	-	TLL	Derived	-
14.	Blade width-to-length ratio	-	BW/BL	Derived	-

were assessed (Table 2, Figures 3 and 4), two were counted, and two were derived.

Statistical Analysis

A logical data check was performed, and data indicating input errors were excluded.

Descriptive statistics included the maximum, minimum, and mean values, standard deviation (SD), and the coefficient of variation (CV) as a relative measure of variability, using all available data. The coefficient of variation was calculated as:

$$CV = \frac{SD}{\bar{x}} \cdot 100\%$$

The population differentiation coefficient (Vst) was calculated as:

$$Vst = \frac{\sigma_i^2}{\sigma_i^2 + \sigma_{j\,(i)}^2} \cdot 100\%$$

where σ_i^2 denotes the variance among populations and $\sigma_{j(i)}^2$ denotes the variance within populations (Wang et al. 2023). The variance components σ_i^2 and $\sigma_{j\,(i)}^2$ were obtained using a nested analysis of variance (ANOVA) (with trees nested within populations), according to the following linear model:

$$Yijk = \mu + \alpha_i + \beta_{j(i)} + e_{(ij)k}$$

where: Y_{ijk} is the k-th observation on the j-th tree in the i-th population; μ is the overall mean; α_i is the random effect of the i-th population; $\beta_{j(i)}$ is the random effect of the j-th tree within the i-th population; and $e_{(ij)k}$ is the experimental error associated with the ijk-th observation, representing the within-tree variation.

The homogeneity of distributions among populations for the assessed traits of leaf pubescence and leaf base shape was tested using the χ^2 test of homogeneity of distributions.

To investigate the correlation among phenotypic traits, the variables were standardized, and Pearson's correlation coefficients and their statistical significance were obtained using the cor.test function in R version 4.1.3 (R Core Team, 2016).

Principal component analysis (PCA) was used to reduce the phenotypic traits into a smaller number of principal components and to explore the continuum of trait variation. PCA was performed using the correlation matrix of standardized mean tree-level variables. The analysis was conducted using the MorphTools2 package in R version 4.1.3 (R Core Team, 2016), following the manual by Koutecký (2015).

Furthermore, a dendrogram of the nearest Euclidean distances was constructed using the unweighted pair-group method with arithmetic mean (UPGMA) to examine the structure among the studied populations. Euclidean distances were calculated using the dist function in R based on population mean values standardized by the Z-score method, and subsequently subjected to cluster analysis (UPGMA method) using the clust function in the MorphTools2 package.

The analysis of correlations between the measured leaf traits and geographic and climatic factors was performed by Pearson's χ^2 Test.

RESULTS

Phenotypic variation of traits

Table 3 presents the results of descriptive statistics calculated for ten phenotypic leaf traits in order to assess phenotypic variability using the entire dataset. The coefficients of variation (CV) ranged widely, from 15.90% for the width of the widest part of the leaf blade to 45.70% for the distance from the petiole to the first tooth on the left side. The mean coefficient of variation was 27.42%.

Phenotypic variation between and within populations

In Table 4, the proportion of variance components, population differentiation coefficients (Vst), and F-values are presented for the ten studied leaf traits (measured, counted, and derived traits). The data are based on all observations from 39 natural populations of *Betula sp.* in Bosnia and Herzegovina and Slovenia, including variation between and within populations.

Analysis of the variance components showed the partitioning of variation in all traits among populations, among trees within populations, and within trees (residual) (Table 4). On average, the highest proportion of variation was observed among populations (mean = 45.70%), followed by within trees (mean = 32.85%), while the lowest proportion of variation occurred among trees within populations (mean = 21.45%).

Certain traits exhibited relatively high variation among populations. These traits included leaf blade length (69.71%), the distance from the widest point of

Table 3. Descriptive statistics of the studied leaf morphological traits for 39 natural populations of Betula sp. in Bosnia and Herzegovina and Slovenia

Variable code	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
LBL (mm)	34.60	77.20	50.20	12.00	23.90
PL (mm)	12.40	28.40	19.60	4.36	22.20
LBW (mm)	27.00	48.20	36.90	5.85	15.90
WPD (mm)	9.05	24.70	15.10	4.32	28.60
FLLTD (mm)	2.60	15.70	8.00	3.66	45.70
FRVIA (°)	25	63	43.70	10.30	23.70
NT2-3	2	7	4.30	1.43	33.30
NT3-4	1	7	4.05	1.76	43.40
TLL	48.90	101.0	69.90	14.50	20.70
BW/BL	0.52	0.95	0.76	0.13	16.80

Table 4. Proportion of variance components, population differentiation coefficient, and F-values for 10 traits based on all data from 39 natural populations of Betula sp. in Bosnia and Herzegovina and Slovenia.

Variable code	Proportion of variance components (%)			Population differentiation coefficient (%)	F - value	
	Among populations	Among trees within populations	Within trees (residual)		Among populations	Among trees within populations
LBL (mm)	69.71	15.06	12.23	53.50	1272.66***	28.82***
PL (mm)	20.36	34.19	45.46	11.33	137.73***	22.02***
LBW (mm)	20.36	37.69	41.95	11.33	161.26***	25.83***
WPD (mm)	50.64	21.39	27.97	33.90	519.37***	22.58***
FLLTD (mm)	38.21	29.85	31.93	23.62	360.55***	26.71***
FRVIA (°)	20.66	24.97	54.37	11.52	123.30***	14.01***
NT2-3	55.62	12.46	31.92	38.52	485.94***	11.55***
NT3-4	63.30	10.93	25.77	46.31	682.04***	12.53***
TLL	59.48	19.98	20.54	42.32	805.90***	28.18***
BW/BL	58.64	7.95	33.41	41.48	479.11***	7.69***
Mean	45.70	21.45	32.85	31.38	502.79***	19.99***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

the blade to the base (50.64%), the distance from the petiole to the first tooth on the left side (38.21%), the number of teeth between the 2nd–3rd (55.62%) and 3rd–4th nerves (63.30%), total leaf length (59.48%), and the leaf blade length-to-width ratio (58.64%). In contrast, traits such as petiole length, leaf blade width, and the insertion angle of the first nerve on the right side showed lower variation among populations.

Regarding within-population variation among individual trees, high variability was observed for petiole length (45.46%), leaf blade width (41.95%), and the insertion angle of the first nerve on the right side (54.37%). The most stable traits within populations were the number of teeth between the 2nd–3rd (12.46%) and 3rd–4th nerves (10.93%), and the leaf blade length-to-width ratio (7.95%), while the least stable trait among individual trees within populations was leaf blade length (12.23%).

The population differentiation coefficient averaged 31.38%. The most pronounced differentiation was observed for leaf blade length (53.50%), followed by the number of teeth between the 3rd and 4th vein (46.31%), total leaf length (42.32%), and the ratio of leaf blade length to width (41.48%). In contrast, traits such as petiole length, leaf blade width, and the insertion angle of the first vein on the right side showed significantly lower values (≈11–12%).

Correlations Between Leaf Traits

In Figure 5, the relationships among ten phenotypic leaf traits at the tree level are illustrated through a Pearson correlation matrix.

The strongest positive correlations were observed between leaf blade length and total leaf length, as well as between the number of teeth between the 2nd–3rd and 3rd–4th veins (r = 0.97–0.98, $p < 0.01$). Moderate positive correlations were detected between leaf blade length, leaf blade width, total leaf length, and the distance from the widest point of the blade to the base (r = 0.66–0.74, $p < 0.01$). Negative correlations were mainly found for the leaf blade length-to-width ratio in relation to leaf blade length, total leaf length, and the distance to the base (r = -0.74–-0.82, $p < 0.01$). The insertion angle of the first vein showed weak or negligible correlations with other traits.

Principal components and cluster analysis

Principal Component Analysis (PCA) was conducted to identify and quantify variability among trees for the studied morphological traits and to identify the principal components explaining the largest portion of total variance (Table 5).

