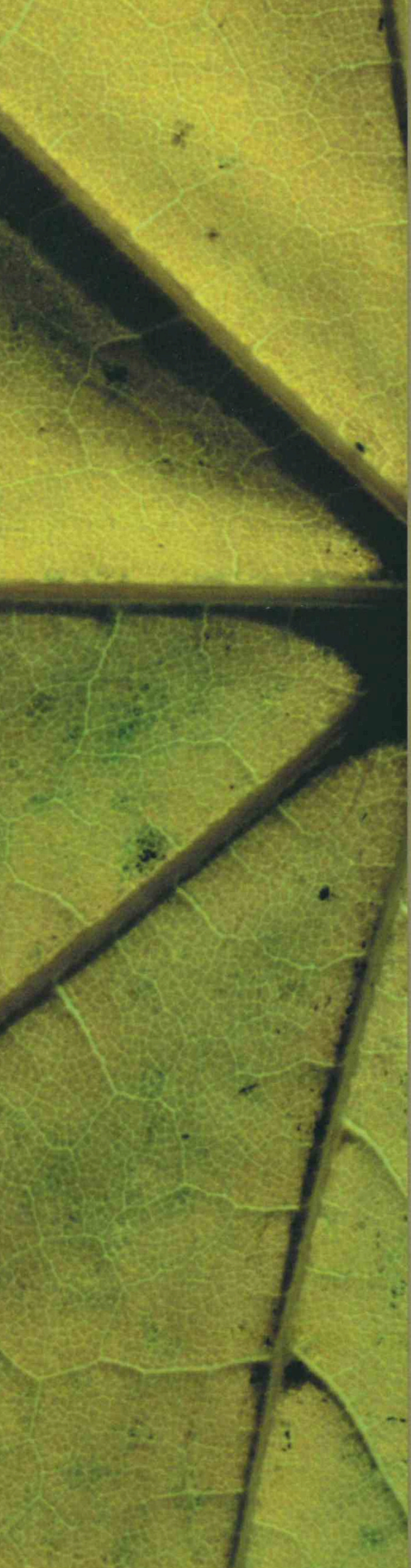

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Exotic *Abies* Species in Czech Provenance Trials: Assessment after Four Decades

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Abstract – The growth of seven exotic true fir (*Abies*) species and native *Abies alba* have been compared in three provenance trials in the Czech Republic, at the relatively advanced ages of 44, 38, and 35 years respectively. A clear differentiation is observable between the species. The closely related species group of *A. alba* and *A. cephalonica* appears rather heterogeneous in its phenotypic behavior. *A. alba* provenances show superiority, but also a high differentiation. Productivity of provenances of *A. cephalonica* fall behind *A. alba*; however *A. cilicica* and *A. pinsapo* provenances have shown total mortality. The high potential of *A. grandis* is confirmed by outstanding growth; provenances from the coastal plain in Washington State performed best. *A. procera* grows slower than *A. grandis*, but still faster than *A. alba* provenances. Health risks, extreme ecologic distances of transfer, trend shifts of growth rate, and rank change with age are uncertainties that require necessary caution when selecting provenances for importation. In recent years, public and institutional perceptions concerning the introduction of non-native tree species and provenances has shifted, and the practice is no longer seen as necessarily inappropriate.

provenance research / assisted migration / Mediterranean firs / *Abies grandis / Abies procera*

Kivonat – Idegenhonos *Abies* fajok cseh származási kísérletekben: eredmények négy évtized után. Nyolc jegenyefenyő faj növekedését hasonlították össze három kísérletben, viszonylag idős, 44, 38 illetve 35 éves korban. A közeli rokon *A. alba*, *A. cephalonica* és *A. borisii-regis* fajok fenotípusos viselkedése eléggé heterogén. A közönséges jegenyefenyő növekedése a legjobb, de erősen differenciált. Az *A. cephalonica* és *A. borisii-regis* jegenyefenyő származások teljesítménye gyengébb, míg az *A. cilicica* és *A. pinsapo* származások teljes mortalitást mutattak. A már korábban is behozatalra alkalmasnak ítélt amerikai *A. grandis* bizonyította kiváló adottságait; a Washington állambeli, parti populációi hozták a legjobb eredményeket. Az *A. nobilis* lassúbb növekedésű, de még így is meghaladja az őshonos *A. alba*-t. A behozatalról hozandó döntést megelőző óvatosságot indokolják az egészségi állapot kockázatai, extrém ökológiai eltérések a származási helyszínhez képest, továbbá a teljesítmény esetleges romlása idősebb korban. Az utóbbi időben a hatóságok és a nyilvánosság korábbi elutasító magatartása az idegenhonos fajok, populációk behozatalával kapcsolatban enyhülni látszik.

származási kísérletezés / támogatott migráció / mediterrán jegenyefenyők / *Abies grandis* / *Abies procera*

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1 INTRODUCTION

Silver fir (*Abies alba* Mill.) has been an important component of forest ecosystems in Central Europe. In the course of the last two centuries, however, the species has suffered a considerable decline in mountain ecosystems across the continent, including the Czech Republic. The share of silver fir in Czech forests has shrunk to a small fraction of its original distribution, presently amounting to a reduced area of 28,700 ha, which represents about 1.1% of total forest area (MZe ČR, 2016). Although there is some disagreement over the reasons for this decline, it is generally assumed that numerous factors are the cause, though air pollution is regarded as the primary reason. The possible replacement of silver fir with introduced species in forest ecosystems nonetheless raises numerous ecological and silvicultural questions. Although both nature conservationists and the public have condemned the introduction of non-native tree species in the past, institutional and public perception of non-native tree species has shifted towards a more tolerant attitude in recent years. Projected climate change scenarios have likely influenced this perception shift. Introduction ("assisted migration") of non-invasive foreign species and provenances to improve the resilience and stability of forest ecosystems is no longer regarded as necessarily inappropriate.

Previous research suggests that Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and grand fir (*A. grandis* (Douglas ex D. Con) Lindl.) have the best prospects for replacing silver fir in domestic forestry, even for close-to-nature forest management systems (see list of references)[1]. However, the introduction of exotic tree species requires further basic research information, particularly the evaluation of comparative trials. The Czech Forestry and Game Management Research Institute (FGMRI) is committed to this task by maintaining national provenance experiments and participating in international co-operations such as IUFRO and COST projects (e.g. Burzynski – Vančura 1985, Vančura 1990, Beran 2006, Dostál et al. 2016) with the aim of evaluation and testing possibilities for *Abies* spp. introduction and their use in forest management of the Czech Republic.

2 MATERIALS AND METHODS

With the aim of comparing the local adaptability and growth of exotic fir species, FGMRI established a national provenance experiment and two IUFRO provenance trials between 1976 and 1984. Besides local and foreign provenances of *A. alba* (silver fir), provenances of seven exotic fir species were tested: *A. cephalonica* Loud., Greek fir, native to Greece, mainly from Macedonia to the Peloponnese; *A. cilicica* (Ant. et Kotschy) Carriere, Cilician or Taurus fir, native to southern Turkey, western Syria and northern Lebanon; *A. pinsapo* Boiss., Spanish fir, native to southern Spain and northern Morocco; *A. borisii-regis* Mattf., King Boris or Balkan fir, a hybrid between *A. alba* and *A. cephalonica* (Krajmerová et al. 2015), native to southern Albania, Bulgaria and northern Greece; *A. grandis* (Dougl. ex D. Don) Lindl.), grand fir, native to western North America, distributed along the Pacific coast from southern British Columbia to northwestern California, in the Cascades of Washington and Oregon and in the Rocky Mountains of southern Alberta, western Montana, Idaho and northeast Oregon; and finally *A. procera* Rehder, noble fir, also native to western North America, distributed mainly in the Cascades of Washington, Oregon and northwestern California.

The origin of provenances included in the trials are listed and presented in *Figures 1–3*. Maps were prepared with use of Google Maps web application (https://maps.google.com).

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[1] A large variety of papers deal with this problem in Czech language. Pertinent publications are included in the list of references

2.1 Provenance trial No. 64, Písek (*Figure 1*)

This trial is located in Písek municipal forests (49.27° N, 14.33° E) and belongs to the national series of FGMRI 1976. It was established in 1976 on the site of an abandoned forest nursery site in the Forest Nature Region Central Hills (Středočeská vrchovina) on its southern border with the Forest Nature Region South Bohemian Basin (Jihočeské pánve) at 395 m above sea level. The average annual temperature is 7.2 °C with an average annual rainfall of 610 mm. The northwest exposure is a mild slope. The soil is of loam-sandy type over granodiorite bedrock. The rectangular-shaped trial covers 0.39 ha.

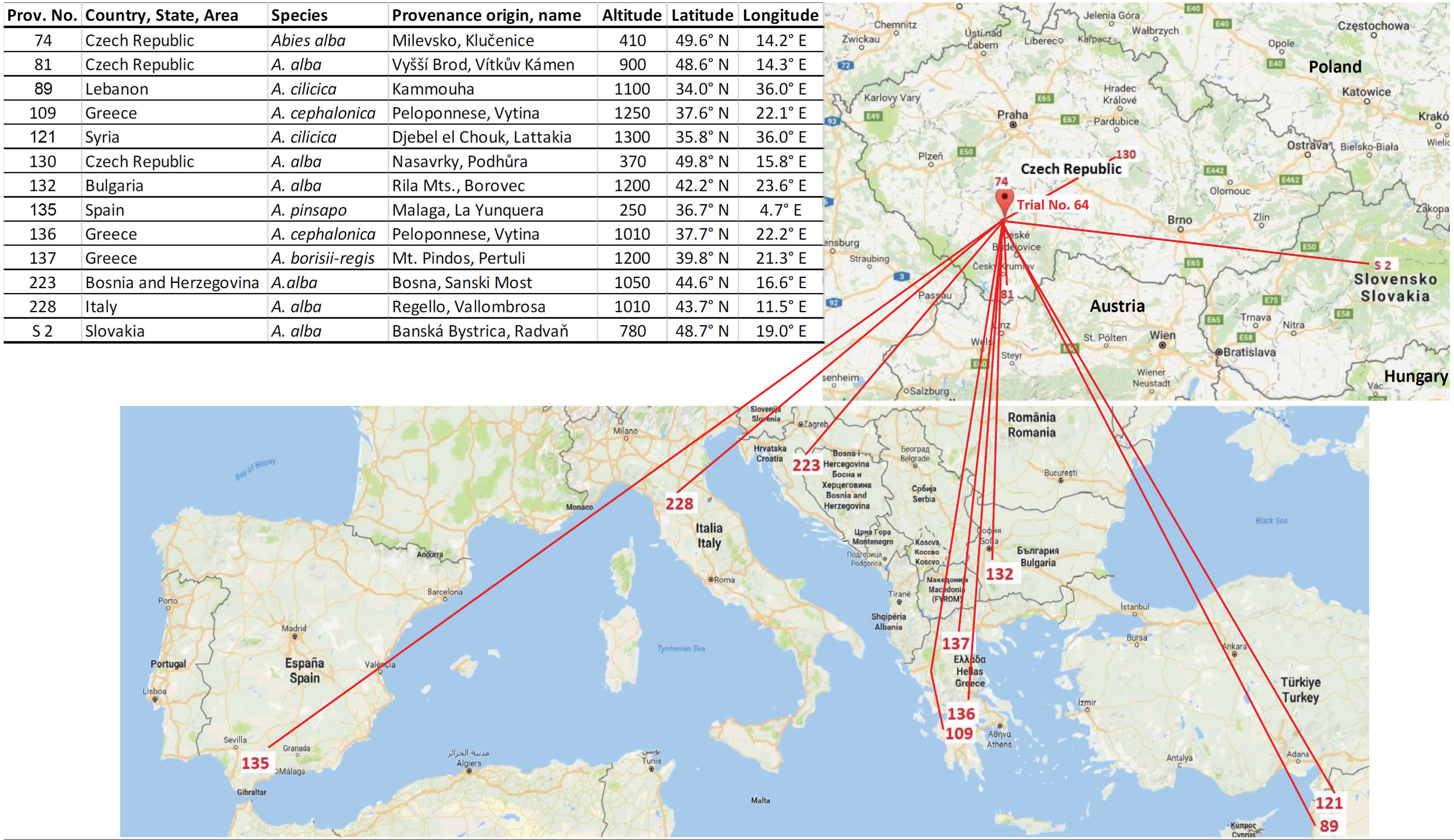
The test was established in a randomized block design with three repetitions and 13 provenances. Each plot is 10 m × 10 m and contained 50 seedlings (5 rows by 10 plants) at a planting spacing of 2 m × 1 m. A total of 1,950 seedlings were planted at the site. The compared species belong to five European taxa; two silver fir provenances served as native standards. Five-year-old bare-root seedlings were manually planted in the spring of 1976. The trial was fenced in order to prevent game damage. Replanting seedlings that did not survive was impossible because reserve plants were unavailable.

The first juvenile thinning was carried out in 1996. Until then only dead individuals had been removed from the trial at irregular intervals. This first thinning was aimed at reducing the low-grade and dying trees and the material was left onsite. The first regular thinning was carried out in 2005 based on the tree markings provided by research staff. Negative sub-level selection was applied and some of naturally regenerated *Abies alba* trees were removed, too. The most recent thinning was carried out in 2014 on crown thinning basis with the aim of preserving the spatial structure and releasing the promising individuals. At the same time, the dead trees were eliminated. All cut trees were removed from the trial.

2.2 Provenance trial No. 213, Zbiroh *(Figure 2)*

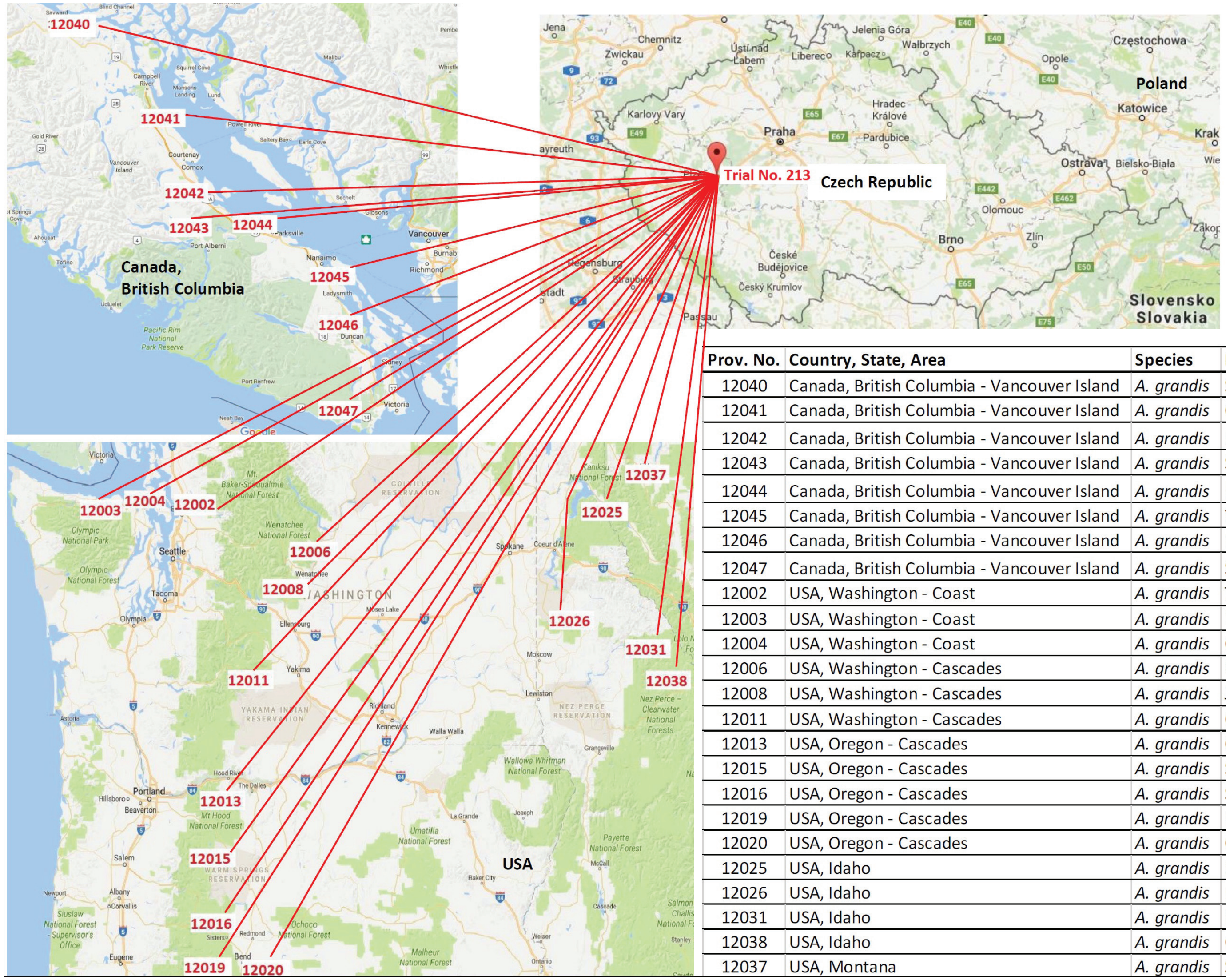
Provenance trial No. 213, Zbiroh is part of the IUFRO international trial series 1977, and was established in 1980 near the village of Volduchy in the Plzeň region (49.79° N, 13.64° E). At present, it is owned by Colloredo-Mansfeld Ltd. The trial lies in the Forest Nature Region Brdská Highlands (Brdská vrchovina). The trial lies on a mild slope with southeast exposure with an altitude of 450 to 460 m above sea level. The average annual temperature does not exceed 7 °C, while the average precipitation reaches 600–650 mm. Pedology conditions are characterized by loamy and pseudogley soils on pleistocene clay bedrock (Krejzek et al. 2015).

The provenance trial was established with three-year-old seedlings grown from seed imported from the USA. It consists of two 0.5 ha rectangles, 80 m apart, divided into plots of 10 m × 10 m. A total of 24 provenances of grand fir were planted with 25 seedlings per plot in four repetitions, in 2 m × 2 m spacing. Originally, each provenance was represented by 100 individuals. At the beginning, young seedlings suffered from water logging (especially replications 1 and 3) and partly from frost hollow conditions (Beran 2006).



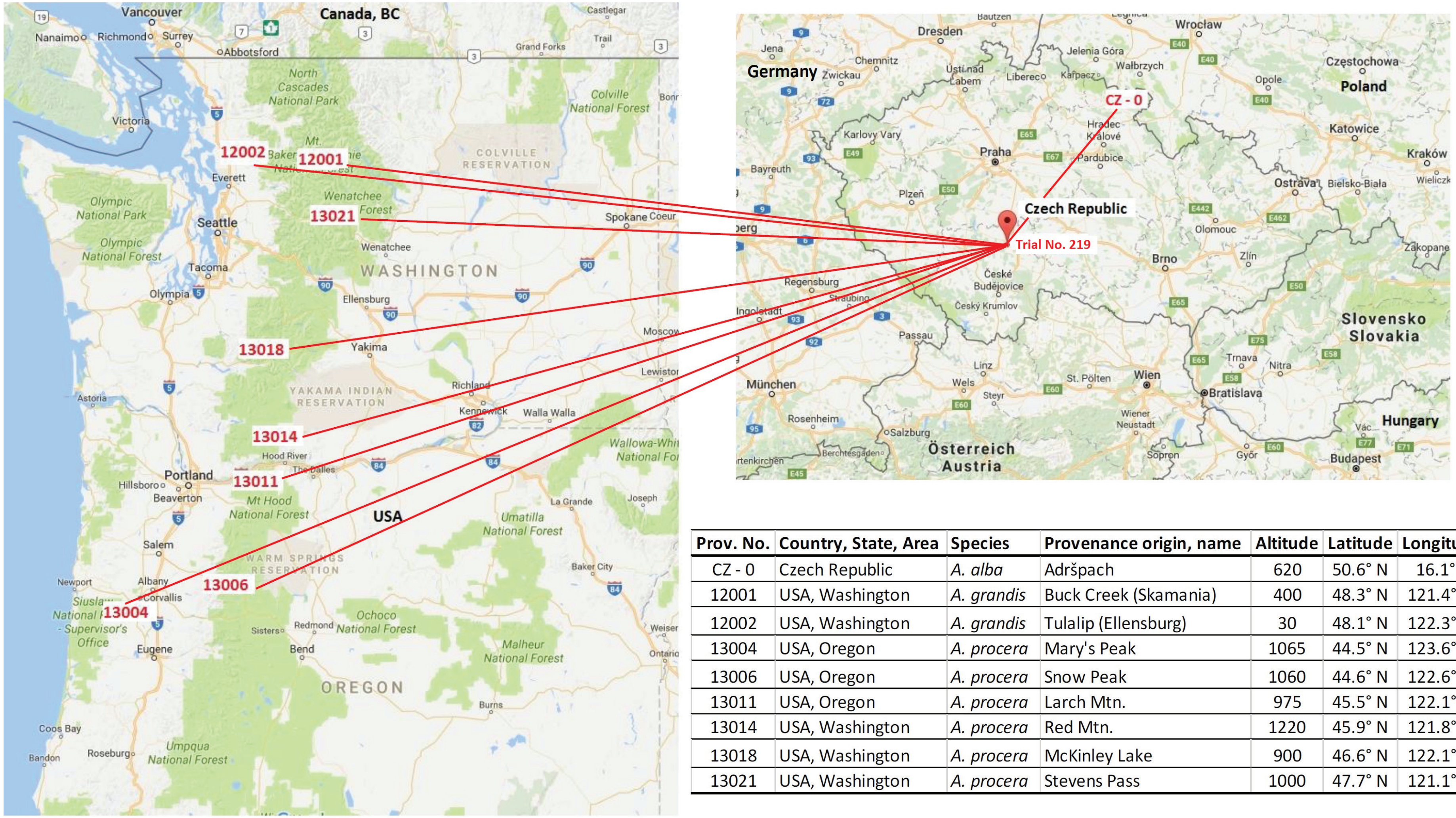
Prov. No.	Country, State, Area	Species	Provenance origin, name	Altitude	Latitude	Longitude
74	Czech Republic	*Abies alba*	Milevsko, Klučenice	410	49.6° N	14.2° E
81	Czech Republic	*A. alba*	Vyšší Brod, Vítkův Kámen	900	48.6° N	14.3° E
89	Lebanon	*A. cilicica*	Kammouha	1100	34.0° N	36.0° E
109	Greece	*A. cephalonica*	Peloponnese, Vytina	1250	37.6° N	22.1° E
121	Syria	*A. cilicica*	Djebel el Chouk, Lattakia	1300	35.8° N	36.0° E
130	Czech Republic	*A. alba*	Nasavrky, Podhůra	370	49.8° N	15.8° E
132	Bulgaria	*A. alba*	Rila Mts., Borovec	1200	42.2° N	23.6° E
135	Spain	*A. pinsapo*	Malaga, La Yunquera	250	36.7° N	4.7° E
136	Greece	*A. cephalonica*	Peloponnese, Vytina	1010	37.7° N	22.2° E
137	Greece	*A. borisii-regis*	Mt. Pindos, Pertuli	1200	39.8° N	21.3° E
223	Bosnia and Herzegovina	*A.alba*	Bosna, Sanski Most	1050	44.6° N	16.6° E
228	Italy	*A. alba*	Regello, Vallombrosa	1010	43.7° N	11.5° E
S 2	Slovakia	*A. alba*	Banská Bystrica, Radvaň	780	48.7° N	19.0° E

Figure 1. Origin of Abies spp. provenances tested in the trial No. 64, Písek



Prov. No.	Country, State, Area	Species	Provenance origin, name	Altitude	Latitude	Longitude
12040	Canada, British Columbia - Vancouver Island	*A. grandis*	Salmon River	50	50.3° N	125.8° W
12041	Canada, British Columbia - Vancouver Island	*A. grandis*	Oyster Bay	5	49.9° N	125.2° W
12042	Canada, British Columbia - Vancouver Island	*A. grandis*	Buckley Bay	45	49.5° N	124.9° W
12043	Canada, British Columbia - Vancouver Island	*A. grandis*	Sproat Lake	25	49.3° N	125.0° W
12044	Canada, British Columbia - Vancouver Island	*A. grandis*	Kay Road	50	49.3° N	124.3° W
12045	Canada, British Columbia - Vancouver Island	*A. grandis*	Yellow Point	30	49.1° N	123.8° W
12046	Canada, British Columbia - Vancouver Island	*A. grandis*	Mount Provost	75	48.8° N	123.8° W
12047	Canada, British Columbia - Vancouver Island	*A. grandis*	Sooke	20	48.4° N	123.8° W
12002	USA, Washington - Coast	*A. grandis*	Tulalip	30	48.1° N	122.3° W
12003	USA, Washington - Coast	*A. grandis*	Indian Creek	140	48.1° N	123.6° W
12004	USA, Washington - Coast	*A. grandis*	Gardiner	30	48.1° N	122.9° W
12006	USA, Washington - Cascades	*A. grandis*	Eagle Creek - low	760	47.7° N	120.6° W
12008	USA, Washington - Cascades	*A. grandis*	Jack Creek	825	47.3° N	120.8° W
12011	USA, Washington - Cascades	*A. grandis*	Clear Lake	945	46.6° N	121.3° W
12013	USA, Oregon - Cascades	*A. grandis*	Cooper Spur	1040	45.5° N	121.7° W
12015	USA, Oregon - Cascades	*A. grandis*	Sisi Butte	975	44.9° N	121.8° W
12016	USA, Oregon - Cascades	*A. grandis*	Santiam Summit	1400	44.4° N	121.9° W
12019	USA, Oregon - Cascades	*A. grandis*	Roaring River	1310	43.5° N	122.0° W
12020	USA, Oregon - Cascades	*A. grandis*	Crescent Creek	1375	43.5° N	121.9° W
12025	USA, Idaho	*A. grandis*	Buckskin Creek	1220	48.0° N	116.2° W
12026	USA, Idaho	*A. grandis*	Plummer Hill	850	47.3° N	116.9° W
12031	USA, Idaho	*A. grandis*	Bertha Hill	1430	46.8° N	115.8° W
12038	USA, Idaho	*A. grandis*	Clearwater	760	46.6° N	115.4° W
12037	USA, Montana	*A. grandis*	Stanley Creek (M)	800	48.3° N	115.9° W

Figure 2. Origin of Abies spp. provenances tested in the trial No. 213, Zbiroh



Prov. No.	Country, State, Area	Species	Provenance origin, name	Altitude	Latitude	Longitude
CZ - 0	Czech Republic	*A. alba*	Adršpach	620	50.6° N	16.1° E
12001	USA, Washington	*A. grandis*	Buck Creek (Skamania)	400	48.3° N	121.4° W
12002	USA, Washington	*A. grandis*	Tulalip (Ellensburg)	30	48.1° N	122.3° W
13004	USA, Oregon	*A. procera*	Mary's Peak	1065	44.5° N	123.6° W
13006	USA, Oregon	*A. procera*	Snow Peak	1060	44.6° N	122.6° W
13011	USA, Oregon	*A. procera*	Larch Mtn.	975	45.5° N	122.1° W
13014	USA, Washington	*A. procera*	Red Mtn.	1220	45.9° N	121.8° W
13018	USA, Washington	*A. procera*	McKinley Lake	900	46.6° N	122.1° W
13021	USA, Washington	*A. procera*	Stevens Pass	1000	47.7° N	121.1° W

Figure 3. Origin of Abies spp. provenances tested in the trial No. 219, Dražičky

2.3 Provenance trial No. 219, Dražičky *(Figure 3)*

Provenance trial No. 219, Dražičky (49.39° N, 14.59° E) is part of an international provenance experiment launched by IUFRO in the 1980s in the former Czechoslovakia and in 16 other European countries (Burzynski – Vančura 1985). This trial, presently owned by K. Vodňanský, was established in 1984, together with two others of this series, in the Forest Nature Region Central Hills (Středočeská vrchovina) on its southern border with the Forest Nature Region South Bohemian Basin (Jihočeské pánve) at 485 m above sea level. The average annual temperature is 8.5 °C with an average annual rainfall of 560 mm. The topography is plain. The bedrock is South Bohemian crystalline unit (gneiss), the soil is sandy loam.

The area of the rectangular trial is 0.36 ha. A randomized block design was employed with 4 repetitions. The trial contains 6 noble fir provenances and 2 provenances of grand fir, grown from seed imported from the USA. One native silver fir provenance was included as a comparative standard. Each block is 10 m × 10 m with a planting spacing of 2 × 2 m. Four-year-old seedlings were used for planting. Each plot was originally planted with 25 seedlings (5 rows by 5 seedlings). Damaged and dead trees were removed during later thinnings.

2.4 Measurements of trials

All three trials were measured in autumn 2015. The measurement age of the trials in the descriptions refers to age from seed (i.e. including nursery raising). Height and diameter at breast height (DBH) were measured. Volume was calculated using published equations for *Abies alba* (Petráš – Pajtík 1991) and *A. grandis* (Rau et al. 2008); the volume of other *Abies* species was calculated using equations for *Abies alba*.

The health status of all trees was visually assessed for trials No. 213 and 219 according to the following scale: 1 = excellent, 2 = good (less vigor, no signs of damage), 3 = dying or showing signs of decline (vigor significantly reduced). The survival of provenances was not evaluated because of thinnings executed in all three trials in previous periods. Stem form was evaluated in all three trials according to the following scale: 1 = straight, 2 = curved once, 3 = curved several times. For the canopy position evaluation of trees in trials No. 64 and No. 213, the modified Kraft-Konšel tree classes were used according to the following scale: 1 = pre-dominant, 2 = co-dominant, 3 = sub-dominant or recessive, 4 = overshadowed but vital, 5 = dying or dead tree. In trial No. 213, branch thickness was assessed using the following classification scale: 1 = weak branches, up to about 1/10 of DBH, sparse branching, 2 = thick branches, between 1/10 and 2/10 of DBH, high density of branching, 3 = very thick branches, above 2/10 of DBH, very high density of branching.

2.5 Statistical analysis

Median values, which suppress extreme or distorting values for height, DBH, and volume production, were calculated in addition to simple means. The processing and preparation of data files for statistical analysis were performed according to standard procedures. Statistical calculations were performed using the QC.Expert 3.1 and NCSS 10 (version: 10.0.6) programs. Data and statistics of quantitative and qualitative traits of provenances are summarized in *Tables 1* and *2*. The significance of differences among provenances was tested using the Kruskal-Wallis One-Way ANOVA test due to the non-normality of the data. Results from Kruskal-Wallis multiple-comparison z-value test for traits are presented in the Appendix, *Tables 3–5*. The one-way ANOVAs for each trait rejected the null hypothesis of equal mean values at $\alpha = 0.05$ level; it is valid for all three trials. Regarding the significance of mean and median differences of provenances, it must be noted that the one-way analysis does not separate error and between-repetition (block) variance; therefore, calculated significant differences appear larger than in reality. The comparison of data from different measurement dates also indicates the higher reliability provenance ranking than proposed by Kruskal-Wallis statistics. Thus, best and worst performers are listed in the results even if differences appear insignificant.

3 RESULTS

3.1 Trial No. 64, Písek *(Figure 4)*

Figure 4. Provenance trial No. 64, Písek at the age of 44 years

A total of 428 trees were measured and assessed in 2015 at the age of 44 years. The overall medians for DBH and height were 15.9 cm and 15.9 m, respectively. Two silver fir provenances, one originating from the Czech Republic (130 Nasavrky, Podhůra, 17.2 cm) and another from Bulgaria (No. 132 Borovec, Rila Mts., 17.2 cm) had the largest DBH medians. The provenances with the smallest DBH medians at this site were silver fir provenances S2 Radvaň, Banská Bystrica, Slovakia (13.9 cm) and 228 Regello, Vallombrosa, Italy (13.3 cm). The lowest height median occurred in two Greek *Abies cephalonica* provenances, No. 109 (14.6 m) and No. 136 (14.6 m), both originating from Vytina, Peloponnese.