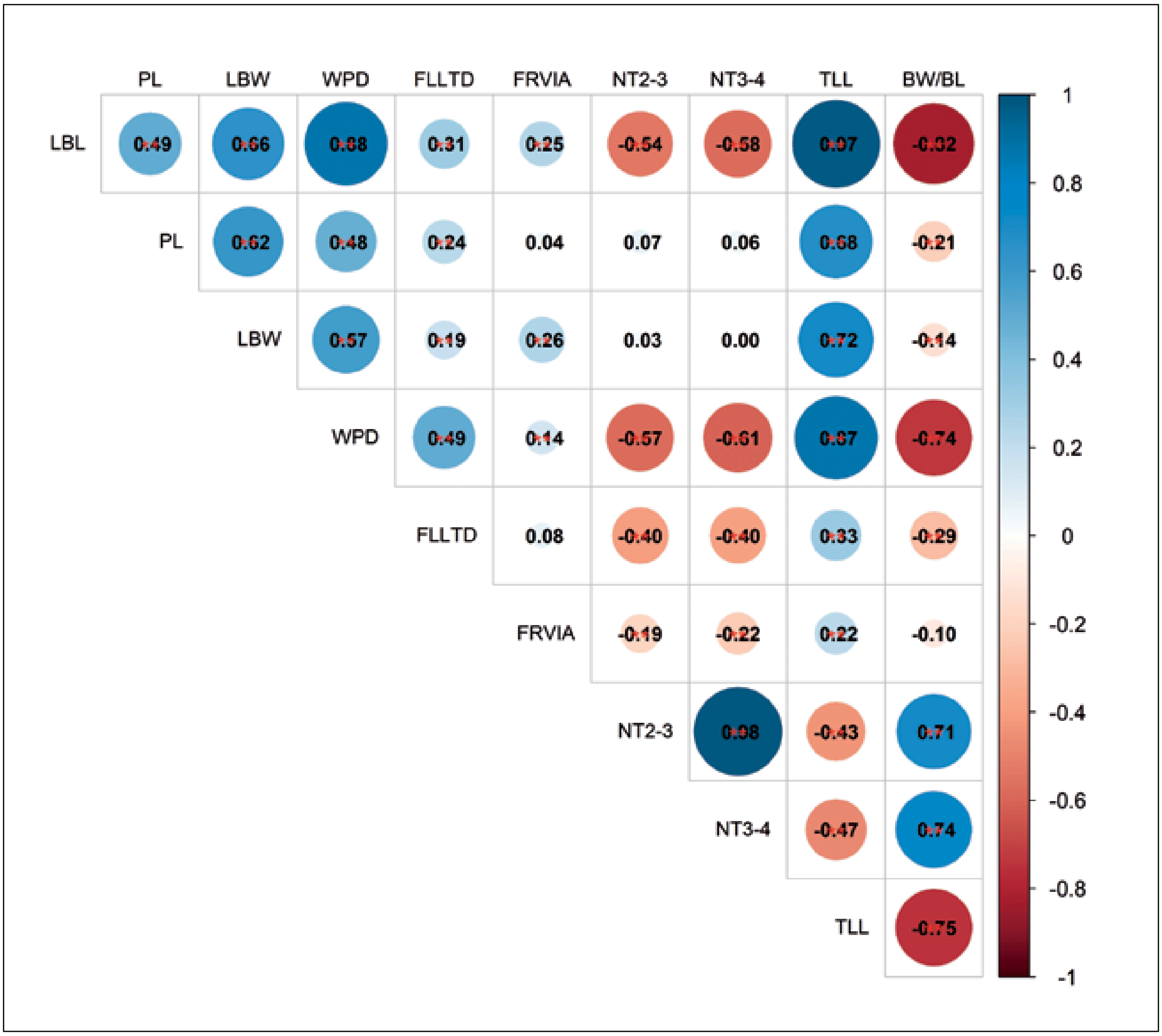

*Figure 5: Correlation analysis of 10 phenotypic leaf traits (measured, counted and derived traits) at the tree level. Blue indicates positive correlations, while red indicates negative correlations. Larger circles and darker colors represent stronger correlations (*p < 0.05; **p < 0.01; ***p < 0.001).*

Table 5. Eigenvalues, contribution rates, and cumulative proportion of the five principal components based on the mean tree values for the studied traits.

Variable code	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
LBL	0.415	0.104	0.026	0.216	-0.134
PL	0.217	0.484	-0.183	-0.100	0.693
LBW	0.246	0.490	0.168	-0.043	-0.572
WPD	0.406	0.052	-0.123	-0.035	-0.221
FLLTD	0.217	-0.083	-0.199	-0.891	-0.023
FRVIA	0.119	0.014	0.927	-0.163	0.248
NT2-3	-0.304	0.463	-0.033	0.023	-0.002
NT3-4	-0.317	0.447	-0.063	0.001	0.012
TLL	0.408	0.215	-0.026	0.155	0.061
BW/BL	-0.365	0.215	0.136	-0.309	-0.246
Eigenvalues	5.252	2.070	1.013	0.847	0.385
Variance contribution rate	0.525	0.207	0.101	0.085	0.038
Cumulative proportion	0.525	0.732	0.833	0.918	0.957

Principal component analysis (PCA) was conducted at both the tree and population levels and is shown in Figure 6.

The first two components explain a total of 73.20% of the variability in the analyzed leaf morphological traits, confirming the stability of the model (Figure 6). The first component was mainly associated with leaf blade dimensions and total leaf length (LBW, PL, TLL, LBL, WPD), with these traits showing strong loadings on this axis. The second component was associated with

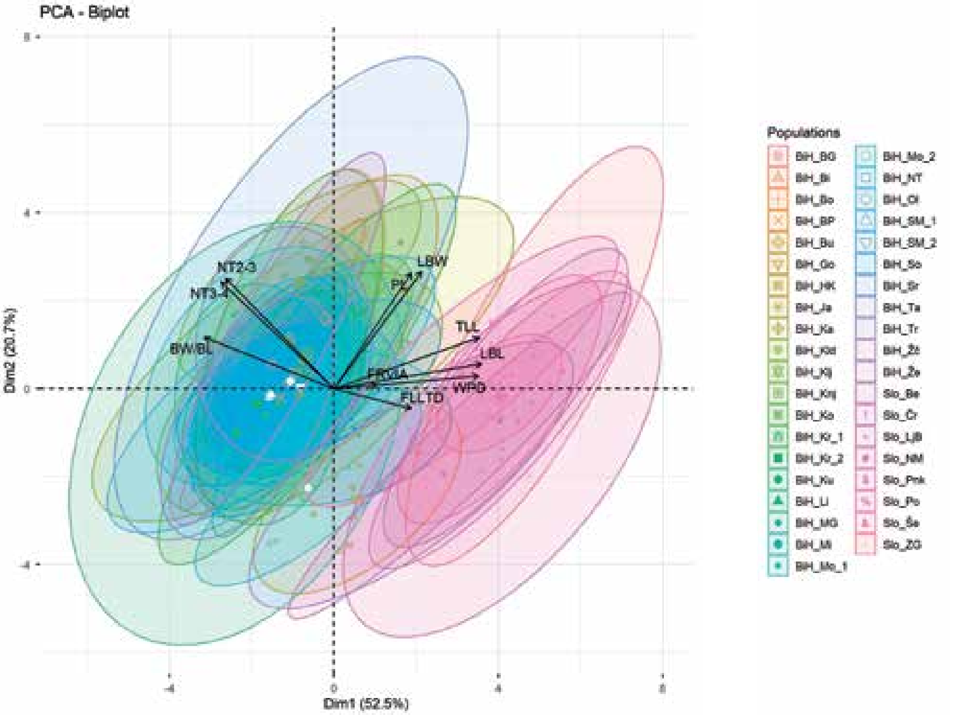

Figure 6: Biplot of the principal component analysis (PCA) based on tree mean values for 10 morphometric traits in 39 studied populations of Betula sp. in Bosnia and Herzegovina and Slovenia.

the number of teeth between the 2nd–3rd and 3rd–4th veins (NT2-3, NT3-4). In contrast, the distance from the petiole to the first left tooth (FLLTD) showed a lower loading on the main axes. The two-dimensional plot shows clear grouping of populations, with populations from Bosnia and Herzegovina overlapping among themselves, and populations from Slovenia forming a partially overlapping group. Populations previously identified as pubescent (*B. pubescens*) (BiH_MG, BiH_HK, BiH_Mo2, BiH_Mo1, and BiH_So) are located within the main Bosnian and Herzegovinian cluster, with BiH_MG, BiH_HK, and BiH_Mo2 positioned closer to the central part of this group, while BiH_Mo1 and BiH_So overlap with the remaining Bosnian and Herzegovinian populations.

The results of the cluster analysis of 39 birch populations from Bosnia and Herzegovina and Slovenia are shown in Figure 7.

Cluster analysis of 39 populations resulted in the formation of two clearly defined macro-clusters (Figure 7). The first macro-cluster includes all 8 populations from Slovenia and one population from Bosnia and Herzegovina (Žepče), while the second macro-cluster comprises the remaining 30 populations from Bosnia and Herzegovina. Populations previously identified as pubescent (*B. pubescens*), including Mrkonjić Grad (BiH_MG), Han Kram (BiH_HK), Mokro 2 (BiH_Mo2), Mokro 1 (BiH_Mo1), and Sokolac (BiH_So), are distributed within the Bosnian and Herzegovinian cluster, with BiH_MG, BiH_HK, and BiH_Mo2 forming a separate subcluster within this group.