Table 1. Quantitative characteristics

Prov. No.	n	DBH (cm)				Height (m)				Volume2) (m^3)			Volume3) (m^3)		
		Mean1)	Mean	Median	Std. Dev.	Mean1)	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Provenance trial No. 64 – Písek															
All	428	–	16.52	15.85	5.75	–	15.42	15.90	3.41	0.24	0.19	0.18	–	–	–
74	33	11.40	17.36	17.15	4.32	9.10	17.19	17.10	2.21	0.27	0.24	0.14	–	–	–
81	15	7.90	16.17	14.60	5.70	7.00	15.47	16.20	3.18	0.24	0.16	0.22	–	–	–
109	44	12.40	17.11	16.08	6.53	9.60	14.19	14.60	3.41	0.25	0.20	0.21	–	–	–
130	49	–	17.49	17.20	5.01	–	16.89	17.20	2.69	0.28	0.24	0.16	–	–	–
132	47	–	17.93	17.20	5.44	–	16.85	17.30	2.65	0.30	0.23	0.19	–	–	–
136	52	8.70	17.26	15.88	5.46	12.10	14.34	14.60	2.82	0.24	0.18	0.16	–	–	–
137	53	8.70	16.75	15.80	5.22	12.30	14.59	14.70	2.68	0.23	0.17	0.16	–	–	–
223	42	–	17.18	17.18	7.15	–	15.61	16.05	4.21	0.29	0.23	0.26	–	–	–
228	46	–	13.51	13.30	4.54	–	14.82	15.95	3.90	0.17	0.15	0.11	–	–	–
S2	47	–	14.32	13.90	6.28	–	14.92	15.50	4.20	0.20	0.14	0.18	–	–	–
Provenance trial No. 213 – Zbiroh															
All	1202	–	19.48	19.48	7.41	-	19.54	20.50	5.05	0.45	0.38	0.34	0.34	0.29	0.26
12002	48	19.48	22.11	23.63	6.32	17.46	22.29	23.25	3.88	0.58	0.59	0.32	0.44	0.45	0.24
12003	57	18.93	23.39	23.35	7.93	16.01	21.48	22.20	4.32	0.64	0.57	0.42	0.49	0.44	0.32
12004	56	17.89	20.20	19.63	5.70	17.15	21.72	22.55	3.51	0.48	0.41	0.28	0.36	0.31	0.21
12006	46	14.98	18.88	18.65	6.78	13.37	19.05	20.10	4.50	0.40	0.33	0.30	0.31	0.26	0.23
12008	43	15.26	17.13	17.50	8.02	13.90	17.30	18.70	7.03	0.36	0.27	0.32	0.27	0.20	0.24
12011	48	17.29	19.52	18.78	7.59	13.88	17.89	18.70	3.90	0.40	0.32	0.35	0.31	0.24	0.27
12013	36	17.50	19.99	18.48	7.76	13.95	18.91	20.50	4.80	0.45	0.34	0.36	0.34	0.26	0.28
12015	36	15.52	18.34	19.28	8.35	13.91	18.19	19.50	6.69	0.42	0.31	0.37	0.32	0.24	0.28
12016	34	15.77	17.15	16.98	7.58	12.76	16.22	17.25	5.36	0.31	0.27	0.28	0.24	0.21	0.22
12019	24	17.73	20.45	19.55	8.30	12.85	17.88	19.05	4.72	0.45	0.36	0.41	0.35	0.28	0.32
12020	24	19.29	20.92	20.68	9.19	14.93	17.90	18.10	5.54	0.50	0.36	0.43	0.38	0.28	0.33
12025	56	11.51	13.87	13.93	6.84	10.30	14.55	15.15	5.62	0.21	0.15	0.22	0.16	0.12	0.17
12026	20	15.98	17.94	16.83	9.42	12.92	16.96	17.55	6.23	0.40	0.25	0.45	0.31	0.19	0.34
12031	63	14.96	17.60	18.25	6.77	13.70	18.17	19.90	5.24	0.35	0.33	0.27	0.27	0.25	0.20
12037	53	16.48	19.38	19.35	7.16	14.13	18.58	19.60	4.33	0.41	0.35	0.32	0.32	0.27	0.25
12038	72	16.64	19.82	20.25	6.47	15.98	21.48	21.55	4.24	0.48	0.41	0.32	0.36	0.31	0.24
12040	44	19.97	23.31	24.83	7.77	17.32	21.81	23.10	4.78	0.65	0.66	0.40	0.49	0.50	0.31
12041	70	18.03	20.36	21.00	6.16	17.30	20.90	21.65	3.89	0.47	0.46	0.29	0.36	0.34	0.22
12042	62	14.71	18.11	17.55	7.05	14.68	19.32	19.50	5.13	0.39	0.30	0.34	0.30	0.23	0.26
12043	58	18.16	20.88	21.08	7.77	15.43	20.05	19.80	4.29	0.50	0.42	0.40	0.38	0.32	0.31
12044	72	15.42	18.22	18.40	6.33	15.39	20.02	21.45	4.88	0.39	0.36	0.26	0.30	0.27	0.20
12045	57	16.96	20.05	19.40	7.61	15.07	20.03	20.40	4.20	0.46	0.41	0.36	0.35	0.31	0.28
12046	63	17.65	20.28	20.05	6.71	16.48	21.38	21.90	3.97	0.50	0.42	0.35	0.37	0.32	0.27
12047	60	16.57	19.53	19.75	7.20	15.15	20.05	20.60	3.82	0.44	0.38	0.34	0.34	0.30	0.26
Provenance trial No. 219 – Dražičky															
All	503	–	19.35	19.35	7.01	–	15.34	15.50	4.90	0.34	0.27	0.27	0.31	0.26	0.23
12001	74	14.60	23.26	23.13	5.12	14.79	20.65	20.80	2.38	0.55	0.50	0.26	0.43	0.39	0.20
12002	66	14.07	22.94	22.48	6.13	12.88	19.75	20.10	3.16	0.54	0.47	0.33	0.42	0.36	0.26
13006	42	12.38	19.30	18.73	7.08	11.98	13.68	14.55	3.31	0.29	0.25	0.21	–	–	–
13014	63	12.97	18.98	18.95	5.80	11.90	14.53	14.90	3.33	0.29	0.25	0.19	–	–	–
13018	64	13.35	19.42	18.78	5.76	12.28	15.16	15.40	3.02	0.31	0.25	0.24	–	–	–
13011	68	12.25	19.44	18.68	5.96	12.17	14.42	14.70	3.04	0.29	0.24	0.22	–	–	–
13004	44	12.93	18.32	18.83	6.30	13.03	12.41	13.55	3.47	0.23	0.22	0.16	–	–	–
13021	50	10.42	17.87	16.85	6.25	11.03	14.00	14.15	4.11	0.27	0.20	0.23	–	–	–
CZ-0	32	2.00	7.17	4.65	6.25	3.81	6.22	4.90	4.44	0.05	0.01	0.08	–	–	–

1) previous evaluations; prov. trial. No. 64 in 1999, No. 213 in 2011, No. 219 in 2010;

2) for *Abies alba*, according to Petráš – Pajtík 1991; 3) for *A. grandis*, according to Rau et al. 2008

Table 2. Qualitative characteristics

Prov. No.	n	Stem form			Health condition			Social status			Thickness of branches		
		Mean	Median	Std. Dev.	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Provenance trial No. 64 – Písek													
All	428	1.909	2.00	0.733	–	–	–	2.367	2.00	1.101	–	–	–
74	33	1.697	2.00	0.728	–	–	–	1.848	2.00	0.712	–	–	–
81	15	2.000	2.00	0.655	–	–	–	2.200	2.00	0.941	–	–	–
109	44	2.023	2.00	0.762	–	–	–	2.614	2.50	1.146	–	–	–
130	49	2.020	2.00	0.777	–	–	–	2.102	2.00	0.984	–	–	–
132	47	1.745	2.00	0.675	–	–	–	2.064	2.00	1.030	–	–	–
136	52	2.115	2.00	0.832	–	–	–	2.654	3.00	0.968	–	–	–
137	53	1.962	2.00	0.733	–	–	–	2.453	2.00	0.932	–	–	–
223	42	1.571	1.00	0.668	–	–	–	2.452	2.00	1.310	–	–	–
228	46	1.870	2.00	0.653	–	–	–	2.500	2.00	1.329	–	–	–
S2	47	2.021	2.00	0.642	–	–	–	2.511	2.00	1.214	–	–	–
Provenance trial No. 213 – Zbiroh													
All	1202	1.233	1.00	0.473	1.145	1.00	0.411	2.329	2.00	1.048	1.095	1.00	0.310
12002	48	1.188	1.00	0.445	1.104	1.00	0.371	1.938	2.00	0.932	1.104	1.00	0.309
12003	57	1.263	1.00	0.518	1.140	1.00	0.398	2.070	2.00	0.961	1.246	1.00	0.434
12004	56	1.286	1.00	0.563	1.089	1.00	0.345	2.125	2.00	0.833	1.107	1.00	0.312
12006	46	1.196	1.00	0.453	1.174	1.00	0.437	2.283	2.00	1.004	1.043	1.00	0.206
12008	43	1.209	1.00	0.412	1.233	1.00	0.480	2.605	2.00	1.256	1.023	1.00	0.152
12011	48	1.229	1.00	0.425	1.167	1.00	0.429	2.542	2.00	0.922	1.063	1.00	0.245
12013	36	1.139	1.00	0.351	1.167	1.00	0.609	2.444	2.00	1.027	1.111	1.00	0.319
12015	36	1.361	1.00	0.762	1.167	1.00	0.378	2.444	2.00	1.423	1.028	1.00	0.167
12016	34	1.147	1.00	0.436	1.176	1.00	0.459	2.912	3.00	1.055	1.029	1.00	0.171
12019	24	1.250	1.00	0.532	1.083	1.00	0.282	2.458	2.00	0.977	1.083	1.00	0.282
12020	24	1.500	1.50	0.511	1.208	1.00	0.415	2.708	3.00	1.197	1.083	1.00	0.282
12025	56	1.089	1.00	0.288	1.286	1.00	0.530	3.218	3.00	1.228	1.161	1.00	0.371
12026	20	1.400	1.00	0.754	1.200	1.00	0.523	2.800	2.50	1.240	1.150	1.00	0.489
12031	63	1.175	1.00	0.383	1.159	1.00	0.447	2.603	2.00	1.056	1.048	1.00	0.215
12037	53	1.170	1.00	0.427	1.132	1.00	0.342	2.415	2.00	0.969	1.115	1.00	0.323
12038	72	1.194	1.00	0.399	1.111	1.00	0.396	2.153	2.00	0.883	1.069	1.00	0.306
12040	44	1.182	1.00	0.390	1.091	1.00	0.362	2.000	2.00	1.034	1.045	1.00	0.211
12041	70	1.286	1.00	0.486	1.100	1.00	0.347	1.929	2.00	0.922	1.030	1.00	0.173
12042	62	1.339	1.00	0.571	1.113	1.00	0.367	2.164	2.00	0.969	1.065	1.00	0.248
12043	58	1.259	1.00	0.442	1.103	1.00	0.307	2.000	2.00	0.858	1.086	1.00	0.339
12044	72	1.250	1.00	0.436	1.153	1.00	0.465	2.347	2.00	1.050	1.069	1.00	0.256
12045	57	1.175	1.00	0.384	1.105	1.00	0.310	2.386	2.00	0.996	1.088	1.00	0.285
12046	63	1.270	1.00	0.545	1.127	1.00	0.381	2.079	2.00	0.885	1.127	1.00	0.381
12047	60	1.233	1.00	0.465	1.183	1.00	0.469	2.333	2.00	0.896	1.267	1.00	0.516
Provenance trial No. 219 – Dražičky													
All	503	1.167	1.00	0.394	1.211	1.00	0.527	–	–	–	–	–	–
CZ-0	32	1.438	1.00	0.669	1.344	1.00	0.701	–	–	–	–	–	–
12001	74	1.149	1.00	0.358	1.068	1.00	0.344	–	–	–	–	–	–
12002	66	1.136	1.00	0.346	1.045	1.00	0.274	–	–	–	–	–	–
13004	44	1.250	1.00	0.438	1.295	1.00	0.632	–	–	–	–	–	–
13006	42	1.190	1.00	0.397	1.095	1.00	0.370	–	–	–	–	–	–
13011	68	1.103	1.00	0.306	1.235	1.00	0.522	–	–	–	–	–	–
13014	63	1.222	1.00	0.419	1.175	1.00	0.459	–	–	–	–	–	–
13018	64	1.109	1.00	0.362	1.375	1.00	0.630	–	–	–	–	–	–
13021	50	1.060	1.00	0.240	1.380	1.00	0.697	–	–	–	–	–	–

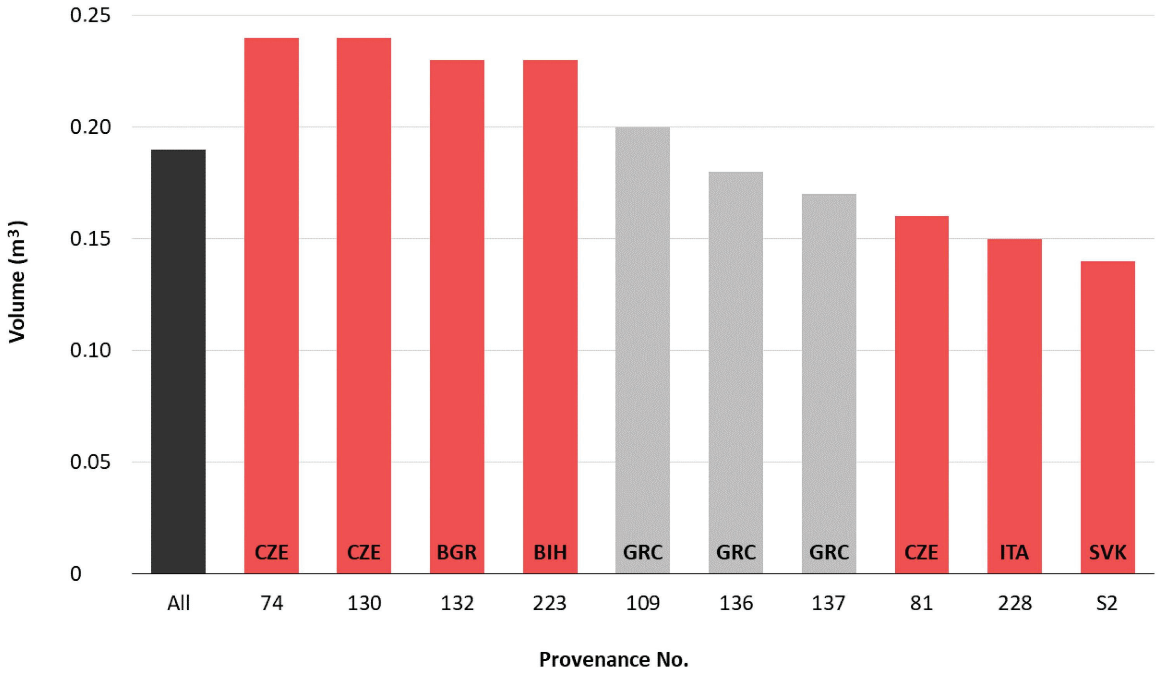


Figure 5. Volume median per tree at the age of 44 years in provenance trial No. 64, Písek. A. alba provenances are marked in color, the rest are other taxa from the Balkans. The graph does not show the provenances of A. cilicica and pinsapo, which suffered total mortality

The average median of stem volume per tree was 0.19 m^3.The best provenances for volume production were the same as those found for DBH and height growth; silver fir provenances originating from the Czech Republic, No. 130 Nasavrky, Podhůra (0.24 m^3) and No. 74 Milevsko, Klučenice (0.24 m^3) and from Bulgaria, No. 132 Borovec, Rila Mts. (0.23 m^3). The Slovakian silver fir provenance S2 Radvaň, Banská Bystrica, (0.14 m^3) had shown the poorest performance, followed by the Italian silver fir provenance 228 Regello, Vallombrosa (0.15 m^3). The third lowest volume was measured for the Czech silver fir provenance 81 Vyšší Brod, Vítkův Kámen (0.16 m^3). Volume production of other *Abies* species was rather average (*Figure 5*, *Table 1*). It needs to be emphasized that the provenances of *A. cilicica* and *A. pinsapo* did not survive the local conditions and therefore do not appear in the *Figure 5* and in the statistics. The reasons may be sought in the poor adaptive capacity of these species to local winter extremes.

Characteristics of stem form were similar across provenances with a median value around class 2, curved once. Canopy positions were also similar with a median value of about 2, co-dominant position. Health status and branch thickness were not evaluated.

3.2 Trial No. 213, Zbiroh *(Figure 6)*

A total of 1,202 trees from 24 grand fir provenances were measured and evaluated at this site in 2015 at the age of 38 years. The average median DBH and height values were 19.5 cm and 20.5 m, respectively. The best provenances regarding both DBH and height were No. 12040 Salmon River, British Columbia, Canada (24.8 cm and 23.1 m, respectively) and No. 12002 Tulalip, Washington, USA (23.6 cm and 23.3 m, respectively). The lowest values of both DBH and height median were measured for provenance No. 12025 Buckskin Creek, Idaho, USA (13.9 cm and 14.6 m, respectively; see *Figure 7*).

Figure 6. Provenance trial No. 213, Zbiroh at the age of 38 years

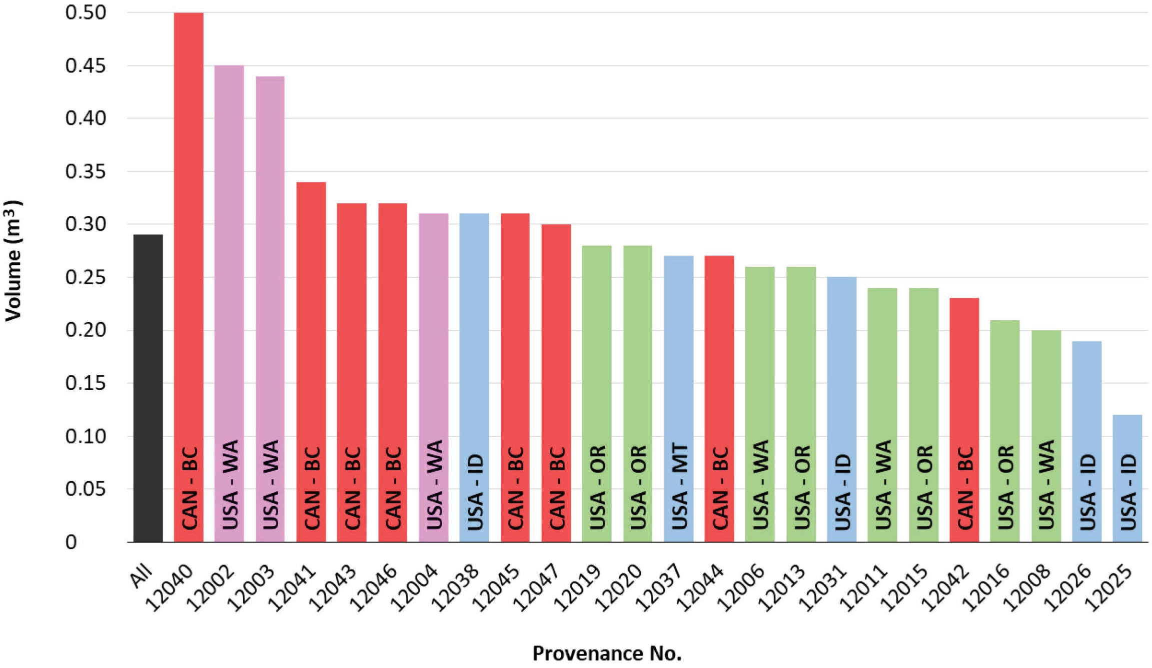


Figure 7. Volume median per tree at the age of 38 years in provenance trial No. 213, Zbiroh. Colors show coastal (red), Cascades Mtn. (green) and inland provenances (blue). The provenances from the best coastal region in Washington State are marked in lilac color

The average median of volume per tree was 0.29 m^3. The following provenances were identified as best: No. 12040 Salmon River, from Vancouver Island, B.C., Canada (0.50 m^3), and the coast provenances from Washington, USA, No. 12002 Tulalip (0.45 m^3) and No. 12003 Indian Creek (0.44 m^3). The lowest values were found for inland provenances from Idaho, USA: No. 12025 Buckskin Creek (0.12 m^3) and No. 12026 Plummer Hill (0.19 m^3), as well as No. 12008 Jack Creek, from the Washington Cascades, USA (0.20 m^3, see *Figure 7, Table 1*).

The majority of the trees in this trial were class 1 (straight). Tree health status was excellent (class 1). The median for branch thickness was close to 1, i.e. the populations have thin branches. There was no local standard provenance for comparison.

3.3 Trial No. 219 Dražičky *(Figure 8)*

Figure 8. Provenance trial No. 219, Dražičky at the age of 35 years

A total of 503 trees were measured and evaluated in 2015, at the age of 35 years. The average median DBH and height were 19.4 cm and 15.5 m, respectively. The best results for both DBH median and height median were found for two grand fir provenances from Washington State, USA, No. 12001 Buck Creek (DBH 23.1 cm and 20.7 m, respectively) and No. 12002 Tulalip (22.5 cm and 19.8 m, respectively). All the noble fir provenances had significantly lower values. The least productive provenance at this site was the local Czech silver fir provenance No. CZ-0 Adršpach (4.7 cm and 4.9 m, respectively).

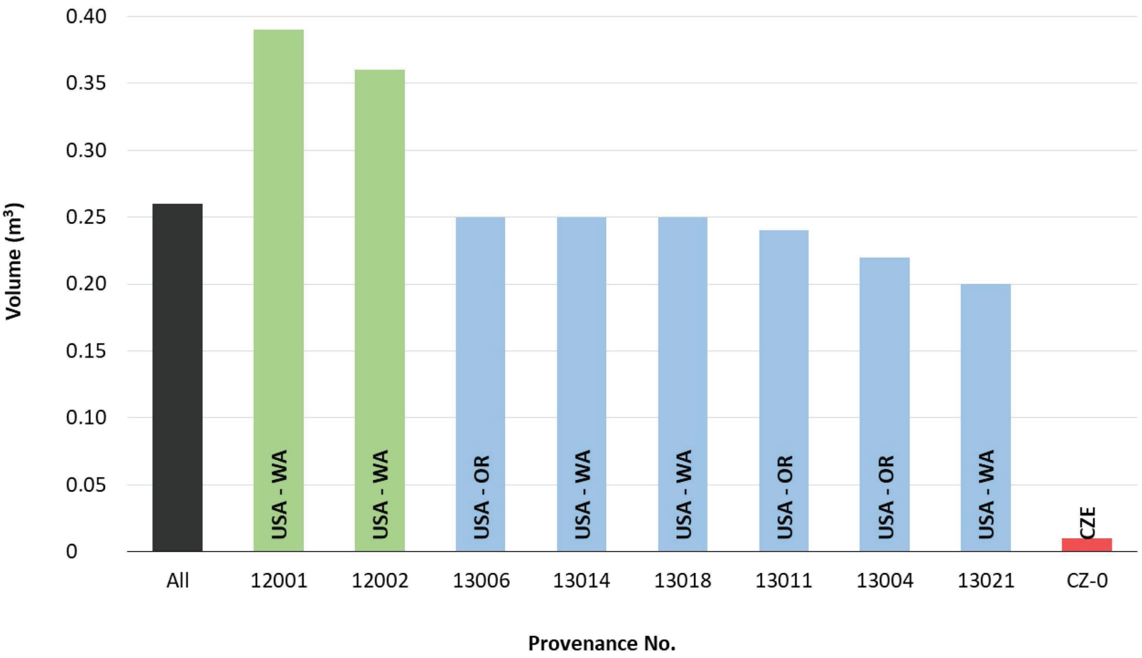


Figure 9. Volume median per tree at the age of 35 years in provenance trial No. 219, Dražičky. Colors show grand fir (green), noble fir (blue), and silver fir (red) provenances

The best volume production was found for the two *A. grandis* provenances No. 12001 Buck Creek (Skamania) Washington, USA, (0.39 m^3 and 0.50 m^3, calculated by equations both for *A. grandis* and *A. alba*, respectively) and No. 12002 Tulalip (Ellensburg), Washington, USA (0.36 m^3 and 0.47 m^3, calculated similarly). Medium (but below average) volume production was found for all noble fir provenances in the trial; none of these provenances had significantly different mean volumes per tree (calculated by equation for *A. alba*) as indicated by the Kruskal-Wallis test. The Czech silver fir provenance No. CZ-0 Adršpach (0.01 m^3, see *Figure 9, Table 1*) had the lowest volume production.

Similar to trials No. 64 and 213, stem form in trial No. 219 was also mostly straight (class 1). The median health status of trees evaluated was excellent (class 1). Branch thickness was not evaluated.

4 DISCUSSION

Over the past two centuries, forest ecosystems in the Czech Republic have experienced the decline of some tree species, biodiversity loss, and the dwindling of basic functions. Forest management practices, human impacts on the forest environment, and the negative consequences of pests and diseases are among the main causes of these phenomena (Šindelář 1993, Šindelář – Frýdl 2008). These factors, along with the newly emerging threat of changing climatic/environmental conditions, must be considered when devising strategies for the introduction and implementation of adaptive, sustainable forest management practices. Appraising the genetic diversity of both domestic and exotic forest trees, designing rules for the use of reproductive material, and selection and breeding programs should be oriented to increase not only the quality and volume of production, but also to improve the resilience and stability of ecosystems, including the preservation of valuable ecotypes and minor forest tree species (Šindelář 1974, 1994, 1996, Frýdl et al. 2011).

The three trials in Písek, Zbiroh and Dražičky were established in a different economic and professional environment and cannot fully answer the requirements formulated above. Their main merit, however, is their age, which permits an assessment that is closer to maturity. Older provenance trials, envisioned in the postwar times, have been largely abandoned and considered obsolete due to the advent of modern molecular genetic methods. A recent development is that such field trials turned out to be indispensable when projecting ecological and silvicultural behavior, especially of introduced species and populations, into the future (Mátyás et al. 2010).

This paper focuses on traits of forest productivity, such as height, diameter growth and volume, survival, and form[2]. All three trial sites have been selected according to careful professional considerations: all are in locations with relatively mild climate and low elevation. This means that the tested provenances have been exposed to higher temperatures and even drought stress conditions that are similar to those expected in future climate scenarios in mountain forests at higher elevations.

The 2015 results from the last survey of the trials show clear differentiation between the tested species in spite of limited comparability due to the original design. In provenance trial No. 64, Písek, provenances of exotic European *Abies* species are compared at the age of 44 years with silver fir. The total mortality of *A. cilicica* and *A. pinsapo* provenances from Lebanon, Syria and Spain is very apparent. The climatic distance of transfer is certainly a decisive cause for their failure, but it cannot be excluded that local degradation processes due to isolation and human interference (overexploitation) contributed to the failure and affected adaptive potential. Silver fir provenances show clear superiority, but there was high variance in median height, which is the genetically most reliable trait. The silver fir provenance with the lowest height, S2 Radvaň (Slovakia), is still higher than populations belonging to other species; Greek fir and Balkan fir provenances are significantly lower. The white fir provenances 81 Vyšší Brod, Vítkův Kámen (Czech Republic), 228 Regello, Vallombrosa (Italy) and S2 from Banská Bystrica, Radvaň (Slovakia) show a differentiation from the other white firs primarily for DBH (a trait sensitive to the microenvironment) according to the Kruskal-Walis test results (*Table 3* in *Appendix*), which can be explained only partly by survival irregularities in plots of provenance Nr. 81, Vítkův Kámen. Accordingly, the phylogenetically closer related species group (Greek, Balkan and silver firs) appears rather heterogeneous in its phenotypic behavior, partly due to strong ecological differences between the sites of origin.

The other two trials in Zbiroh and Dražičky compare the growth of NW American species grand fir and noble fir. In provenance trial No. 213, Zbiroh, the performance of *A. grandis* provenances was exclusively evaluated. All three provenances from the coastal plain in Washington (No. 12002, 12003, 12004) reached above-average values of DBH, height growth and volume production at the age of 38 years. Similarly, provenance No. 12040 Salmon River, from the coast of Vancouver Island (B.C., Canada), was among the best of all provenances. The rank differences between them were insignificant according to the Kruskal-Wallis test. The performance of the other provenances was also comparable, including even the far inland sources from Idaho and Montana, with one exception: No. 12025 Buckskin Creek, Idaho, USA, which is among the most distant from all other grand fir provenances (see *Figure 7*, *Tables 1 and 4* in *Appendix*). Therefore, earlier recommendations (Krejzek et al. 2015) for importing grand fir to the Czech Republic, in concordance with revised rules for the transfer of grand fir reproductive material from North America (Beran et al. 2016), are corroborated.

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[2] Questions of adaptability and stability under future conditions will be discussed in a further paper currently under preparation (Mátyás et al. 2018).

Trial No. 219, Dražičky provides an opportunity to compare noble fir provenances and relate them to grand fir and silver fir. Obviously none of the noble fir provenances reach the growth of grand fir; nonetheless, they are probably still superior to native silver fir provenances. This assertion may be vaguely questioned because the local standard, CZ-0 Adršpach, originates from a rather cool and moist location and is likely suffering from the higher temperatures at the trial site (the noble firs have shown better tolerance to similar change of conditions). It may be concluded that both American species are suitable competitors of the native species. The most productive is grand fir; noble fir grows slower, but still faster than domestic silver fir up to the present age (see *Figure 9, Tables 1 and 5 in Appendix*). Further monitoring of the trial until the age of 50 years is planned. In the project COST CZ LD14116, additional provenance trials with various species of *Abies* have been established in different locations in the Czech Republic. Comprehensive assessment of these provenance trials will provide further information to formulate recommendations.

Caution should be taken when deciding upon the introduction of exotics. Health risk is a serious threat, especially in view of expected climatic changes. In the Czech Republic, health deterioration and mortality symptoms are continuously observed in certain grand fir populations (Beran 2006). The main reasons are the attack by honey root fungi (*Armillaria sp.)* and subsequent damage by bark beetles. Currently, a strong attack by bark beetles (*Pityokteines sp.*) and by sucking insects of the genus *Dreyfusia* are reported in Bolehošť (Eastern Bohemia) where the occurrence of honey root fungi had been observed earlier. The damages are apparently related to extreme droughts during the summer of 2015 (Modlinger 2016, in litt.).

The potential shifts of growth rate and ranking of provenances established in juvenile age may be also of concern. In the provenance trial No. 64 Písek, DBH and height ranks may be compared between age of 28 years (Šindelář – Beran 2008a) and the recent results at age of 44 years. While the highest DBH at the age of 28 was produced by the Greek provenance No. 109 *Abies cephalonica*, Vytina, Central Peloponnese, at the age of 44, this provenance was only average. Comparison of height data for age 28 versus age 44 shows a similar result. At the age of 28, the best mean height was measured for provenance No. 223 *A. alba*, Sanski Most, Bosnia (7.1 m), while 16 years later, its rank (out of 10 tested populations) decreased to fourth. Accordingly, rank shifts may be expected over longer time intervals. Therefore, results of provenance regions should be followed first of all as these are more reliable than the data of individual provenances.

Only a shorter time interval comparison is possible in the other two trials, Zbiroh and Dražičky. These are, however, still of interest as they indicate rather good agreements for two independent survey data sets measured in a close time interval. This confirms that rankings qualified as non-significant by the Kruskal-Wallis statistics may be more reliable than indicated (see details in the subchapter on statistics).

For grand fir provenances, recent performance at age of 38 in trial No. 213, Zbiroh may be compared with data at age of 34 years (Krejzek et al., 2015). The rank differences are minor. In 2011, the highest median DBHs recorded were those of Pacific coast provenances No. 12040 Salmon River, Vancouver Island, B.C., Canada (20.5 cm) and No. 12002 Tulalip, WA, USA (19.3 cm), followed by the provenance No. 12020 Crescent Creek OR, USA, (19.1 cm), from the Cascades. The rank by DBH at age 38 is rather similar: the first three provenances were all from the Pacific coast, No. 12003 Indian Creek, WA, USA (23.4 cm), No. 12040 Salmon River, Vancouver Island, B.C., Canada, (23.3 cm) and No. 12002 Tulalip, WA, USA, (22.1 cm). The comparison of heights and volumes at the age of 34 and 38 years brought similar results, Pacific coast provenances are leading. Regarding the sources with the lowest volume, the results were almost the same for ages 34 and 38 years.

Data of provenance trial No. 219, Dražičky has previously been reported by Beran – Dostál (2012) for 2010, at age of 30 years. Only DBH, height and some qualitative characteristics were measured. As medians were not calculated, averages were used for comparison with the recent assessment (at 35 years). There was no significant change in provenance ranks between the two rankings. At both ages, the same two provenances of *A. grandis* and one provenance of *A. procera* ranked best for DBH: *A. grandis* No. 12001 Buck Creek (Skamania), WA, USA, (14.60 cm and 23.26 cm), followed *A. grandis* No. 12002 Tulalip (Ellensburg), WA, USA, (14.07 cm and 22.94 cm) and by *A. procera* No. 13018 McKinley Lake, WA, USA, (13.35 cm and 19.44 cm, all for 30 and 35 years). The same three provenances ranked at the top for height as well. Similar results were found when comparing the lowest values of DBH and height. Slowest growth was reported for the Czech comparative standard, silver fir provenance No. CZ–0, Adršpach at both ages. The second and third lowest DBH and height growth ranks at the age of 30 and 35 years were occupied by noble fir provenances from high-elevation locations in the Cascades in Washington, USA, (No. 13021 Stevens Pass, and No. 13014 Red Mtn.) as well as in Oregon, USA (No. 13004 Mary's Peak and No. 13006 Snow Peak).

Summing up, the comparisons indicate that rank changes were not significant either at the top or at the lower end of the list. More important than individual ranking changes is the fact that the ranks of provenance regions did remain the same, which supports the validity of ranking by provenance regions, e.g. of the superiority of coastal provenances of grand fir.

5 CONCLUSIONS

Although the comparability of tested trials is partially limited, regarding their original experimental design, clear differentiation in performance is observable between the tested species. The phylogenetically related species group of *A. alba, A. borisii-regis* and *A. cephalonica* appears rather heterogeneous in its phenotypic behavior, partly due to strong ecological differences between the sites of origin. Silver fir provenances show an unexpected differentiation. The provenances of Greek and Balkan fir do not show superiority to the native silver fir in the experiments. On the other hand, the total mortality of *A. cilicica* and *A. pinsapo* provenances from Lebanon, Syria, and Spain reveal the effect of extreme geographic and climatic distance of transfer, but possibly also the effects of local degradation due to isolation and human interference and of consequent genetic diversity loss.