Homogeneity of evaluated leaf trait distributions among populations (Pearson's χ^2 Test)

The homogeneity of distributions among populations for the evaluated leaf traits: shape, margin, pubescence, and texture was tested using Pearson's χ^2 test of homogeneity. The obtained χ^2 values were 994.35 (df = 38, $p <$

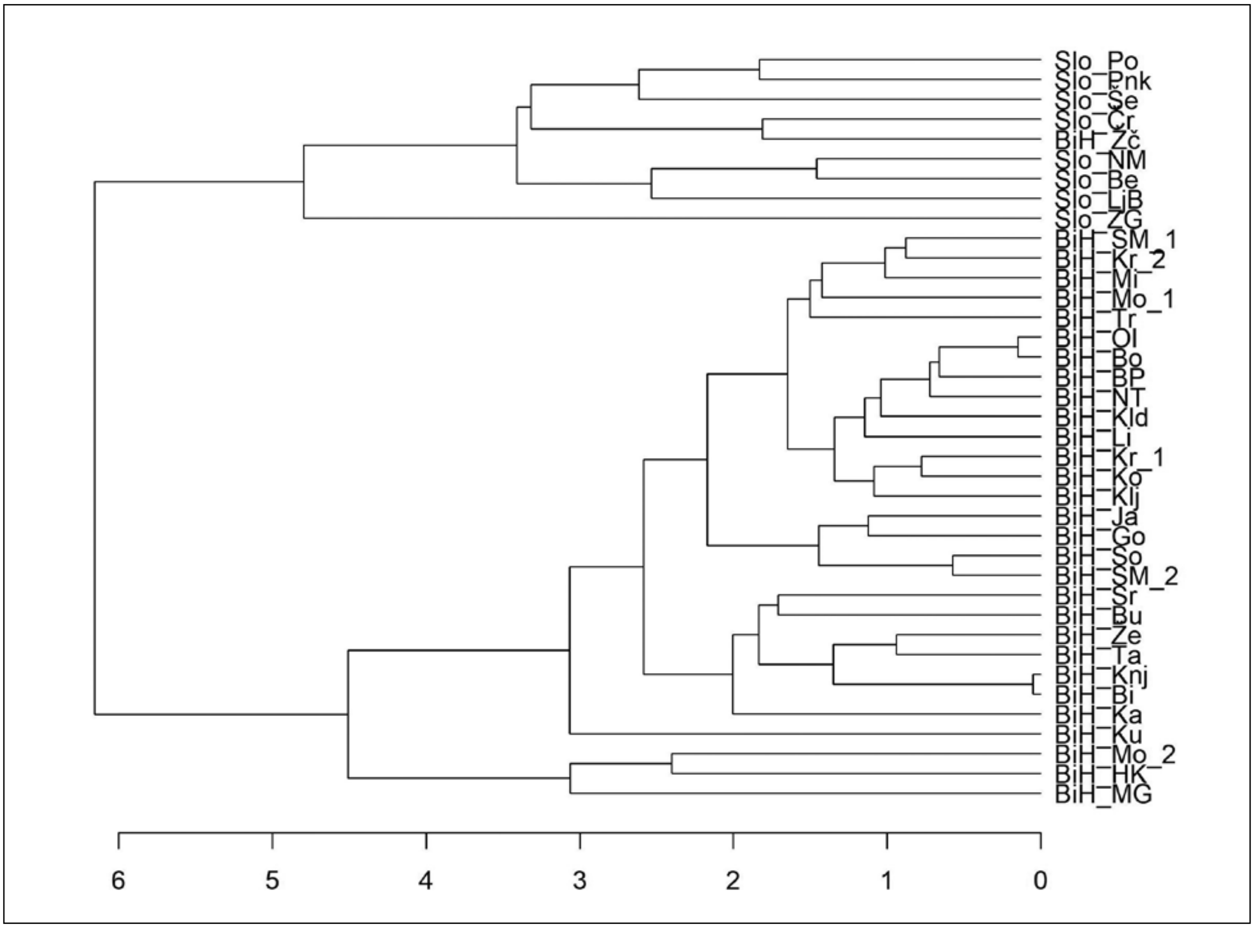

Figure 7. Dendrogram of Betula sp. populations in Bosnia and Herzegovina and Slovenia, constructed using the UPGMA method based on the analyzed morphological traits.

0.001) for leaf shape, 16,094.00 (df = 76, $p < 0.001$) for leaf margin, 4,552.70 (df = 38, $p < 0.001$) for leaf pubescence, and 994.35 (df = 114, $p < 0.001$) for leaf texture. All tests showed statistically significant differences in the distribution of categories among populations.

Percentage distribution of leaf shape traits among *Betula* sp. populations

The maximum percentage representation of the leaf shape trait LS1 was recorded in the population Srebrenik (Bosnia and Hercegovina) with 59.5%. Other populations from Bosnia and Herzegovina also showed a notable representation of LS1: Kakanj (45.3%), Mokro 2 (42.3%), and Mrkonjić Grad (38.8%), whereas the populations Goražde and Kladanj showed much lower values, 7.4% and 7.0%, respectively. Among Slovenian populations, Begunje showed 48.0% representation of LS1, while in some other Slovenian population (Ljubljansko Barje, Ponikva, and Pongrac) this category was not recorded (0.0%).

The highest percentage representation of the leaf shape LS2 was recorded in the Slovenian populations Ljubljansko Barje and Pongrac (100.0%), followed by Ponikva (98.6%). High values among populations from Bosnia and Herzegovina was observed in Kladanj (92.7%) and Sokolac (92.2%). The lowest percentage representation of LS2 was recorded in the Bosnian-Herzegovinian population Srebrenik (40.5%), followed by Slovenian population Begunje (40.9%). All the populations previously described as pubescent birch (Fukarek 1957, Stefanović 1961) had the highest percentage of LS2 (Han Kram 76.9%, Mokro 1 64.0%, Mokro 2 57.0%, Mrkonjić Grad 57.0%, and Sokolac 89.8%).

The highest percentage of leaf shape LS3 was also recorded in the Slovenian population Begunje (11.2%), while this category was absent (0.0%) in the populations Ljubljansko Barje, Pongrac, and Zgornje Gorje. Among the populations from Bosnia and Herzegovina, the highest percentage was recorded in Mrkonjić Grad (9.7%). The leaf shape LS3 was not recorded in the Bosnian and Herzegovinian populations Jajce, Kakanj, Kreševo 1, Sanski Most 1, Srebrenik, and Tarčin.

Percentage distribution of leaf margin traits among *Betula* sp. populations

The maximum representation of category LM1 (coarsely serrate) among the Slovenian populations was recorded in populations Ljubljansko Barje and Pongrac (100.0%), followed by Šenčur (90.0%), Zgornje Gorje (89.9%), Begunje (75.8%), and Novo Mesto (40.3%). Populations Črnomelj and Ponikva had no LM1. Among the populations from Bosnia and Herzegovina the highest value of LM1 was observed in Žepče (93.3%), while other populations had small percentage or no LM1.

For category LM2 (doubly serrate), the highest representation among the Slovenian populations was recorded in Črnomelj and Ponikva (100.0%), followed by Novo Mesto (59.7%), Begunje (24.2%), and Šenčur (10.0%). In Bosnia and Herzegovina, LM2 was recorded in Mrkonjić Grad (25.5%) and Han Kram (9.7%), while 32 populations showed values within the interval 0.0%–2.0%.

In category LM3 (irregularly serrate), high representation was observed in Bosnia and Herzegovina, where 28 populations showed values above 90.0%. Among Slovenian populations, LM3 was recorded only in Zgornje Gorje (10.1%), while the remaining seven populations showed no representation (0.0%). All the populations previously described as pubescent birch (Fukarek 1957, Stefanović 1961) had the highest percentage of LM3 (Han Kram 73.6%, Mokro 1 100.0%, Mokro 2 100.0%, Mrkonjić Grad 69.4%, and Sokolac 99.3%).

Leaf margin category LM4 (entire margin) was not recorded in any of the studied populations.

Percentage distribution of leaf pubescence on the abaxial side traits among *Betula* sp. populations

The results of the assessment of the leaf pubescence (LP) showed that the highest percentage of pubescent leaves was recorded in the populations Han Kram and Mokro 2 (100.0%), which were previously described as pubescent (Fukarek 1957; Stefanović 1961). Other populations previously identified as pubescent (Mokro 1, and Mrkonjić Grad, and Sokolac) showed lower percentage of leaves with pubescence (1.4%, 6.8%, and 26.5%, respectively). The populations Ključ and Sanski Most 2 exhibited 56.7% and 53.8% of leaves with pubescence, respectively. Among the Slovenian populations, pubescence was not observed.