Earlier recommendations of importing grand fir to the Czech Republic are corroborated by the growth of that species in the trials Zbiroh and Dražičky. While nearly all provenances displayed excellent growth, the provenances from the coast plain around Puget Sound in Washington State reached the best DBH, height, and volume production data. The variability in growth performance between coast and inland provenances was lower than compared to that of Douglas fir in European trials. The other American species, noble fir, grows slower, but still faster than the compared domestic Czech silver fir provenances. Both American species are suitable competitors of the native silver fir.

However, as health risk is a serious threat, the necessary caution should be taken when introducing exotic reproductive material. Although no attacks or damages had been observed in the trials with American species, health deterioration and damages are observed in other grand fir stands by honey root fungi and insects (*Pityokteines, Dreyfusia sp.*). The damages are apparently related to extreme droughts. Also, the total failure of *A. cilicica* and *A. pinsapo* provenances points out that long-distance transfers from ecologically dissimilar environments may be extremely risky.

Correlation between juvenile and mature performance and potential shifts of growth rate and ranking of provenances may be also of concern. Individual rank shifts can occur over longer time intervals; therefore, the growth trends of provenance regions, based on the performance of numerous populations, should be followed first of all as these are more reliable than data of individual provenances. This way the chance of selecting a source based on a single population misrepresenting its potential, caused by random genetic effects or incorrect sampling, may be avoided.

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REFERENCES

In addition to the publications cited in the study, the list contains further domestic papers on the subject, published in the Czech Republic, mostly in Czech language.

BERAN, F. (2006): Některé poznatky z hodnocení mezinárodního provenienčního pokusu s jedlí obrovskou – *Abies grandis* (Douglas) Lindl. [Some findings from the evaluation of international provenance experiment with a grand fir - *Abies grandis* (Douglas) Lindl.]. In: *Douglaska a jedle obrovská – opomíjení giganti* [*Douglas fir and grand fir - the giants ignored*]. Sborník recenzovaných referátů z konference [Proceedings reviewed papers from the conference]. Kostelec nad Černými lesy 12. –13. 10. 2006, ed. P. Neuhöferová, 146 s. – KPL FLE ČZU v Praze a ŠLP v Kostelci nad Černými lesy, pp. 17–27. (in Czech)

BERAN, F. – DOSTÁL, J. (2012): Jedle vznešená (*Abies procera* Rehd.), vzácný druh jedle v lesích ČR. [Noble Fir (*Abies procera* Rehd.), a rare species of fir in the Czech Republic forests]. Zprávy lesnického výzkumu 57 (4): 361–371. (in Czech)

BERAN, F. – ŠINDELÁŘ, J. (1996): Perspektivy vybraných cizokrajných dřevin v lesním hospodářství České republiky [Prospects for selected exotic trees in the Czech Republic forestry]. Lesnictví-Forestry 42 (8): 337–355. (in Czech)

BERAN, F. – CAFOUREK, J. – NOVOTNÝ, P. (2016): Návrh změny pravidel přenosu reprodukčního materiálu jedle obrovské (*A. grandis* /Douglas ex D. Con/ Lindl.) z USA a Kanady [Proposal for the change of rules for grand fir (*A. grandis* /Douglas ex D. Con/ Lindl.) forest reproductive material transfer from the USA and Canada]. Forestry and Game Management Research Institute, Strnady 136, 252 02 Jiloviste, Czech Republic, 15 pp. (in Czech)

BURZYNSKI, G. – VANČURA, K. (1985): Comparative analysis of provenance experiment with the grand fir (*Abies grandis* Lindl.), IUFRO 1976, in Poland and Czechoslovakia. Communicationes Instituti Forestalis Bohemicae 14: 25–40.

DOSTÁL, J. – FRÝDL, J. – BERAN, F. – FULÍN, M. (2016): Evaluation of quantitative and qualitative characteristics of various species of genus *Abies* in the Czech Republic. In: *IUFRO Abies 2016*, Proceedings, Hokkaido University, Sapporo, Japan, pp. 56.

FRÝDL, J. – MALÁ, J. – PROCHÁZKOVÁ, Z. (2011): Forest Tree Species Breeding and Improvement Programs in the Forestry and Game Management Research Institute (FGMRI/VÚLHM). In: *Applied Forestry Research in the 21st Century*. *Book of abstracts.* International conference held on the occasion of the 90th anniversary of the Forestry and Game Management Research Institute, Prague-Průhonice September 13–15 2011, s. 52. Strnady, FGMRI, 88 pp.

KRAJMEROVÁ, D. – PAULE, L. – ZHELEV, P. – VOLEKOVÁ, M. – EVTIMOV, I. – GAGOV, V. – GÖMÖRY, D. (2015): Natural hybridization in eastern-Mediterranean firs: The case of *Abies borisii-regis*. Plant Biosystems 150 (6): 1189–1199. https://doi.org/10.1080/11263504.2015.1011723

KREJZEK, R. – NOVOTNÝ, P. – PODRÁZSKÝ, V. – BERAN, F. – DOSTÁL, J. (2015): Evaluation of the IUFRO provenance plot with grand fir in the Habr locality (Western Bohemia) at the age of 31 years. Journal of Forest Science 61 (12): 551–561. https://doi.org/10.17221/74/2015-JFS

MaP-FGR utilized for: COST Action FP1202 Strengthening conservation: a key issue for adaptation of marginal/peripheral populations of forest trees to climate change in Europe. http://map-fgr.entecra.it;

MÁTYÁS, C. – KÓCZÁN-HORVÁTH, A. – DOSTÁL, J. – BERAN, F. – ČÁP, J. – BOŽIČ, G. – FRÝDL, J. (2018): Between- and within species sensitivity to changing climatic conditions in *Abies* species. (unpublished manuscript)

MÁTYÁS, C. – NAGY, L. – UJVÁRI-JÁRMAY, É. (2010): Genetic background of response of trees to aridification at the xeric forest limit and consequences for bioclimatic modelling. Forstarchiv 81: 130–141.

MZe (2016): Výroční zpráva o stavu lesa a lesního hospodářství České republiky v roce 2016 [Annual report on the state of forests and forest management in the Czech Republic in 2016]. (Accessed on 19th March, 2017). (in Czech)

NCSS (2010. NCSS 10 Statistical Software. NCSS, LLC. Kaysville, Utah, USA. Available at http://www.ncss.com/software/ncss.

NOVOTNÝ, P. (2010): Problematika pěstování kaštanovníku jedlého (*Castanea sativa* Mill.) [The issue of the sweet chestnut (*Castanea sativa* Mill.) cultivation]. In: Aktuality v pěstování introdukovaných dřevin [News in the cultivation of introduced species]. Sborník z konference, Kostelec nad Černými lesy, 23. 9. 2010, ed. H. Prknová, pp. 53–60. – FLD ČZU v Praze, Kostelec nad Černými lesy, 87 pp. (in Czech)

NOVOTNÝ, P. – BERAN, F. (2008): Introdukované dřeviny v lesním hospodářství ČR [Introduced tree species in the Czech Republic forestry]. Lesnická práce 87 (6): 394–395. (in Czech)

NOVOTNÝ, P. – ČÁP, J. – PEŠKOVÁ, V. – MODLINGER, R. (2010): Vyhodnocení růstu proveniencí borovice černé (*Pinus nigra* Arnold) na výzkumné ploše č. 41 – Lesy Steinských, Roblín ve věku 41 let. In: Aktuality v pěstování introdukovaných dřevin. [Evaluation of growth provenances of black pine (*Pinus nigra* Arnold) on a research plot no. 41 - Steinských Forests, Roblín, at the age of 41 years. In: News in the cultivation of introduced species]. Sborník z konference, Kostelec nad Černými lesy, 23. 9. 2010, ed. H. Prknová, pp. 61–67. – FLD ČZU v Praze, Kostelec nad Černými lesy, 87 pp. (in Czech)

NOVOTNÝ, P. – MODLINGER, R. – PEŠKOVÁ, V. – ČÁP, J. (2012). Vyhodnocení růstu a zdravotního stavu borovice černé (*Pinus nigra* Arnold) ve středních Čechách ve věku 41 let [Evaluation of growth and the health status of black pine (*Pinus nigra* Arnold) in central Bohemia, at the age of 41 years]. Zprávy lesnického výzkumu 57 (3): 266–273. (in Czech)

OTTO, H.J. (1993): Fremdländische Baumarten in der Waldbauplanung [Exotic tree species in silvicultural planning]. Forst und Holz 48: 454–456. (in German)

PETRÁŠ, R. – PAJTÍK, J. (1991): Sústava česko-slovenských objemových tabuliek drevín [Czech-Slovak system of tree species volume tables]. Lesnícky časopis 37 (1): 49–56. (in Czech)

QC-Expert 2.5. Trilobyte Statistical Software. TriloByte, Ltd. Pardubice - Staré Hradiště, Czech Republic. Available at http://www.trilobyte.cz/Nase-Produkty/QC-Expert.html

RAU, H.M. – KÖNIG, A. – RUETZ, W. – RUMPF, H. – SCHÖNFELDER, E. (2008): Ergebnisse des westdeutschen IUFRO-Küstentannen-Provenienzversuches im Alter 27 [Results of the West German provenance trial of grand fir at the age of 27 years]. Beiträge aus der Nordwestdeutschen

Forstlichen Versuchsanstalt. Göttingen, Universitätsdruckerei im Universitätsverlag Göttingen, 65 pp. (in German)

ŠIKA, A. – VANČURA, K. (1987): První výsledky provenienčního výzkumu jedle obrovské (*Abies grandis* /Douglas./ Lindl.) v ČSR [The first results of Grand fir (*A. grandis* /Douglas ex D. Con/ Lindl.) provenance research In Czechoslovakia]. Lesnictví 33: 399–412. (in Czech)

ŠINDELÁŘ, J. (1974): Možnosti zvyšování produkce dřeva šlechtěním a introdukcí dřevin [Possibilities of wood production increasing by tree species breeding and introduction]. Lesnická práce 53 (3): 101–107. (in Czech)

ŠINDELÁŘ, J. (1993): Biodiverzita [Biodiversity]. In: Ministerská konference o ochraně lesů v Evropě. Sborník závěrů z pracovních seminářů [Ministerial Conference on the Protection of Forests in Europe. Proceedings of the workshops‘ conclusions]. Kostelec nad Černými lesy, pp. 528–539. (in Czech)

ŠINDELÁŘ, J. (1994): Možnosti optimalizace druhové skladby lesů ČR [Possibilities of optimization of tree species composition in the Czech Republic forests]. *Studie* [Study], VÚLHM Jíloviště-Strnady, pp. 82. (in Czech)

ŠINDELÁŘ, J. (1996): Představa o druhovém složení původních přirozených lesů na území České republiky [The concept of indigenous species composition of natural forests in the Czech Republic]. Živa 44 (82), 1, 2–3. (in Czech)

ŠINDELÁŘ, J. – BERAN, F. (2004): Srovnání druhů rodu *Abies* v lesích města Písku [Comparison of *Abies* species in the Písek Municipal Forests]. Lesnická práce 83 (1): 19–21. (in Czech)

ŠINDELÁŘ, J. – BERAN, F. (2008a): Comparison of some exotic species of *Abies* genus with chosen silver fir provenances on the plots of town Písek. Communicationes Instituti Forestalis Bohemicae 24: 99–113.

ŠINDELÁŘ, J. – FRÝDL, J. (2004): Obecné předpoklady pro využívání vhodných cizokrajných lesních dřevin v lesním hospodářství ČR. In: *Introdukované dřeviny a jejich produkční a ekologický význam.* [General requirements for the appropriate use of exotic forest tree species in the Czech Republic forestry. In: Introduced species and their production and ecological importance]. *Sborník z konference*, Kostelec nad Černými lesy 10.–11. 11. 2004, ed. P. Neuhöferová, 192 pp. – KPL FLE ČZU, Praha, pp. 9–14. (in Czech)

ŠINDELÁŘ, J. – FRÝDL, J. (2008): K problematice genetických změn v populacích lesních dřevin v důsledku narušování lesů škodlivými vlivy prostředí [Towards genetic changes in populations of forest tree species due to forest disturbance by harmful environmental influences]. Zprávy lesnického výzkumu 53 (2): 116–119. (in Czech)

ŠINDELÁŘ, J. – NOVOTNÝ, P. (2004): Možnosti a perspektivy uplatňování ořešáku černého (*Juglans nigra* L.) v lesním hospodářství ČR. In: *Introdukované dřeviny a jejich produkční a ekologický význam. [*Possibilities and perspectives of black walnut (Juglans nigra L.) utilization in the Czech Republic forestry. In: Introduced species and their production and ecological importance]. Sborník z konference, Kostelec nad Černými lesy 10.–11. 11. 2004, ed. P. Neuhöferová, 192 pp. – KPL FLE ČZU, Praha, pp. 117–126. (in Czech)

ŠKORPÍK, P. – NOVOTNÝ, P. – BERAN, F. – HYNEK, V. – DOSTÁL, J. – STEJSKAL, J. (2013): Výsledky hodnocení proveniencí jedle obrovské (*Abies grandis* /Douglas ex D. Don/ Lindl.) na lokalitě Strnady-Gamapole ve věku 28 let [Results of grand fir (*Abies grandis* /Douglas ex D. Don/ Lindl.) provenances evaluation on the locality Strnady-Gamapole at the age of 28 years]. Zprávy lesnického výzkumu 58 (1): 58–65. (in Czech)

VANČURA, K. (1990): Provenienční pokus s jedlí obrovskou série IUFRO ve věku 13 let [Provenance experiment with grand fir of the IUFRO series at the age of 13 years]. Práce VÚLHM 75: 47–66.

VANČURA, K. – BERAN, F. (1996). Zhodnocení výzkumných ploch s cizokrajnými druhy rodu *Abies* [Evaluation of research plots with exotic *Abies* species]. Závěrečná zpráva [Final Report]. VÚLHM, Jíloviště-Strnady, 16 p. (in Czech)

Further related Czech literature, not cited in the text

ŠINDELÁŘ, J. – BERAN, F. (2008b): Exotic species of fir (*Abies* spec. div.) at the age of 30 years in the nature forest region No. 10 – Středočeská pahorkatina (Central Bohemian Upland). Communicationes Instituti Forestalis Bohemicae 24: 115–130.

ŠINDELÁŘ, J. – BERAN, F. – FRÝDL, J. – NOVOTNÝ, P. (2006a): K možnostem lesnického využití některých cizokrajných druhů rodu *Abies* v ČR na základě hodnocení jejich růstu na lokalitě Jíloviště-Cukrák ve věku 30 let [Towards the forestry use of some exotic *Abies* species in the Czech Republic on the basis of their growth evaluation on the locality Jíloviště-Cukrák at the age of 30 years]. Zprávy lesnického výzkumu 51 (4): 235–242. (in Czech)

ŠINDELÁŘ, J. – BERAN, F. – FRÝDL, J. – NOVOTNÝ, P. – CHLÁDEK, J. (2006b): Towards possibilities of some exotic *Abies* species use in the Czech Republic forestry practice on the base of evaluation of their progenies growth on the locality Jiloviste – Cukrak in Central Bohemia at the age of 30 years. In: Low input breeding and genetic conservation of forest tree species. *Volume of abstracts of the IUFRO Division 2* Conference, Antalya, Turkey, 9.–13. 10. 2006, p. 69.

APPENDIX

Table 3. Trial No. 64 - Kruskal-Wallis Multiple-Comparison Z-Value Tests

DBH	
Prov. No.	Different from provenances
130	228, S2
132	228, S2
223	228, S2
74	228, S2
109	228, S2
136	228, S2
137	228, S2
81	
S2	74, 109, 130, 132, 136, 137, 223
228	74, 109, 130, 132, 136, 137, 223
Height	
Prov. No.	Different from provenances
74	81, 109, 136, 137, 223, 228, S2
132	109, 136, 137, 228, S2
130	109, 136, 137, 228, S2
81	74
223	74, 109, 136, 137
228	74, 130, 132
S2	74, 130, 132
137	74, 130, 132, 223
109	74, 130, 132, 223
136	74, 130, 132, 223
Volume	
Prov. No.	Different from provenances
74	228, S2
130	228, S2
223	228
132	228, S2
109	
136	
137	
81	
228	74, 130, 132, 223
S2	74, 130, 132

Table 4. Trial No. 213 - Kruskal-Wallis Multiple-Comparison Z-Value Tests

DBH	
Prov. No.	Different from provenances
12025	12002, 12003, 12004, 12006, 12008, 12011, 12013, 12015, 12019, 12020, 12031, 12037, 12038, 12040, 12041, 12042, 12043, 12044, 12045, 12046
12026	12002, 12003, 12040
12016	12002, 12003, 12040, 12041, 12043
12008	12002, 12003, 12025, 12040, 12041, 12043
12042	12002, 12003, 12025, 12040, 12041, 12043
12031	12002, 12003, 12025, 12040, 12041, 12043
12044	12002, 12003, 12025, 12040
12013	12003, 12025, 12040
12006	12002, 12003, 12025, 12040
12011	12002, 12003, 12025, 12040
12015	12002, 12003, 12025, 12040
12037	12002, 12003, 12025, 12040
12045	12003, 12025, 12040
12019	12025
12004	12003, 12025, 12040
12047	12002, 12003, 12025, 12040
12046	12003, 12025, 12040
12038	12003, 12025, 12040
12020	12025
12041	12003, 12008, 12016, 12025, 12031, 12040, 12042
12043	12008, 12016, 12025, 12031, 12042
12003	12004, 12006, 12008, 12011, 12013, 12015, 12016, 12025, 12026, 12031, 12037, 12038, 12041, 12042, 12044, 12045, 12046, 12047
12002	12006, 12008, 12011, 12015, 12016, 12025, 12026, 12031, 12037, 12042, 12044, 12047
12040	12004, 12006, 12008, 12011, 12013, 12015, 12016, 12025, 12026, 12031, 12037, 12038, 12041, 12042, 12044, 12045, 12046, 12047

Table 4 cont. Trial No. 213 - Kruskal-Wallis Multiple-Comparison Z-Value Tests

Height	
Prov. No.	Different from provenances
12025	12002, 12003, 12004, 12006, 12008, 12011, 12013, 12015, 12019, 12020, 12031, 12037, 12038, 12040, 12041, 12042, 12043, 12044, 12045, 12046, 12047
12016	12002, 12003, 12004, 12006, 12013, 12015, 12038, 12040, 12041, 12042, 12043, 12044, 12045, 12046, 12047
12026	12002, 12003, 12004, 12038, 12040, 12041, 12044, 12046
12020	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12046
12008	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12044, 12046
12011	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12042, 12043, 12044, 12045, 12046, 12047
12019	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12044, 12046
12015	12002, 12003, 12004, 12016, 12025, 12038, 12040, 12046
12042	12002, 12003, 12004, 12011, 12016, 12025, 12038, 12040, 12046
12037	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12044, 12046
12043	12002, 12003, 12004, 12011, 12016, 12025, 12038, 12040, 12046
12031	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12044, 12046
12006	12002, 12003, 12004, 12016, 12025, 12038, 12040, 12041, 12046
12045	12002, 12003, 12004, 12011, 12016, 12025, 12040
12013	12002, 12003, 12004, 12016, 12025, 12038, 12040, 12046
12047	12002, 12003, 12004, 12011, 12016, 12025, 12040
12044	12002, 12008, 12011, 12016, 12019, 12025, 12026, 12031, 12037, 12040
12038	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043
12041	12006, 12008, 12011, 12016, 12019, 12020, 12025, 12026, 12031, 12037
12046	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043
12003	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043, 12045, 12047
12004	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043, 12045, 12047
12040	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043, 12044, 12045, 12047
12002	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12020, 12025, 12026, 12031, 12037, 12042, 12043, 12044, 12045, 12047

Table 4 cont. Trial No. 213 - Kruskal-Wallis Multiple-Comparison Z-Value Tests

Volume	
Prov. No.	Different from provenances
12040	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12025, 12026, 12031, 12037, 12038, 12042, 12043, 12044, 12045, 12046, 12047
12002	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12025, 12026, 12031, 12037, 12042, 12044, 12045, 12047
12003	12006, 12008, 12011, 12013, 12015, 12016, 12019, 12025, 12026, 12031, 12037, 12038, 12042, 12043, 12044, 12045, 12047
12041	12008, 12016, 12025, 12031, 12042
12043	12003, 12008, 12016, 12025, 12031, 12040
12046	12008, 12016, 12025, 12031, 12040
12045	12002, 12003, 12016, 12025, 12040
12038	12003, 12008, 12016, 12025, 12031, 12040
12004	12008, 12016, 12025, 12031, 12042
12047	12002, 12003, 12025, 12040
12020	12025
12019	12002, 12003, 12025, 12040
12044	12002, 12003, 12025, 12040
12037	12002, 12003, 12025, 12040
12013	12002, 12003, 12025, 12040
12006	12002, 12003, 12025, 12040
12031	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12043, 12046
12011	12002, 12003, 12025, 12040
12015	12002, 12003, 12025, 12040
12042	12002, 12003, 12004, 12025, 12040, 12041
12016	12002, 12003, 12004, 12038, 12040, 12041, 12043, 12045, 12046
12008	12002, 12003, 12004, 12025, 12038, 12040, 12041, 12043, 12046
12026	12002, 12003, 12040
12025	12002, 12003, 12004, 12006, 12008, 12011, 12013, 12015, 12019, 12020, 12031, 12037, 12038, 12040, 12041, 12042, 12043, 12044, 12045, 12046, 12047

Table 5. Trial No. 219 - Kruskal-Wallis Multiple-Comparison Z-Value Tests

DBH

Prov. No.	Different from provenances
12002	13004, 13006, 13011, 13014, 13018, 13021, CZ - 0
13004	12001, 12002, CZ - 0
13018	12001, 12002, CZ - 0
13006	12001, 12002, CZ - 0
13021	12001, 12002, CZ - 0
13011	12001, 12002, CZ - 0
13014	12001, 12002, CZ - 0
CZ - 0	12001, 12002, 13004, 13006, 13011, 13014, 13018, 13021
12001	13004, 13006, 13011, 13014, 13018, 13021, CZ - 0

Height

Prov. No.	Different from provenances
12002	CZ - 0, 13004, 13011, 13006, 13021, 13014, 13018
13004	12001, 12002, 13018, CZ - 0, 13014, 13011
13021	12001, 12002, CZ - 0
13018	12001, CZ - 0, 12002, 13004
13014	12001, 12002, CZ - 0, 13004
13011	12001, 12002, CZ - 0, 13004
CZ - 0	12001, 12002, 13018, 13014, 13011, 13021, 13006, 13004
13006	12001, 12002, CZ - 0
12001	CZ - 0, 13004, 13011, 13021, 13014, 13006, 13018

Volume

Prov. No.	Different from provenances
12001	13004, 13006, 13011, 13014, 13018, 13021, CZ - 0
12002	13004, 13006, 13011, 13014, 13018, 13021, CZ - 0
13014	12001, 12002, CZ - 0
13018	12001, 12002, CZ - 0
13006	12001, 12002, CZ - 0
13011	12001, 12002, CZ - 0
13004	12001, 12002, CZ - 0
13021	12001, 12002, CZ - 0
CZ - 0	12001, 12002, 13004, 13006, 13011, 13014, 13018, 13021

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An Approach for Computing the Heat Sources in Logs Subjected to Freezing

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Abstract – This study suggests an approach for computing the specific energies of the internal heat sources in logs subjected to freezing. The approach maximally considers the physics of the freezing processes of both the free and the bound water in wood. It reflects the influence on the mentioned energies of the wood density above and below the hygroscopic range. It also considers the icing degrees formed separately by both the free and bound water in the logs, as well as the influence of the fiber saturation point of each wood species on its respective amount of non-frozen water depending on temperatures below 272.15 K. Mathematical descriptions of the specific heat energies $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ released in logs during free water freezing in the range from 0 °C to –1 °C and of the bound water below –1 °C, respectively, have been executed. These descriptions are introduced in own 2D non-linear mathematical model of the freezing process of logs. For the solution of the model and computation of the energies $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$, a software program based on the suggested approach and mathematical descriptions was prepared in FORTRAN, which was input into the calculation environment of Visual Fortran. With the aid of the program, computations were completed to determine the energies $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ and their sum, $Q_{\text{v-total}}$ of a beech log subjected to freezing. The beech log had a diameter of 0.24 m, a length of 0.48 m, an initial temperature of 20.5 °C, a basic density of 683 $\text{kg}\cdot\text{m}^{-3}$, and a moisture content of 0.48 $\text{kg}\cdot\text{kg}^{-1}$ during its 30 hours in a freezer at approximately –30 °C.

internal heat sources / latent heat / free water / bound water / freezing / logs

Kivonat – Egy módszer a fagyásnak kitett farönk belső hőmérlegének számítására. A jelen tanulmány egy olyan módszert ír le, amellyel fagyásnak kitett farönkök belső hőforrásainak fajlagos energiái becsülhetők. A módszer teljes mértékben figyelembe veszi a szabad- és kötött víztartalom fagyási folyamatainak fizikai vonatkozásait valamint tükrözi a fa sűrűségének hatását az említett energiákra a rosttelítettségi tartomány alatt és felett. Emellett számol a szabad- és a kötött víz által okozott jegesedés mértékével, valamint a rosttelítettségi pontnak a nem-fagyott víz mennyiségére gyakorolt hatásával 272,15 K hőmérséklet alatt. Módszerünkkel matematikai becslést adunk a farönkökben fagyás során felszabaduló fajlagos energiákra ($Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$) a szabad víz esetében a 0 °C és –1 °C közötti hőmérséklet tartományra, kötött víz esetében –1 °C alatti körülményekre. A számítások eredményeit integráltuk a farönkök fagyási folymatait modellező saját fejlesztésű 2 dimenziós nemlineáris modellünkbe. A közölt matemaikai eljárások és módszerek alapján egy FORTRAN szoftver került kifejlesztésre, mellyel a $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ energiák értékei számíthatók és a modell megoldható. A fejlesztett szoftvert Visual Fortran környezetbe adaptáltunk. A program segítségével egy fagyásnak kitett bükk rönk esetében kiszámoltuk a $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ energiákat, valamint ezek összegét, $Q_{\text{v-total}}$-t. A vizsgált bükk törzs 0,24 m átmérőjű, 0,48 m hosszú volt. A kb. –30 °C-on végzett fagyasztás megkezdése előtt a rönk kezdeti hőmérséklete 20,5 °C, sűrűsége 683 $\text{kg}\cdot\text{m}^{-3}$, nedvesség tartalma pedig 0.48 $\text{kg}\cdot\text{kg}^{-1}$ volt.

belső hő források / látens hő / szabad víz / kötött víz / fagyás / farönk

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1 INTRODUCTION

The duration and energy consumption of thermally treating frozen logs in the winter to plasticize the wood for veneer production depend on the degree of icing (Chudinov 1966, 1968, Shubin 1990, Požgaj et al. 1997, Trebula – Klement 2002, Videlov 2003, Pervan 2009, Deliiski – Dzurenda 2010, Deliiski 2011, 2013b). Reports about the temperature distribution in frozen logs subjected to defrosting are limited in the accessible specialized literature (Steinhagen 1986, 1991, Steinhagen – Lee 1988, Khattabi – Steinhagen 1992, 1993, 1995, Deliiski 2004, 2009, 2011, Deliiski – Dzurenda 2010, Deliiski et al. 2015a, Hadjiski – Deliiski 2015, 2016). In addition, research into the temperature distribution in logs during the freezing process has been limited (Deliiski – Tumbarkova 2016, 2017). Thus, there is considerable scientific and practical interest in the modeling and the multi-parameter study of the freezing process of logs.

Different engineering and technological calculations require the determination of the non-stationary temperature field in logs depending on the temperature of the gaseous or liquid medium influencing them. These calculations also require information concerning the duration of logs remaining in this medium. Such calculations are completed using mathematical models that adequately describe the complex freezing processes of both the free and bound water in wood. The internal sources of latent heat of the water, which are released within the wood during water crystallization and influence the duration and energy consumption of a log's freezing process, are an important component of these models (Deliiski – Tumbarkova 2017). No information about the approaches for quantitative determination of the internal heat sources during wood freezing exists in the available literature regarding the hydrothermal treatment of frozen wood materials.

The present paper aims to suggest an approach to compute the specific energies of internal heat sources in logs subjected to freezing; the approach takes into account, to a maximum degree, the physics of the freezing processes of both the free and bound water in wood.

Symbols:

c	– specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$),
D	– diameter (m),
L	– specific latent heat ($J \cdot kg^{-1}$) or length (m),
N	– number of the knots of the calculation mesh, (-),
Q	– internal heat source ($J \cdot m^{-3}$) or specific heat energy ($Wh \cdot m^{-3}$),
R	– radius (m),
r	– radial coordinate: $0 \le r \le R$ (m),
S	– shrinkage (%),
T	– temperature (K): $T = t + 273.15$,
t	– temperature (^{o}C): $t = T - 273.15$,
u	– moisture content ($kg.kg^{-1}$ = %/100),
z	– longitudinal coordinate: $0 \le z \le L/2$ (m),
α	– heat transfer coefficients between log surfaces and the surrounding air medium ($W \cdot m^{-2} \cdot K^{-1}$),
λ	– thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$),
ρ	– density ($kg \cdot m^{-3}$),
σ	– root square mean error (^{o}C),
τ	– time (s),
Ψ	– relative icing degree of logs or relative degree of solidification of the metal (-).

Subscripts:

avg – average (for root square mean error of calculated values of the temperature),
b – basic (for wood density, based on dry mass divided to green volume),
cr – crystallization,
dfr – defrosting,
fr – freezing,
fsp – fiber saturation point,
ice – ice (for logs' icing degrees or for numbers of knots of the calculation mesh),
m – medium,
M – metal,
Ms – metal in solid state,
nfw – non-frozen water,
0 – initial,
p – parallel to the wood fibers,
r – radial direction,
total – total (for the whole amount of knots of the calculation mesh or for energy of the latent heat sources),
v – volume,
vM – volume of the metal,
w – wood,
we – wood effective (for specific heat capacity of the wood),
wL – wood with liquid water in it,
wS – wood with solid state of water (ice) in it,
wUfsp – wood at fsp,
wUnfw– wood at nfw.

Superscripts:

272.15 – at 272.15 K, i.e. at –1 °C,
293.15 – at 293.15 K, i.e. at 20 °C.

2 MATERIALS AND METHODS

Mathematical model of the 2D heat distribution in logs subjected to freezing

The heat conduction equation can describe the distribution mechanism in logs subjected to freezing. When log length does not exceed log diameter by more than 3 – 4 times, the heat transfer through the frontal sides of the logs cannot be neglected because it influences the temperature change of the log cross sections, which are equally distant from the frontal sides (Chudinov 1966, 1968, Shubin 1990, Deliiski 2011). In such cases, the following 2D model for the calculation of the temperature change in the longitudinal sections of the logs (i.e. along the coordinates *r* and *z* of these sections) during their freezing in an air medium can be used (Deliiski – Tumbarkova 2017):

$$c_{\mathrm{we}}\rho_{\mathrm{w}}\frac{\partial T(r,z,\tau)}{\partial \tau}=\lambda_{\mathrm{wr}}\left[\frac{\partial^{2}T(r,z,\tau)}{\partial r^{2}}+\frac{1}{r}.\frac{\partial T(r,z,\tau)}{\partial r}\right]+\frac{\partial \lambda_{\mathrm{wr}}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial r}\right]^{2}+ \\ +\lambda_{\mathrm{wp}}\frac{\partial^{2}T(r,z,\tau)}{\partial z^{2}}+\frac{\partial \lambda_{\mathrm{wp}}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial z}\right]^{2}+Q_{\mathrm{v}} \qquad (1)$$

with an initial condition

$$T(r,z,0)=T_{0} \qquad (2)$$

and boundary conditions for convective heat transfer:

- along the radial coordinate *r* on the logs' frontal surface during the freezing process:

$$\frac{\mathrm{d}T(r,0,\tau)}{\mathrm{d}r}=-\frac{\alpha_{\text{p-fr}}(r,0,\tau)}{\lambda_{\text{wp}}(r,0,\tau)}\left[T(r,0,\tau)-T_{\text{m-fr}}(\tau)\right] \tag{3}$$

- along the longitudinal coordinate z on the logs' cylindrical surface during the freezing:

$$\frac{\mathrm{d}T(0,z,\tau)}{\mathrm{d}z}=-\frac{\alpha_{\text{r-fr}}(0,z,\tau)}{\lambda_{\text{wr}}(0,z,\tau)}\left[T(0,z,\tau)-T_{\text{m-fr}}(\tau)\right]. \tag{4}$$

Equations (1) to (4) represent a common form of a mathematical model of 2D heat distribution in logs subjected to freezing.