Percentage distribution of leaf texture traits among *Betula* sp. populations

Among the Slovenian populations, high percentages of smooth leaves were recorded in the populations Novo Mesto (69.8%) and Zgornje Gorje (59.6%). Among the populations from Bosnia and Herzegovina, higher percentages of glabrous leaves were observed in the populations Jajce (70.3%) and Trnovo (45.3%).

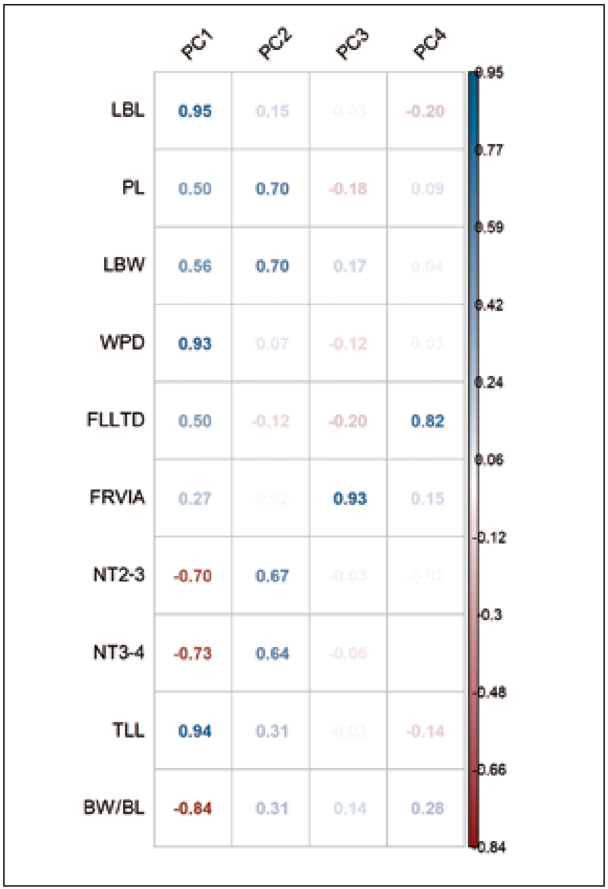

Figure 8. Contribution of morphological variables to the principal components.

Correlation between the investigated morphological traits and climatic factors

Figure 8 shows the contribution of the analyzed morphological variables to the principal components.

The morphological variability of the analyzed leaf traits at the population level was reduced to five principal components, which cumulatively explain 95.7% of the total variance. The first two components explain (73.2%) of the total variance. The first component is mainly associated with leaf dimensions (LBL, WPD, TLL, LBW, and PL). The second principal component (PC2) is associated with length–width and numerical traits (LBW, PL, NT2-3, and NT3-4). The third principal component is mainly associated with the angle of insertion of the first vein on the right side (FRVIA), while the fourth principal component is associated with the distance from the petiole to the first left tooth (FLLTD) (Figure 8).

Figure 9 illustrates the correlation relationships between the first four principal components of leaf morphological traits and bioclimatic variables. PC1 shows a strong positive correlation with temperature variables BIO1 (mean annual temperature) and BIO9 (mean temperature of the driest quarter) (r = 0.97). PC2 is associ-

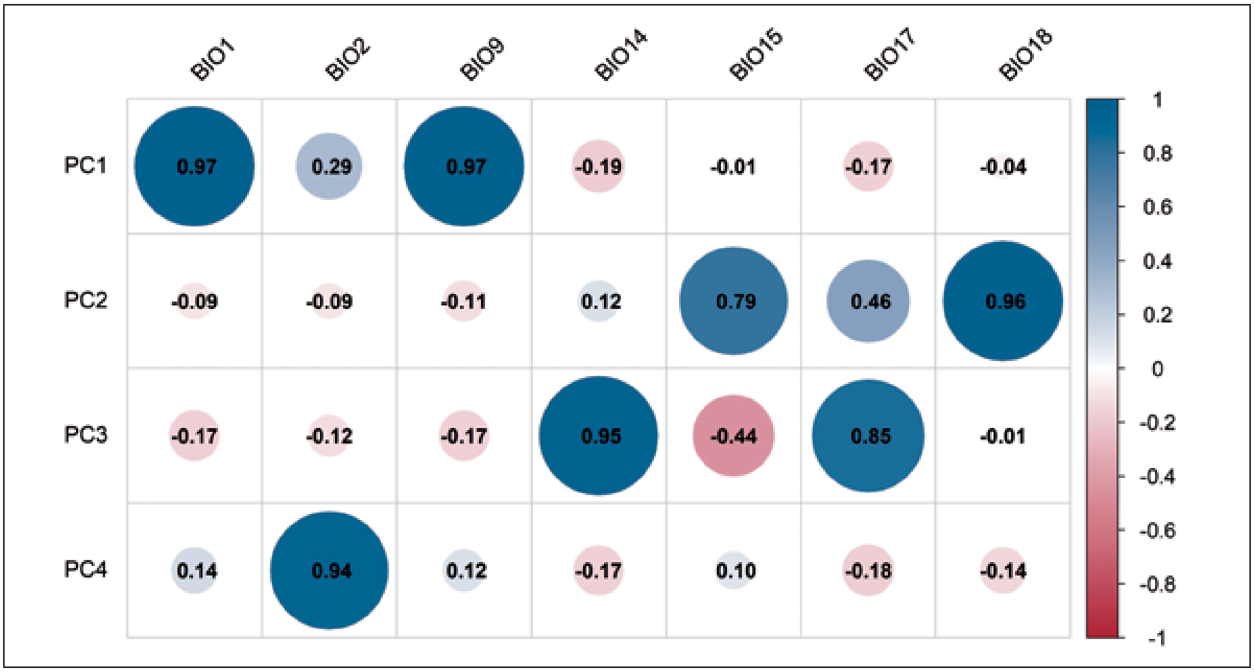

*Figure 9. Correlation analysis between climatic variables and principal components. Blue indicates a positive correlation, while red indicates a negative correlation. Larger circles and darker colors represent stronger correlations (*p < 0.05; ** p < 0.01; *** p < 0.001).*

ated with seasonality and precipitation variables, particularly BIO15 (precipitation seasonality) and BIO18 (precipitation of the warmest quarter). PC3 is associated with extreme precipitation variables (BIO14 and BIO17), while PC4 is correlated with diurnal temperature range (BIO2).

Regression analysis was conducted to assess the relationship between the first principal component (PC1), representing leaf dimensions, and the climatic variables that showed high intercorrelation. Linear regression identified mean annual temperature (BIO1) as the best single predictor of the temperature gradient. The model showed that BIO1 explains 94.0% of the total variability in PC1 ($R^2 = 0.94$; $p < 0.001$). The standardized regression coefficient ($\beta = 0.97$) indicates a strong positive linear relationship between mean annual temperature and leaf dimensions. An increase of one standard deviation in mean annual temperature corresponds to an increase of approximately 0.97 standard deviations in PC1. Due to high collinearity between BIO1 and BIO9 ($r = 0.996$), only BIO1 was retained in the interpretation to avoid multicollinearity between temperature variables. Both variables confirm that the variability in leaf dimensions is structured along a general temperature gradient.

DISCUSSION

Variation and differentiation of quantitative leaf traits

The present study highlights substantial phenotypic variability in leaf morphological traits of natural *Betula* sp. populations in Bosnia and Herzegovina and Slovenia, reflecting considerable heterogeneity consistent with patterns observed in other widespread woody species known for broad environmental tolerance and adaptive plasticity (Silfver et al. 2007; Cornelissen et al. 2011).

Certain leaf traits appear highly variable, likely responding to microenvironmental conditions or local selective pressures, a phenomenon also reported in temperate trees such as oaks and poplars, where leaf shape and tooth characters vary with moisture, temperature, and light regimes (Peppe et al. 2011; Memišević Hodžić et al. 2024; Ballian et al. 2018, Wang et al. 2022). Conversely, traits like leaf width and shape tend to be more conserved, likely constrained by functional demands associated with photosynthesis, water-use efficiency, and heat dissipation (Nicotra et al. 2011; Li et al. 2020). Our variance components analysis further indicates that the largest proportion of phenotypic variation occurs among populations, underscoring the importance of spatial structuring in leaf morphological traits across the landscape. This pattern suggests that populations occupy distinct phenotypic space, likely reflecting both local adaptation to environmental gradients and historical genetic structure. Similar among-population divergence has been observed in *Betula pendula* across Europe (Silfver et al. 2007) and in *Quercus petraea* and *Q. robur* in Bosnia and Herzegovina along climatic and altitudinal gradients (Memišević Hodžić et al. 2024; Ballian et al. 2018). In other forest tree species, including *Fagus sylvatica*, strong among-population variation in leaf traits has also been linked to adaptive differentiation along climatic gradients (Ballian et al. 2018; Kardošová et al. 2020). These observations collectively suggest that leaf morphological traits in long-lived deciduous trees reflect not only plastic responses but also inherited genetic variation structured by environmental heterogeneity.