Mathematical description of the internal heat sources in logs subjected to freezing

The internal heat source in logs, Q_v, in eq. (1) reflects the influence of the latent heat of the water in the wood on the logs' freezing process. As mentioned above, no information on the approaches of the quantitative determination of the heat source Q_v could be found in the available literature for hydrothermal treatment of frozen wood materials. That is why, as a methodology for the determination of Q_v during the freezing of logs, the present paper applies a perspective that has been applied for the determination of the internal heat source Q_vM during the solidification process of melted metal (Salcudean – Abdullah 1988, Dantzig 1989, Hu – Argyropoulos 1996, Mihailov – Petkov 2010). According to this methodology, the heat source Q_vM is equal to

$$Q_\text{vM}=\rho_\text{MS}L_\text{crM}\frac{\partial\psi_\text{MS}}{\partial\tau}. \tag{5}$$

Based on the physics of the log freezing process, for the density of the wood, ρ_w, during its freezing, it could be written that

$$\rho_\text{w}=\rho_\text{wL}+\rho_\text{wS}, \tag{6}$$

$$\rho_\text{wS}=\rho_\text{w}-\rho_\text{wL} \tag{7}$$

For the numerical solution of eq. (1) it is suitable to present eq. (7) in the following form:

$$\rho_\text{wS}=\left(\rho_\text{w}-\rho_\text{wL}\right)\cdot\frac{\rho_\text{w}}{\rho_\text{w}}. \tag{8}$$

Using eq. (8), analogously to eq. (5), for the internal heat source in the wood it is obtained that

$$Q_\text{v}=\rho_\text{wS}\cdot L_\text{cr-ice}\frac{\partial\Psi_\text{ice}}{\partial\tau}=\rho_\text{w}\cdot\left(\frac{\rho_\text{w}-\rho_\text{wL}}{\rho_\text{w}}\right)\cdot L_\text{cr-ice}\frac{\partial\psi_\text{ice}}{\partial\tau}, \tag{9}$$

where $L_\text{cr–ice}$ is the specific latent heat of the water, also known as the "heat of crystallization". This heat is released in the wood during the water freezing process and is equal to $L_\text{cr–ice}=3.34\cdot10^5$ J·kg^{-1} (Chudinov 1966, 1968, Efimov 1985, Pahi 2010, Deliiski – Tumbakova 2016).

Based on the data in the references cited above, the value of $3.34\cdot10^5$ J·kg^{-1} as constant for the specific latent heat for both the free and the bound water in the wood materials has been accepted in the present paper. Our wide experiments with different wood species showed that the free water freezing occurs in the small range from 0 °C to –1 °C (Deliiski – Tumbarkova 2016). This means that the acceptance of the non-temperature dependent constant value of $3.34 \cdot 10^5$ J·kg^{-1} as a specific latent heat of the free water is correct.

We did not find data in the accessible specialized literature that reflects the temperature dependence of the specific latent heat of bound water in the wood. Rogers – Yau 1989 contains data for the specific latent heat of the sublimation and deposition from and into ice in the range from –40 °C to 0 °C (in J·g^{-1}), which can be approximated by the following equation: $L_{\mathrm{ice}} = 2834.2 - 0.29T - 0.004T^2$. Deposition is a thermodynamic process – a phase transition in which gas (or water steam) solidifies without passing through the liquid phase. The reverse of deposition is sublimation.

Calculation of L_{ice} with the equation given above at T = 243.15 K (i.e. at t = –30 °C, which is the lowest T reached during our experiment described below), and at T = 272.15 K (i.e. at t = –1 °C) show that the obtained results differ from each other by only 2.7%. Because liquid water is a far more stable substance compared to steam, it can be surmised that the specific latent heat of the bound water at t = –30 °C differs negligibly from its value at t = –1 °C. This allowed us to accept a constant value of the specific latent heat of the bound water during log freezing equal to $3.34 \cdot 10^5$ J·kg^{-1}.

Designating the expression in the brackets from eq. (9) with K_ψ, i.e.

$$K_\psi = \frac{\rho_{\mathrm{w}} - \rho_{\mathrm{wL}}}{\rho_{\mathrm{w}}} \tag{10}$$

and substituting eq. (10) into eq. (9), the following final expression for Q_{v} is obtained:

$$Q_{\mathrm{v}} = K_\psi \cdot \rho_{\mathrm{w}} \cdot L_{\mathrm{cr\text{-}ice}} \frac{\partial \psi_{\mathrm{ice}}}{\partial \tau}. \tag{11}$$

Mathematical description of the internal heat source in logs during freezing of the free water

According to eq. (11), during the free water freezing process in wood, the consequent formed source of latent heat $Q_{\mathrm{v\text{-}fw}}$ is equal to

$$Q_{\mathrm{v\text{-}fw}} = K_{\psi\mathrm{-fw}} \cdot \rho_{\mathrm{w}} \cdot L_{\mathrm{cr\text{-}ice}} \frac{\partial \psi_{\mathrm{ice\text{-}fw}}}{\partial \tau}, \tag{12}$$

where based on the physics of the process and on the form of eq. (10), it is obtained that

$$K_{\psi\mathrm{-fw}} = \frac{\rho_{\mathrm{w}} - \rho_{\mathrm{wUfsp}}}{\rho_{\mathrm{w}}}, \tag{13}$$

given that $\Psi_{\mathrm{ice\text{-}fw}}$ is the relative icing degree of the logs, which results from the freezing of the free water in them. An approach and an algorithm for its calculation are given in Deliiski – Tumbarkova (2017).

The difference $\rho_{\mathrm{w}} - \rho_{\mathrm{wUfsp}}$ in the right-hand part of eq. (13) reflects the entire mass of free water (in kg), which is contained in 1 m^3 of the logs.

The wood densities ρ_{w} and ρ_{wUfsp}, which participate in eq. (13), are determined above the hygroscopic range according to the below equations (Chudinov 1968, Pervan 2009, Deliiski 2011, Deliiski et al. 2015b, Hrčka 2017)

$$\rho_{\mathrm{w}} = \rho_{\mathrm{b}} \cdot (1 + u), \tag{14}$$

$$\rho_{\mathrm{wUfsp}} = \rho_{\mathrm{b}} \cdot (1 + u_{\mathrm{fsp}}). \tag{15}$$

Mathematical description of the internal heat source in logs during bound water freezing

Analogously to eq. (11) and eq. (12), during the freezing of the bound water in the wood, the consequently formed source of latent heat in it, $Q_{\text{v-bw}}$, is equal to

$$Q_{\text{v-bw}} = K_{\psi-\text{bw}} \cdot \rho_{\text{w}} \cdot L_{\text{cr-ice}} \frac{\partial \psi_{\text{ice-bw}}}{\partial \tau}, \tag{16}$$

where based on the physics of the process and on the form of eq. (10), it is obtained that

$$K_{\psi-\text{bw}} = \frac{\rho_{\text{wUfsp}} - \rho_{\text{wUnfw}}}{\rho_{\text{w}}}, \tag{17}$$

given that $\Psi_{\text{ice-bw}}$ is the relative icing degree of the logs, which results from the freezing of the bound water in them. An approach and an algorithm for its calculation are given in Deliiski – Tumbarkova (2017);

ρ_{wUnfw} – density of the wood, determined according to the following equation in relation to the present entirely liquid quantity of water in the wood (kg·m^{-3}), corresponding to the current temperature $T < 272.15$ K (Chudinov 1966, Deliiski 2013b):

$$\rho_{\text{wUnfw}} = \rho_{\text{b}} \cdot \frac{1 + u_{\text{nfw}}}{1 - \frac{S_{\text{v}}}{100}\left(u_{\text{fsp}}^{272.15} - u_{\text{nfw}}\right)}, \tag{18}$$

$u_{\text{fsp}}^{272.15}$ – fiber saturation point of the wood (kg·kg^{-1}) at $T = 272$ K (i.e. at $t = -1$ °C). At this temperature the freezing of the bound water begins in the wood.

While observing the freezing of the logs from various wood species with different moisture contents above the hygroscopic range during our wide experiments, we determined that freezing of the bound water begins at $t = -1$ °C (Deliiski – Tumbarkova 2016) and not at $t = -2$ °C, which was determined by Chudinov (1966, 1968) and, consequently, was widely accepted in the relevant literature.

The fiber saturation point $u_{\text{fsp}}^{272.15}$ can be calculated according to the following equation (Stamm 1964, Deliiski 2013a):

$$u_{\text{fsp}}^{272.15} = u_{\text{fsp}}^{293.15} + 0.021, \tag{19}$$

where $u_{\text{fsp}}^{293.15}$ is the standardized value of the fiber saturation point of the wood (kg·kg^{-1}) at 293.15 K, i.e. at 20 °C;

u_{nfw} – non-frozen quantity of bound water in the wood (kg·kg^{-1}) at a given temperature $T < 272.15$ K. It can be calculated according to the equation (Chudinov 1968, Deliiski 2013b):

$$u_{\text{nfw}} = 0.12 + \left(u_{\text{fsp}}^{272.15} - 0.12\right) \cdot \exp\left[0.0567(T - 272.15)\right] \quad @ \quad 213.15 \text{ K} \le T \le 272.15 \text{ K}. \tag{20}$$

Experimental research of the log freezing process

Experimentally obtained data about the change in the temperature field in logs during their freezing were required for the application and verification of the approach suggested above. Consequently, we carried out such experiments.

The logs subjected to experimental research, produced from the sapwood of freshly felled beech trunks (*Fagus sylvatica* L.), had diameters of D = 240 mm, lengths of L = 480 mm, and moisture contents above the hygroscopic range.

Before the experiments, four holes, with differing lengths and diameters of 6 mm were drilled into each log. Sensors with long metal casings were positioned in these four holes to measure wood temperature during the experiments. The point coordinates of the logs are as follows:

Point 1: along the radius r =30 mm and along the length z =120 mm;
Point 2: along the radius r =60 mm and along the length z =120 mm;
Point 3: along the radius r =90 mm and along the length z =180 mm;
Point 4: along the radius r=120 mm and along the length z=240 mm.

These characteristic point coordinates make it possible to sense the impact of the heat fluxes simultaneously in radial and longitudinal directions on the temperature distribution in logs during the freezing process.

For log freezing according to the methodology suggested by the authors (Deliiski – Tumbarkova 2016), a horizontal freezer with a fitted with temperature sensors and was horizontally situated on a special stand in the open freezer that was initially at room temperature. The freezer was then closed and switched on to full power; the temperature of the freezing air medium in the freezer, t_{m}, was lowered gradually until it reached approximately –30 °C (*Figure 1*).

The automatic measuring and recording of the temperature and humidity of the air processing medium in the freezer and the temperature in the 4 points in the logs during the experiments was implemented with the help of Data Logger type HygroLog NT3 produced by the Swiss firm ROTRONIC AG (http:/www.rotronic.com).

As an example, *Figure 1* presents the change in the temperature of the processing air medium, t_{m} and in its humidity, φ_{m}, and also in the temperature in four characteristic points of a beech log with u = 0.48 kg·kg^{-1} and ρ_{b} = 683 kg·m^{-3} during 30 h of freezing. The record of all data was made automatically by Data Logger in 5 minute intervals.

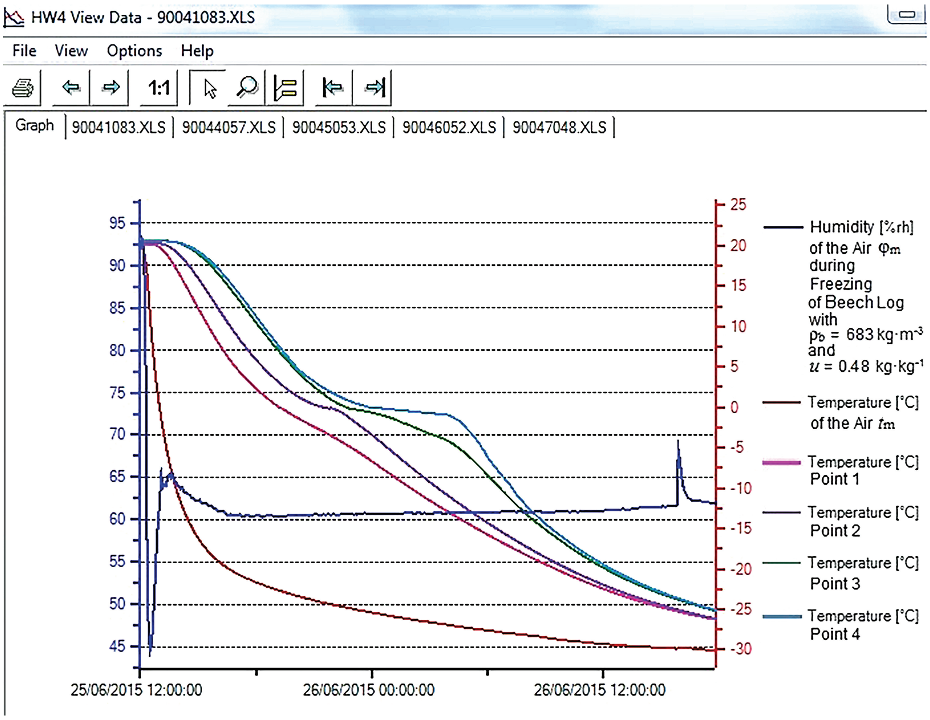

Figure 1. Experimentally determined change in t_m, φ_m, *and t in 4 characteristic points of beech log with* $D = 0.24$ *m,* $L = 0.48$ *m,* $u = 0.48$ *kg·kg*$^{-1}$, $\rho_b = 683$ *kg·m*$^{-3}$ *(i.e.* $\rho_w = 1010.8$ *kg·m*$^{-3}$*), and* $t_0 = 20.5$ *°C during its 30 h freezing*

3 RESULTS AND DISCUSSION

The mathematical descriptions of the internal heat sources $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ created above and the mathematical descriptions of the thermo-physical characteristics of frozen and non-frozen wood suggested earlier (Deliiski 2004, 2009, 2011, 2013a) are introduced in the mathematical model of the log freezing process, which consists of eqs. (1) – (20). This model has been solved with the help of explicit schemes of the finite difference method, analogous to the one used and described in (Deliiski 1977, 1988, 2009, 2011, Deliiski et al. 2015a) for the solution of a model of the heating process of prismatic and cylindrical wood materials. For this purpose, the calculation mesh has been built on ¼ of the longitudinal section of the log due to the circumstance that this ¼ is mirror symmetrical towards the remaining ¾ of the same section (*Figure 2*).

Computation of 2D non-stationary temperature distribution in logs during their freezing

For the numerical solution of the mathematical model, a software program was prepared in FORTRAN in the calculation environment of Visual Fortran Professional. With the help of the program, computations were made for the determination of the 2D non-stationary change of *t* in ¼ of the longitudinal section of the beech log whose experimentally determined temperature distribution is shown on *Figure 1* as an example.

The model was solved with step $\Delta r = \Delta z = 6$ mm along the coordinates *r* and *z* and with the same initial and boundary conditions, as they were during the experimental research. This means that the calculation mesh consists of 20 x 40 = 800 knots: 20 along *r* and 40 along *z*.

The solution of the model gives the non-stationary change of the temperature in calculation mesh knots (*Figure 2*) and of different energy characteristics of logs subjected to freezing.

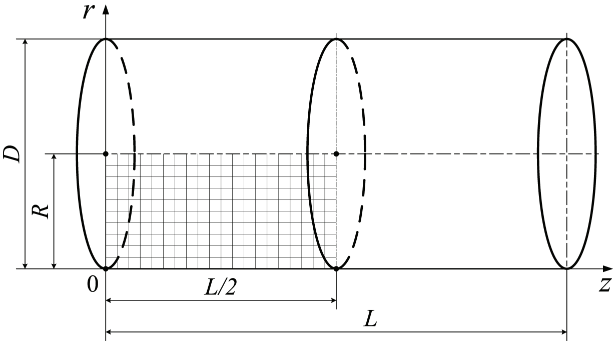

Figure 2. Positioning of the knots of the calculation mesh on ¼ of the longitudinal section of a log subjected to freezing

During the solving of the model, the mathematical descriptions of the thermo-physical characteristics of beech wood with fiber saturation point $u_{\text{fsp}}^{293.15} = 0.31 \text{ kg} \cdot \text{kg}^{-1}$ and volume shrinkage S_{v} = 17.3% were used (Nikolov – Videlov 1987).