Certain traits exhibiting high among-population variance, such as leaf size and tooth number likely carry strong adaptive signals. Leaf morphology influences key functional processes including light interception, transpiration, and thermoregulation (Nicotra et al. 2011). Larger leaves are often associated with warmer, wetter environments, while smaller leaves and increased tooth frequency tend to occur in cooler or drier climates, reflecting adaptation to local thermal and water-use demands (Peppe et al. 2011). Pronounced differentiation in these traits among *Betula* populations likely reflects divergent selection along climatic gradients in southeastern Europe.

In contrast, traits such as petiole length, leaf width, and vein insertion angle showed greater variation within populations, suggesting that these traits are more homogeneous across populations and are influenced primarily by microenvironmental conditions and developmental plasticity. Similar patterns have been reported in other tree species, where fine-scale variations in light, nutrients, and ontogeny drive within-population trait diversity (Valladares et al. 2002; Poorter et al. 2009). Lower population differentiation in these traits implies they may be less subject to large-scale divergent selection or buffered by local plastic responses. The population differentiation observed indicates moderate genetic structuring among the studied populations, consistent with other temperate tree species with wind-dispersed seeds and high gene flow, where moderate among-population divergence is common (Alberto et al. 2013; Kremer et al. 2012). Traits showing stronger differentiation may reflect adaptive divergence that overcomes gene flow, a pattern supported by studies combining common garden and landscape analyses (Savolainen et al. 2013).

Overall, the observed patterns of phenotypic variation and population differentiation in *Betula* leaf traits suggest the combined influence of environmental gradients, genetic differentiation, and phenotypic plasticity. Similar trends in *Quercus* and *Populus* species in the region indicate that leaf morphology often mirrors environmental heterogeneity, supporting the idea that adaptive differentiation in leaf traits is common among temperate broadleaf trees (Memišević Hodžić et al. 2024; Ballian et al. 2018). Future work integrating genetic markers with common garden experiments could help to disentangle the contributions of genotype and environment and identify climatic drivers of adaptive variation.

Variation in qualitative leaf morphological traits

Pearson's χ^2 test revealed significant heterogeneity in qualitative leaf traits among the studied populations, including leaf shape, margin, pubescence, and texture, indicating systematic differences rather than random variation. Such patterns likely reflect the combined effects of genetic variation, environmental influences, and phenotypic plasticity, consistent with observations in other widespread forest tree species (Nicotra et al. 2011; Cornelissen et al. 2011). Pronounced differences in traits like leaf shape and margin suggest that birch populations in the studied region occupy distinct ecological niches, with leaf morphology corresponding to environmental drivers such as temperature, water availability, and light to optimize energy balance, transpiration, and photosynthetic efficiency (Wright et al. 2017; Peppe et al. 2011).

Leaf shape varied considerably among populations from both Bosnia and Herzegovina and Slovenia. Such variation aligns with previous studies showing that birch leaf form responds to environmental gradients, particularly temperature and moisture, which affect energy balance and water relations (Nicotra et al. 2011). Populations previously identified as *B. pubescens* were dominated by the LS2 leaf shape category. Although *B. pendula* leaves are generally more triangular and *B. pubescens* leaves more ovate, the observed overlap and the occurrence of 100% LS2 in the Slovenian populations Ljubljansko Barje and Pongrac indicate that leaf shape alone is not sufficient for reliable species discrimination. This supports the use of leaf shape as one of diagnostic traits, alongside other leaf characteristics and suggests that the dominance of specific shapes may reflect local adaptation or phenotypic plasticity.

Leaf margin categories showed clear geographic structuring, with LM3 dominant in most populations from Bosnia and Herzegovina, and LM1-LM2 prevailing in Slovenian populations. All populations previously identified as *B. pubescens* were consistently dominated by LM3. *B. pendula* typically has coarser serration, whereas *B. pubescens* exhibits finer, less sharp teeth (Atkinson, 1992), supporting its use as a diagnostic trait alongside leaf shape and pubescence (Fukarek 1957; Stefanović 1961). However, our results only partially conform to the expected species-level pattern, as LM1–LM2 and LM3 categories showed overlap among populations and between species groups. This indicates that leaf margin morphology does not form discrete species-specific categories, but instead exhibits continuous variation influenced by both species identity and environmental conditions.

Leaf pubescence on the abaxial surface was most pronounced in the Han Kram and Mokro 2 populations, confirming their identification as *B. pubescens*, consistent with taxonomic descriptions where pubescence distinguishes it from the generally glabrous *B. pendula* (Atkinson 1992). In *B. pubescens*, long shoots are hairy with glandular hairs and lack lenticels, whereas in *B. pendula*, shoots are smooth with lenticels (Atkinson 1992). Other populations showed only minor pubescence, highlighting the trait's diagnostic value for species differentiation, especially in regions of overlapping distributions. Pubescence was absent in all Slovenian populations, suggesting they are predominantly *B. pendula*. However, reliable species identification should be based on a combination of morphological characters rather than a single trait, due to possible overlap and phenotypic plasticity. Given the potential for hybridization in Europe, genetic analyses would help clarify species identity and possible introgression (Atkinson, 1992).

Leaf texture varied among populations, with smooth leaves recorded in certain populations from both countries. Surface characteristics can influence water retention, herbivory, and pathogen resistance, reflecting ecological strategies for balancing hydration and defense (Valladares et al. 2007).

Although geographic structuring was less pronounced for leaf texture than for other qualitative traits, these differences highlight overall morphological heterogeneity among populations.

Overall, the observed variation in qualitative leaf traits highlights substantial phenotypic diversity within natural Betula populations across Bosnia and Herzegovina and Slovenia. Similar patterns have been reported in other temperate tree species, where traits such as leaf shape, margin morphology, and pubescence respond to environmental gradients while also retaining signals of genetic differentiation (Nicotra et al. 2011; Peppe et al. 2011). Although several qualitative traits were useful for distinguishing groups of populations, particularly those previously identified as B. pubescens, considerable overlap among categories indicates that no single trait can reliably separate species. Instead, species identification and population differentiation are best interpreted using multiple morphological characters in combination with ecological and genetic information. The consistent differentiation of several populations previously identified as B. pubescens nevertheless demonstrates that qualitative leaf traits retain considerable taxonomic value when evaluated collectively.

A limitation of the present study is that species identification was evaluated primarily using leaf morphological characters. Although several diagnostic traits commonly used to distinguish Betula pendula and B. pubescens were assessed, not all taxonomically informative characters were systematically recorded during field sampling. In particular, bark characteristics, branching architecture, reproductive structures, and cytological traits were not examined. Consequently, species assignments should be interpreted with caution, especially for populations exhibiting intermediate morphological characteristics. Future studies integrating a broader set of diagnostic traits together with genetic analyses would provide more robust species identification and help clarify the extent of potential hybridization or introgression among populations.

Trait correlations and functional integration of leaf morphology

Correlation analysis revealed strong positive relationships among leaf size traits, such as leaf blade length and total leaf length, and among tooth numbers, reflecting coordinated growth and shared developmental pathways. Similar patterns in *B. pendula* and other broadleaved trees indicate functional integration of leaf morphology, which supports light interception and hydraulic balance (Nicotra et al. 2011; Peppe et al. 2011; Cornelissen et al. 2011). Moderate correlations among leaf length, width, and position of the widest part of the blade further suggest an integrated morphological syndrome influencing photosynthetic surface, transpiration, and thermal regulation, consistent with adaptations to temperature, moisture, and light conditions (Nicotra et al. 2011; Wright et al. 2017). In contrast, the insertion angle of the first vein showed weak correlations with other traits, implying partial independence and regulation by biomechanical or hydraulic constraints rather than overall leaf allometry (Sack and Scoffoni 2013).

Multivariate patterns of leaf trait variation and population differentiation

Principal component analysis confirmed that most morphological variability among sampled trees can be explained by two major axes of variation. The first axis is associated with overall leaf size, reflecting its dominant role in individual differentiation and its ecological responsiveness in woody plants (Nicotra et al. 2011; Wright et al. 2017). The second axis corresponds to leaf tooth frequency, an independent trait often linked to climate, where populations in cooler regions exhibit more pronounced or numerous teeth, enhancing early-season photosynthesis and hydraulic efficiency (Peppe et al. 2011). PCA also revealed regional structuring: populations from Bosnia and Herzegovina and Slovenia tended to cluster within their respective regions, reflecting environmental similarities and geographic proximity, while overlap within regions indicates substantial local variation and gene flow, as commonly observed in wind-pollinated, wind-dispersed species (Kremer et al. 2012; Alberto et al. 2013).

Cluster analysis further supported regional differentiation among populations, forming two major groups that broadly separated Slovenian from Bosnian-Herzegovinian populations, suggesting that geographic distance and environmental variation shape leaf morphology. Similar patterns have been reported in other European forest trees, where climatic gradients, historical migration, and limited long-distance gene flow drive population differentiation (Kremer et al. 2012; Savolainen et al. 2013). An exception was the Žepče population, which clustered with Slovenian populations, potentially reflecting historical connectivity, similar environmental conditions, or retained ancestral variation. In addition, cluster analysis showed clear differentiation of the Mrkonjić Grad, Han Kram, and Mokro 2 populations, consistent with their identification as B. pubescens (Fukarek 1957; Stefanović 1961). This pattern was less evident in the PCA, likely because PCA summarizes overall variation along a limited number of principal components, whereas cluster analysis is based on pairwise similarities among samples and can reveal groupings that are not strongly represented on the major axes of variation. Because this study relies on morphological data alone, integrating genetic markers in future work would help clarify whether this pattern reflects shared ancestry, recent gene flow, or convergent adaptation.

For three populations from Bosnia and Herzegovina (Mrkonjić Grad, Han Kram, and Mokro 2) cluster analysis showed clear differentiation in leaf traits, consistent with their identification as *B. pubescens* (Fukarek 1957; Stefanović 1961). In contrast, two other populations previously described as pubescent birch (Mokro 1 and Sokolac) (Fukarek 1957, Stefanović 1961) clustered with *Betula pendula*, possibly reflecting intraspecific variation, phenotypic plasticity, or potential misidentification in earlier studies, highlighting the need for complementary genetic or cytological analyses to confirm species identity. Morphological differences between *B. pendula* and *B. pubescens*, including leaf shape, venation, and pubescence, are well documented (Atkinson 1992), and the distinct clustering of three populations supports the reliability of leaf traits for species-level differentiation.

Climatic drivers of morphological differentiation

Our results showed strong influence of temperature on leaf morphology across the studied populations, with larger leaves in warmer environments, consistent with reports indicating that temperature is a dominant driver shaping leaf traits (Nicotra et al. 2011; Wright et al. 2017). Precipitation and seasonal moisture were significantly correlated to leaf shape and tooth number of studied populations, reflecting plant water balance and growth dynamics (Peppe et al., 2011). Certain traits, such as venation angles and tooth positioning, appear sensitive to climatic extremes and short-term fluctuations. Our results suggest that while climate is a major factor, historical and genetic effects also contribute, particularly in populations with unusual trait combinations or high divergence from nearby populations. Compared with *B. pendula* populations in Croatia, where environmental correlations with leaf morphology were weak and morphology was mainly influenced by historical or genetic factors (Kovačić & Nikolić, 2005), our study, by including *B. pubescens,* indicates that species identity, reflected in traits, such as leaf pubescence, LS2 shape, LM3 margin is an important source of leaf morphological variation alongside environmental conditions.

Implications for adaptation and forest genetic resources

Overall, the strong correlations between morphological traits and climatic variables indicate that leaf morphology in the studied *Betula* populations is structured along environmental gradients. Such patterns are commonly interpreted as evidence of local adaptation or environmentally induced phenotypic plasticity. In long-lived forest tree species with extensive gene flow, both processes often operate simultaneously to shape population-level trait variation (Kremer et al. 2012; Savolainen et al. 2013).

The pronounced differentiation observed among populations from Bosnia and Herzegovina and Slovenia therefore likely reflects the combined influence of regional climate variation, geographic distance, and historical population dynamics. Understanding these patterns is important for forest management and conservation, particularly in the context of ongoing climate change. Morphological traits associated with climatic adaptation may help identify populations with specific adaptive potential that could be valuable for future reforestation and restoration programs.

CONCLUSIONS

This study revealed substantial morphological variability in leaf traits among natural populations of *B. pendula* and *B. pubescens* from Bosnia and Herzegovina and Slovenia. Both quantitative and qualitative traits showed significant differences among populations, indicating pronounced phenotypic differentiation across the studied region.

Multivariate analyses demonstrated that leaf size parameters represent the main axis of morphological variation, while traits related to leaf teeth form a secondary component of differentiation. Qualitative traits such as leaf shape, margin, pubescence, and texture also varied significantly among populations. In particular, the presence of leaf pubescence was confirmed in two populations (Han Kram and Mokro 2), supporting their identification as *B. pubescens*.

The analyses further indicated regional structuring of populations and a strong relationship between leaf morphology and climatic variables. Leaf dimensions were strongly associated with temperature gradients, suggesting that climatic factors play an important role in shaping morphological differentiation.

Overall, the results highlight the importance of environmental gradients and potential genetic differentiation in structuring leaf morphological variation in birch populations and provide useful baseline information for future ecological, genetic, and forest management studies in south-eastern Europe.

VSEBINA

Navadna in puhasta breza (*Betula pendula* Roth in *Betula pubescens* Ehrh.) sta ekološko in ekonomsko pomembni gradnici zmernih in borealnih gozdnih ekosistemov po vsej Evropi. Za njiju sta značilni široka ekološka amplituda in velika morfološka variabilnost, kar jima omogoča, da zasedata raznolike habitate in se odzivata na okoljske gradiente. Zlasti morfologija listov odraža tako genetsko diferenciacijo kot fenotipsko plastičnost in zato omogoča dragocen vpogled v prilagoditvene procese v naravnih populacijah. Kljub široki razširjenosti obeh vrst brez so podrobne študije morfološke variabilnosti v JV Evropi še vedno relativno omejene. Cilj te študije je bil raziskati morfološko variabilnost listov v naravnih populacijah obeh vrst brez v Bosni in Hercegovini (BiH) ter Sloveniji (SI) ter oceniti povezave med morfološkimi lastnostmi in okoljskimi dejavniki.

V obdobju 2020–2022 smo zbrali vzorce listov iz 39 populacij, od tega 31 populacij v BiH ter 8 populacij v SI. V vsaki populaciji smo vzorčili deset odraslih dreves, z vsakega drevesa pa smo zbrali 30 listov s kratkih poganjkov v delih krošnje, izpostavljenih soncu. Skupno smo analizirali 11.700 listov. Geografske koordinate in nadmorske višine vseh lokacij vzorčenja smo zabeležili z GPS-om. Podnebne podatke smo pridobili iz baze podatkov WorldClim, vključevali pa so več bioklimatskih spremenljivk, ki opisujejo temperaturne in padavinske režime.

Morfometrične analize smo izvedli na posušenih vzorcih listov. Izmerili, ocenili, prešteli in izpeljali smo več fenotipskih lastnosti, da bi opredelili velikost, obliko listov, značilnosti žilnatosti in strukturo zobcev. Za vse lastnosti smo izračunali opisno statistiko, vključno s povprečnimi vrednostmi, standardnimi odkloni in koeficienti variabilnosti. Za oceno komponent variance in oceno porazdelitve fenotipske variabilnosti znotraj populacij in med njimi smo uporabili gnezdeno analizo variance. Izračunali smo tudi koeficiene diferenciacije populacij (Vst). Razmerja med lastnostmi smo ovrednotili s Pearsonovo korelacijsko analizo. Za identifikacijo glavnih osi morfološke variabilnosti smo uporabili analizo glavnih komponent (PCA), za raziskovanje strukture in združevanja populacij pa analizo grozdov na podlagi evklidskih razdalj (metoda UPGMA). Homogenost kategoričnih lastnosti listov med populacijami smo preizkusili s Pearsonovim χ^2 testom. Nazadnje smo preučili korelacije med morfološkimi lastnostmi in podnebnimi spremenljivkami, da bi ugotovili potencialne okoljske dejavnike fenotipske variabilnosti.

Rezultati so pokazali znatno morfološko variabilnost med preučevanimi populacijami. Koeficienti variabilnosti so se za večino lastnosti listov gibali od zmernih do visokih, kar kaže na izrazito fenotipsko raznolikost znotraj preiskovane regije. Analiza komponent variabilnosti je pokazala, da je bil znaten delež celotne variabilnosti porazdeljen med populacijami, kar kaže na prostorsko strukturiranje morfoloških lastnosti po celotnem preučevanem območju. Močne korelacije smo opazili med več parametri velikosti listov, zlasti med dolžino listne ploskve in skupno dolžino lista, pa tudi med lastnostmi, povezanimi s številom listnih zobcev.

Analiza glavnih komponent je pokazala, da prvi dve glavni komponenti pojasnjujeta več kot 70 % celotne morfološke variabilnosti. Prva glavna komponenta je bila povezana predvsem s parametri velikosti listov, kot so dolžina listne ploskve, širina listne ploskve, dolžina peclja in skupna dolžina listov, kar predstavlja prevladujočo morfometrično dimenzijo variabilnosti. Druga glavna komponenta je bila povezana predvsem z numeričnimi značilnostmi listnih zobcev. Ti rezultati kažejo, da velikost listov in značilnosti zobcev predstavljata dve ključni osi morfološke diferenciacije med preučevanimi populacijami.

Analiza grozdov je pokazala jasno združevanje populacij glede na geografsko poreklo. Večina populacij iz BiH je tvorila grozd, ločen od slovenskih populacij, kar kaže na regionalno diferenciacijo, na katero so verjetno vplivale okoljske razmere, geografska oddaljenost in zgodovinski populacijski procesi. Izjema je bila populacija iz Žepč (BiH), ki se je združila s slovenskimi populacijami, kar verjetno odraža podobne ekološke razmere ali zgodovinsko povezavo med populacijami.

Pomembna heterogenost je bila opažena tudi v porazdelitvi kvalitativnih listnih lastnosti, vključno z obliko listov, vrsto roba, dlakavostjo in teksturo. Rezultati Pearsonovega χ^2 testa so potrdili statistično značilne razlike med populacijami za vse ocenjene kategorije / lastnosti. Posebej pomembna je bila prisotnost listne dlakavosti v populacijah Han Kram in Mokro 2, kjer so bili vsi analizirani listi dlakavi. Ti populaciji sta bili prej opisani kot puhasta breza (*B. pubescens*), sedanji rezultati pa potrjujejo diagnostično vrednost listne dlakavosti kot razlikovalne lastnosti med puhasto brezo in pretežno neodlakano navadno brezo. V slovenskih populacijah dlakavosti nismo opazili, kar kaže na to, da vzorčeni sestoji v Sloveniji sestojijo predvsem iz vrste *B. pendula*.

Analiza povezav med morfološkimi značilnostmi in podnebnimi spremenljivkami je pokazala močan vpliv okoljskih dejavnikov na morfologijo listov. Dimenzije listov so bile močno povezane s temperaturnimi spremenljivkami, zlasti s povprečno letno temperaturo, kar je pojasnilo velik delež variabilnosti v glavni komponenti, ki predstavlja velikost listov. Populacije iz območij s toplejšim podnebjem so imele običajno večje liste, kar je skladno objavljenimi globalnimi vzorci, ki povezujejo velikost listov s podnebnimi razmerami. Dodatne povezave med morfološkimi značilnostmi in spremenljivkami, povezanimi s padavinami, nadalje kažejo, da lahko razpoložljivost vlage in sezonska spremenljivost podnebja vplivata na nekatere vidike strukture listov.

Rezultati na splošno kažejo na izrazito morfološko raznolikost med naravnimi populacijami brez (dveh vrst iz rodu *Betula*) v Bosni in Hercegovini ter Sloveniji. Opazovana variabilnost najverjetneje odraža kombiniran vpliv okoljskih gradientov, fenotipske plastičnosti in potencialne genetske diferenciacije med populacijami. Te ugotovitve prispevajo k boljšemu razumevanju znotrajvrstne variabilnosti pri obeh vrstah brez in zagotavljajo dragocene izhodiščne informacije za prihodnje študije, ki bodo vključevale morfološke, ekološke in genetske pristope. S praktičnega vidika dokumentirana variabilnost poudarja pomen ohranjanja regionalne populacijske raznolikosti kot potencialnega vira prilagodljivosti. Takšne informacije so še posebej pomembne za upravljanje gozdnih genskih virov, načrtovanje ohranjanja in izbiro primernega reprodukcijskega materiala za pogozdovanje in obnovo v spreminjajočih se podnebnih razmerah v jugovzhodni Evropi.

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NAVODILA AVTORJEM

Folia biologica et geologica so znanstvena revija IV. razreda SAZU za naravoslovne vede. Objavljajo naravoslovne znanstvene razprave in pregledne članke, ki se nanašajo predvsem na raziskave v etničnem območju Slovenije, pa tudi raziskave na območju Evrope in širše, ki so pomembne, potrebne ali primerljive za naša preučevanja.

1. ZNANSTVENA RAZPRAVA

Znanstvena razprava zajema celovit opis izvirne raziskave, ki vključuje teoretični pregled tematike, podrobno predstavlja rezultate z razpravo in zaključki ali sklepi in pregled citiranih avtorjev. V izjemnih primerih so namesto literaturnega pregleda dovoljeni drugi viri, če to zahteva vsebina razprave.

Razprava naj ima klasično razčlenitev (uvod, material in metode, rezultati, diskusija z zaključki, zahvale, literatura idr.).

Dolžina razprave, vključno s tabelami, grafikoni, slikami ipd., ne sme presegati 3 avtorskih pol oziroma 45 strani tipkopisa. Zaželene so razprave v obsegu ene avtorske pole oziroma do dvajset strani tipkopisa.

Razpravo ocenjujeta vsaj dva recenzenta.

Razprava gre v tisk, ko jo na predlog urednika sprejme uredniški odbor

2. PREGLEDNI ČLANEK

Pregledni članek objavljamo po posvetu urednika z avtorjem. Na predlog urednika ga sprejme uredniški odbor. Članek naj praviloma obsega največ 3 avtorske pole oziroma do 45 tipkanih strani.

3. NOVOSTI

Revija objavlja krajše znanstveno zanimive in aktualne prispevke do 7000 znakov.

4. IZVIRNOST PRISPEVKA

Razprava oziroma članek, objavljen v reviji *Folia biologica et geologica*, ne sme biti predhodno objavljen v drugih revijah ali knjigah.

5. JEZIK

Razprava ali članek sta lahko pisana v slovenščini ali angleščini.

Prevod iz svetovnih jezikov in jezikovno lektoriranje oskrbi avtor prispevka, če ni v uredniškem odboru dogovorjeno drugače.

6. POVZETEK

Za razprave ali članke, pisane v slovenščini, mora biti povzetek v angleščini, za razprave ali članke v tujem jeziku pa ustrezen slovenski povzetek. Povzetek mora biti dovolj obširen, da je tematika jasno prikazana in razumljiva domačemu in tujemu bralcu. Dati mora informacijo o namenu, metodi, rezultatu in zaključkih. Okvirno naj povzetek ne obsega več kot 10 do 20 % obsega razprave oziroma članka.

7. IZVLEČEK

Izvleček (praviloma dolg do 300 besed) mora podati jedrnato informacijo o namenu in zaključkih razprave ali članka. Napisan mora biti v slovenskem in angleškem jeziku.

8. KLJUČNE BESEDE

Število ključnih besed naj ne presega 10 besed. Predstaviti morajo področje raziskave, podane v razpravi ali članku. Napisane morajo biti v slovenskem in angleškem jeziku.

9. NASLOV RAZPRAVE ALI ČLANKA

Naslov razprave ali članka naj bo kratek in razumljiv. Za naslovom sledi ime/imena avtorja/avtorjev (ime in priimek).

10. NASLOV AVTORJA/AVTORJEV

Pod ključnimi besedami spodaj je naslov avtorja/avtorjev, in sicer akademski naslov (če obstaja, t.j. dr., ali mag.), ime, priimek, ustanova, mesto z oznako države in poštno številko, država, in elektronski poštni naslov.

11. UVOD

Uvod se mora nanašati le na vsebino razprave ali članka. Vsebovati mora cilje prispevka oziroma raziskave.

12. ZAKLJUČKI ALI SKLEPI

Zaključki ali sklepi morajo vsebovati sintezo glavnih ugotovitev glede na zastavljena vprašanja in razrešujejo ali nakazujejo problem raziskave.

13. ZAHVALE

Priporočeno je v zahvali navesti vse pomočnike in financerje avtorjev in raziskave.

14. TABELE, TABLE, GRAFIKONI, SLIKE IPD.

Tabele, table, grafikoni, slike ipd. v razpravi ali članku naj bodo jasne, njihovo predlagano mesto mora biti nedvoumno označeno, njihovo število naj racionalno ustreza vsebini.

Spremno besedilo, podnapisi, napisi, naslov in legenda naj bodo napisani v slovenskem in angleškem jeziku.

Slike, ilustracije, grafikoni, tabele ipd. **v bitnem zapisu** naj v imenu datoteke vsebujejo naslov ali avtorja članka in zaporedno številko v članku (npr. I Kreft_Figure 01). Priložene naj bodo tudi kot samostojne datoteke. V imenih datotek ne uporabljajte prepovedanih znakov kot so .,/. Za ločevanje besed v imenu datoteke poleg presledkov uporabljajte znaka - ali _. Oddane naj bodo v *.JPG zapisu z minimalno kompresijo (maximum ali high - visoka kakovost). Ločljivost bitnih datotek naj bo **300 DPI/inch pri 1:1** želeni velikosti uporabe v publikaciji (širina obeh stolpcev v publikaciji je 165 mm, enega stolpca pa 79 mm). Če publikacija izide samo v digitalni obliki, je zadostna velikost bitnih datotek **72 DPI/inch pri 1:1** želeni velikosti uporabe v publikaciji. Barvnega okolja **RGB** na spreminjajte v **CMYK** barvno okolje, to bodo storili izvajalci.

Grafikoni, risbe, ilustracije ipd. **v vektorskem zapisu** naj bodo oddani v ***.EPS**, ***.SVG**, ***.PDF** ali ***.AI** formatu. Ločljivost pri vektorskem zapisu ni pomembna, saj je tako datoteko mogoče povečevati do neskončnosti brez izgube kvalitete.

Pri fitocenoloških tabelah se tam, kjer se posamezna rastlinska vrsta, sicer vpisana v tabelo, ne pojavlja, natisne pika.

15. LITERATURA IN VIRI

Uporabljeno literaturo citiramo med besedilom. Citirane avtorje pišemo v velikih tiskanih črkah (kapitelkah). Enega avtorja pišemo » (Priimek leto)« ali »(Priimek leto: strani)« ali »Priimek leto« [npr. (Bukry 1974) ali (Oberdorfer 1979: 218) ali ... Poldini (1991) ...]. Če citiramo več del istega avtorja, objavljenih v istem letu, posamezno delo označimo po abecednem redu »Priimek leto mala črka« [npr. ...Horvatić (1963 a)... ali (Horvatić 1963 b)]. Avtorjem z enakim priimkom dodamo pred priimkom prvo črko imena (npr. R Tuxen ali J Tuxen). Več avtorjev istega dela citiramo po naslednjih načelih: delo do treh avtorjev »Priimek, Priimek & Priimek leto: strani« [npr. (Shearer, Papike & Simon 1984) ali Pearce & Cann (1973: 290-300)...]. Če so več kot trije avtorji, citiramo »Priimek prvega avtorja *et al.* leto: strani« ali »Priimek prvega avtorja s sodelavci leto« [npr. Noll *et al.* 1996: 590 ali ...Meusel s sodelavci (1965)].

Literaturo uredimo po abecednem redu. Imena avtorjev pišemo v velikih tiskanih črkah:

– Razprava ali članek:

Dakskobler L 1997: *Geografske variante asociacije Seslerio autumnalis-Fagetum (Ht.) M. Wraber ex Borhidi 1963.* Razprave IV razreda SAZU (Ljubljana) 38 (8): 165–255.

Le Loeuff J, Buffeaut E, Martin M & H Tong 1993: *Decouverte d'Hadrosauridae (Dinosauria, Ornithischia) dans le Maastrichtien des Corbieres (Aude, France).* C. R. Acad. Sci. Paris, t. 316, Ser. II: 1023–1029.

Unuk T & T Grebenc 2017: Silver fir (*Abies alba* Mill.) ectomycorrhiza across its areal – a review approach / Ektomikorizni simbionti bele jelke (*Abies alba* Mill.) na naravnem območju razširjenosti – pregled. Folia Biol Geol 58: https://doi.org/10.3986/fbg0025

– Knjiga:

Gortani L & M Gortani 1905: *Flora Friuliana.* Udine.

Če sta različna kraja založbe in tiskarne, se navaja kraj založbe.

– Elaborat ali poročilo:

Prus T 1999: *Tla severne Istre.* Biotehniška fakulteta. Univerza v Ljubljani. Center za pedologijo in varstvo okolja. Oddelek za agronomijo. Ljubljana. (Elaborat, 10 str.).

– Atlasi, karte, načrti ipd.:

KLIMATOGRAFIJA Slovenije 1988: Prvi zvezek: *Temperatura zraka 1951–1980.* Hidrometeorološki zavod SR Slovenije. Ljubljana.

LETNO poročilo meteorološke službe za leto 1957. Hidrometeorološki zavod SR Slovenije. Ljubljana.

Za vire veljajo enaka pravila kot za literaturo. Pri elektronskih virih se vpiše datum dostopa.

Pri vseh navedbah literature dodamo doi oznako, če v originalu obstaja in sicer v obliki: https://doi... In ne v obliki DOI....

16. ZNANSTVENA (LATINSKA) IMENA TAKSONOV

Znanstvena (latinska) imena rodov, vrst in infraspecifičnih taksonov se pišejo v kurzivi. V fitocenoloških razpravah ali člankih se vsi sintaksoni pišejo v kurzivi.

17. FORMAT IN OBLIKA RAZPRAVE ALI ČLANKA

Članek naj bo oddan v formatu ***.docx**, ***.doc**, ***.rtf**, ***.txt**, ali ***.odt** z medvrstičnim razmikom 1,15 na A4 (ISO 216) formatu. Uredniku je treba oddati izvirnik članka. Za boljšo informacijo izvajalcem lahko priložite še *.PDF datoteko članka z umeščenimi slikami, grafi, tabelami, risbami ipd. na želena mesta v članku, ki jih bomo upoštevali, kolikor je mogoče. Tabele in slike v bitnem zapisu naj bodo posebej priložene besedilu. Materiale do skupne velikosti 20 MB posredujte uredniku na njegov elektronski naslov. Pred pošiljanjem lahko datoteke stisnete z brezplačnim programom ZIP, ki je del operacijskega sistema Windows. Če materiali kljub vsemu presegajo skupno velikost 20 MB, jih lahko pošljete preko katere od brezplačnih spletnih aplikacij (npr. WeTransfer).

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Folia biologica et geologica is a scientific periodical of the Class IV: Natural sciences that publishes original scientific results and review articles referring mainly to life and earth sciences studies in the Slovenian ethnic region, as well as in Europe and worldwide, which are of importance or necessary for comparison to our researches.

1. ORIGINAL SCIENTIFIC PAPER

It is the entire description of novel research including the theoretical review of the subject, presenting in detail the results, conclusions, and the survey of literature of the authors cited. In exceptional cases the survey of literature may be replaced by sources, if the purport requires it.

It should be composed in classic manner: introduction, material and methods, results, discussion with conclusions, acknowledgments, literature, etc.

The original scientific paper should not be longer than 45 pages, including tables, graphs, figures and others. The preferred length of the manuscript is 20 pages.

The submitted texts are reviewed by two reviewers.

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On consultation of the author with the editor in chief, the review article can be accepted for publication by the editorial board. Preferably, it should not be longer than 45 pages.

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It should give concise information about the aims and conclusions of the article, preferably in up to 300 words. It must be written in English and Slovenian.

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The number of key words should not exceed 10 words. They must present the topic of the research in the article and written in English and Slovenian languages.

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The address of author/authors should be at the bottom of the page: academic title, name, surname, institution, town and state mark, post number, state, and e-mail of the author/authors.

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Its contents should refer to the purports of the article only. It should include the aims of the study presented.

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Conclusions ought to include the synthesis of the aims resolved or indicate the problems of the research.

13. ACKNOWLEDGEMENTS

It is recommended to list all assistants and funders of the authors and research in the acknowledgements.

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In phytocenological tables, a dot is printed where an individual plant species, otherwise entered in the table, does not appear.

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The literature used is to be cited within the text. The citation of the authors is to be marked in capitals. One writes the single author as follows: "(Surname year)" or "(Surname year: pages)" or "Surname year" [(Bukry 1974) or (Oberdorfer 1979: 218) or ... Poldini (1991)...]. The works of the same author are to be cited in alphabetical order: "Surname year small letter" [... Horvatić (1963 a)... or (Horvatić (1963 b)]. The first letter of the author's name is to be added when the surname of several authors is the same (R. Tuxen or J. Tuxen). When there are two or three authors, the citation is to be as follows: "Surname, Surname & Surname year: pages" [(Shearer, Papike & Simon 1984) or Pearce & Cann (1973: 290-300)...]. When there are more than three authors, the citation is to be as follows: "Surname of the first one et al. year: pages" or "Surname of the first one with collaborators year" [Noll *et al.* 1996: 590 or Meusel with collaborators (1965)].

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Le Loeuff J, Buffeaut E, Martin M & H Tong 1993: *Déecouverte d'Hadrosauridae (Dinosauria, Ornithischia) dans le Maastrichtien des Corbieres (Aude, France).* C. R. Acad. Sci. Paris, t. 316, Ser. II: 1023-1029.

– **Book:**

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– **Elaborate or report:**

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– **Atlases, maps, plans, etc.:**

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LETN0 poročilo meteorološke službe za leto 1957. Hidrometeorološki zavod SR Slovenije. Ljubljana.

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Latin names for genera, species, and infraspecific taxa are to be written in *italics*. All syntaxa written in phytocoenological articles are to be in *italics*.

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