The curvilinear change shown in *Figure 1* in the freezing air medium temperature, $T_{\text{m-fr}}$, with high accuracy (correlation 0.99 and Root Square Mean Error (*RSME*) 0.14 °C) has been approximated with the help of the software package Table Curve 2D (http://www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php) by the equation

$$T_{\text{m-fr}} = \frac{a_{\text{fr}} + c_{\text{fr}}\tau^{0.5} + e_{\text{fr}}\tau + g_{\text{fr}}\tau^{1.5}}{1 + b_{\text{fr}}\tau^{0.5} + d_{\text{fr}}\tau + f_{\text{fr}}\tau^{1.5} + h_{\text{fr}}\tau^{2}}, \tag{21}$$

whose coefficients are equal to:

$a_{\mathrm{fr}} = 293.0642230$, $b_{\mathrm{fr}} = -0.01985592$, $c_{\mathrm{fr}} = -5.66878889$, $d_{\mathrm{fr}} = -0.000298843$, $e_{\mathrm{fr}} = 0.080801194$, $f_{\mathrm{fr}} = -6.7184 \cdot 10^{-7}$, $g_{\mathrm{fr}} = -0.00019564$, and $h_{\mathrm{fr}} = -1.7404 \cdot 10^{-10}$.

Equation (21) was used for the solving of eqs. (3) and (4) of the model.

Figure 3 presents the change in $t_{\text{m-fr}}$, log surface temperature t_{s}, and t of 4 points of the studied beech log, which have the same coordinates, as during the experimental research.

The comparisons of the analogical curves in *Figure 1* and *Figure 3* show good qualitative and quantitative conformity between the calculated and experimentally determined changes in the complicated temperature field of the log during its freezing. It was calculated that the *RSME* for all studied four points in the log is $\sigma_{\mathrm{avg}} = 1.42$ °C.

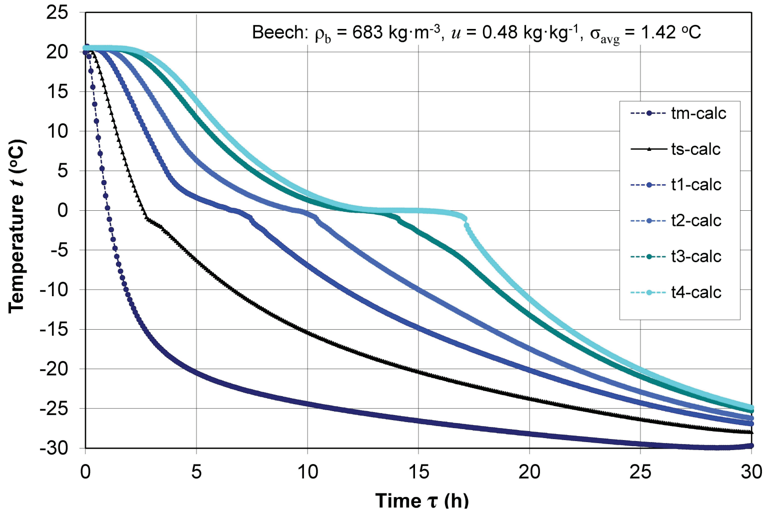

Figure 3. Calculated with the model change in $t_{m\text{-}fr}$, t_s, and t of 4 characteristic points of the studied beech log during its 30 h freezing

Change of log icing degrees $\Psi_{\text{ice-fw}}$ and $\Psi_{\text{ice-bw}}$

A logical condition in the software for the model's solution that registers and records the moments when the temperature of each knot decreases below 273.15 K (i.e. below 0 °C) and then registers and records temperature conditions for the crystallization of the free water separately for each knot has been introduced earlier (Deliiski – Tumbarkova 2016).

This means that the current number of the knots in which the free water already "crystallizes", $N_{\text{ice-fw}}$, has been constantly determined synchronously with the obtaining of the temperature distribution. The relationship between $N_{\text{ice-fw}}$ and the total number of knots of the entire calculation mesh, $N_{\text{ice-total}} = 800$, is used for the estimation of the current relative icing degree of logs, $\Psi_{\text{ice-fw}}$, which has happened by the freezing of the free water up to the present moment of log's cooling.

The relative icing degree of logs, which is caused by the freezing of the bound water in them, $\Psi_{\text{ice-bw}}$, has been estimated according to a similar but more complicated approach given in (Deliiski – Tumbarkova 2017). A logical condition to solve the model in the software has also been introduced. This condition registers and records the moments when the temperature of each of the knots decreases below 272.15 K (i.e. below –1 °C) and then temperature conditions for the crystallization of the bound water separately for each knot arise.

Figure 4 presents the calculated change of log icing degrees $\Psi_{\text{ice-fw}}$ and $\Psi_{\text{ice-bw}}$ during the 30 h freezing process of the studied beech log (Deliiski – Tumbarkova 2017).

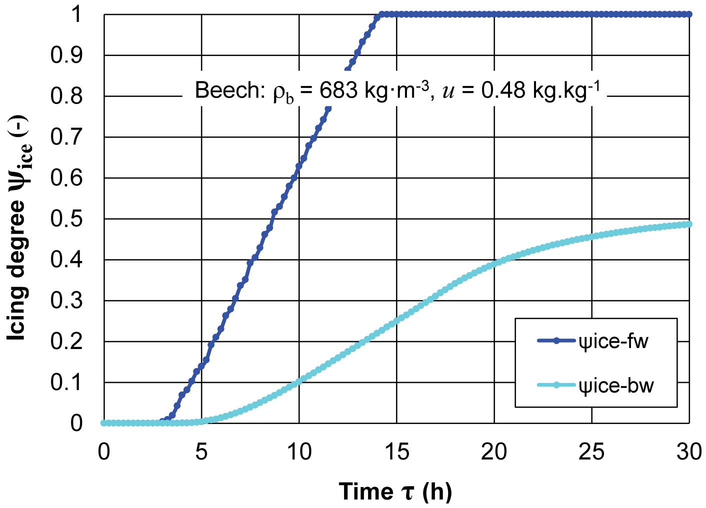

Figure 4. Change in $\Psi_{ice\text{-}fw}$ and $\Psi_{ice\text{-}bw}$ during the freezing of the studied beech log

The icing degree $\Psi_{\text{ice-fw}}$ varies from 0 to 1 (*Figure 4*). It has a value of 0 during the first 2.92 hours the log spends in the freezer when all the water in the wood is in a liquid state. This icing degree becomes equal to 1 after 14.08 h when the free water has frozen completely. The icing degree $\Psi_{\text{ice-bw}}$ varies from 0 to 0.486 (*Figure 4*). It has a value of 0 during the first 3.50 hours the log spends in the freezer, while the temperature of the peripheral layers of the log decreases below –1 °C and the freezing of the bound water in these layers starts. This icing degree becomes equal to 0.486 at the end of the 30 h in the freezer. The calculated average log mass temperature is then equal to –26.38 °C (i.e. 246.77 K) and the calculated according to eq. (21) amount of the non-frozen water u_{nfw} is equal to 0.170 kg·kg^{-1}. This value of u_{nfw} and the value $u_{\text{fsp}}^{272.15} = 0.31 + 0.021 = 0.331 \text{ kg} \cdot \text{kg}^{-1}$ (see eq. (20)) ensure a value of $\Psi_{\text{ice-bw}} = 0.486$ (see equation $\Psi_{\text{ice-bw}} = 1 - \dfrac{u_{\text{nfw}}}{u_{\text{fsp}}^{272.15}}$ given in Deliiski – Tumbarkova (2017)). This means that 1 – 0.486 = 0.514 relative parts (i.e. 51.4%) of the bound water in the studied beech log remains in a liquid state at the end of 30 h of freezing when the calculated according to eq. (22) temperature in the freezer becomes equal to $t_{\text{m-fr}} = -29.69$ °C (*Figure 3*) and the average log mass temperature is equal to –26.38 °C.

Change of the specific energies of the internal heat sources $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$

Figure 5 presents the calculated change of specific energies of the internal heat sources $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$, and their sum $Q_{\text{v-total}} = Q_{\text{v-fw}} + Q_{\text{v-bw}}$ during the 30 h freezing process of the studied beech log. The values of the heat sources are calculated as specific (for 1 m^3 wood) heat energies in Wh·m^{-3} instead of in J·m^{-3}. For this purpose, the values obtained by eqs. (12) and (16) have been divided by 3600.

During the first 17.00 h of the freezing process, the energies $Q_{\text{v-fw}}$ and $Q_{\text{v-total}}$ increase according to three mutually connected almost linear sections. During the first 2.92 h, when the entire amount of the free and bound water in the log is in a liquid state, these energies remain equal to 0. After that they increase rapidly until reaching 52.27 Wh·m^{-3} and 65.34 Wh·m^{-3} respectively at the end of the freezing of the free water in the log, which takes 14.08 h. From the 14.08th h to 17.00th h, the energy $Q_{\text{v-fw}}$ remains constant and equal to 52.27Wh·m^{-3} and the energy $Q_{\text{v-total}}$ increases from 65.34 Wh·m^{-3} to 70.25 Wh·m^{-3}.

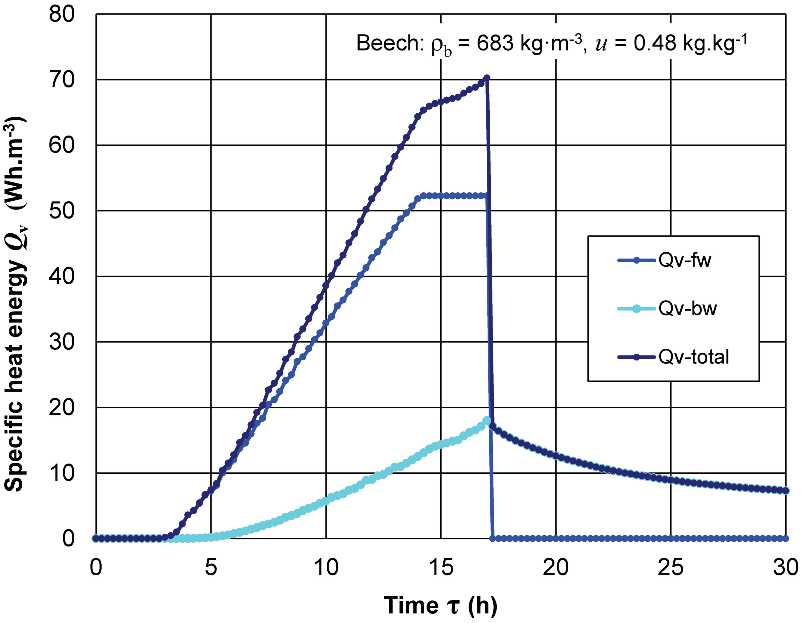

Figure 5. Change in $Q_{v\text{-}fw}$, $Q_{v\text{-}bw}$, and $Q_{v\text{-}total}$ during the freezing of the studied beech log

During the first 3.50 h, when all the bound water in the log is in a liquid state, the energy $Q_{\text{v-bw}}$ remains equal to 0. From 3.50th h to 17.00th h, when the gradual crystallization of the bound water in all knots of the calculation mesh (incl. in the log center) has begun, the specific energy $Q_{\text{v-bw}}$ increases exponentially from 0 to 17.98 Wh·m^{-3}.

After the 17.00th h, the energy $Q_{\text{v-fw}}$ is equal to 0 (all the free water is frozen) and the energy $Q_{\text{v-bw}}$ decreases exponentially; at the end of 30 h of freezing process, it reaches a value of 7.31 Wh·m^{-3}. From the 17.00th h to 30.00th h of the freezing process, the total energy $Q_{\text{v-total}}$ is equal to $Q_{\text{v-bw}}$. The reason for the decreasing of $Q_{\text{v-bw}}$ during this time interval is the decrease of the first derivative of the icing degree $\Psi_{\text{ice-bw}}$ in eq. (16) due to the decreasing slope of the dependence of this icing degree on the time during this interval in comparison to its slope prior to that (*Figure 4*).

We executed extensive simulations to verify the mathematical model given above and to study the freezing process of logs from various wood species with different moisture contents. By varying the values of the energies $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$ we determined that:

- the larger values of $Q_{\text{v-fw}}$ in comparison to those calculated by eq. (12) cause an acceleration of the computed freezing process, i.e. they cause a shortening of the horizontal sections of the temperatures in the log's central layers in the range between 0 °C and –1 °C (*Figure 1* and *Figure 3*). On the contrary, the lower values of $Q_{\text{v-fw}}$ in comparison to those calculated by eq. (12) cause a deceleration of the computed freezing process of the logs;
- the larger values of $Q_{\text{v-bw}}$ in comparison to those calculated by eq. (16) make the curves of the temperature field of the log below –1 °C steeper. On the contrary, the lower values of $Q_{\text{v-fw}}$ in comparison to those calculated by eq. (16) make the mentioned curves more lenient.

During our simulations with the model, using the approach suggested above and the mathematical descriptions of $Q_{\text{v-fw}}$ and $Q_{\text{v-bw}}$, we obtained good qualitative and quantitative conformity between the calculated and experimentally determined temperature distribution in the log's longitudinal section during the whole process of the freezing of both the free and the bound water not only in the studied beech log for the purposes of this paper, but also many other logs above the hygroscopic range (including the poplar logs presented in Deliiski – Tumbarkova (2016, 2017)).

The heat energies for the freezing of the free and bound water are not equal to the specific latent heat of the water. As pointed out in (Deliiski – Tumbarkova 2016), the latent heat is used for description of the thermal energy only, which is needed for the change of the aggregate state of a given substance without changing its temperature.

In (Chudinov 1966, 1968, Deliiski 2004, 2011, 2013b), it has been shown that the energies required for the freezing of the free and bound water (or for the melting of the ice formed by them) in the wood depend mainly on the specific heat capacity of the free water in a frozen state, c_{fw}, and on the specific heat capacity of the bound water in a frozen state, c_{bw}, respectively. Both specific heat capacities depend on the specific latent heat of the water.

In addition, c_{fw} depends on the amount of free water in the wood and does not depend on the temperature because the free water freezes in the small range from 0 $^{\mathrm{o}}$C to –1 $^{\mathrm{o}}$C.

The specific heat capacity c_{bw} depends on the wood moisture content and on the temperature since the bound water freezes gradually in the range from –1 $^{\mathrm{o}}$C to the set or desired end temperature of the freezing, T_{end} (Deliiski 2013b, 2013c). However, even at the lowest climate temperatures on the earth about 0.12 kg·kg^{-1} of the bound water remains in a non-frozen state (Chudinov 1968).

4 CONCLUSIONS

The present paper describes an approach offered by the authors for the computation of the specific energies of the internal heat sources in logs subjected to freezing.

This approach takes into account, to a maximum degree, the physics of the freezing process of both the free and the bound water in the wood. It reflects the influence of the latent heat of the water in the wood on these energies. It also considers the wood density above and below the hygroscopic range, the icing degrees of the logs formed separately by both the free and bound water at each moment of log freezing, and the influence of the fiber saturation point of each wood species on its non-frozen water depending on the current temperature in the logs below 272.15 K.

Mathematical descriptions of the specific heat energies $Q_{\mathrm{v\text{-}fw}}$ and $Q_{\mathrm{v\text{-}bw}}$, released in logs during the freezing of the free water in the range from 0 $^{\mathrm{o}}$C to –1 $^{\mathrm{o}}$C, and of the bound water below –1 $^{\mathrm{o}}$C, respectively, have been carried out. These descriptions are introduced in our own 2D non-linear mathematical model of the freezing process of logs.

A software program for the solution of the model and computation of the energies $Q_{\mathrm{v\text{-}fw}}$ and $Q_{\mathrm{v\text{-}bw}}$ according to the suggested approach and mathematical descriptions has been prepared in FORTRAN, which has been input in the calculation environment of Visual Fortran Professional developed by Microsoft.

With the help of the program, computations for the determination of the energies $Q_{\mathrm{v\text{-}fw}}$ and $Q_{\mathrm{v\text{-}bw}}$ and their sum, $Q_{\mathrm{v\text{-}total}}$, have been completed as an example for the case of a beech log with a diameter of 0.24 m, length of 0.48 m, initial temperature of 20.5 $^{\mathrm{o}}$C, basic density of 683 kg·m^{-3}, and moisture content of 0.48 kg·kg^{-1} subjected to 30 h of freezing in a freezer at about –30 $^{\mathrm{o}}$C.

It has been determined that the values of the specific heat energies $Q_{\mathrm{v\text{-}fw}}$, $Q_{\mathrm{v\text{-}bw}}$, and $Q_{\mathrm{v\text{-}total}}$ of the studied log change according to complex relationships, as follows:

- the energy $Q_{\mathrm{v\text{-}fw}}$, which is released by the freezing of only the free water in the wood, changes from 0 to 52.27 Wh·m^{-3} during the time from 2.92nd h to 14.08th h of the freezing process;
- the energy $Q_{\mathrm{v\text{-}bw}}$, which is released by the freezing of a portion of the bound water in the wood, changes from 0 to 17.98 Wh·m^{-3} during the time from 3.50th h to 17.00th h of the freezing process. After the 17.00th h this energy decreases exponentially and at the end of 30 h of freezing process it reaches a value of 7.31 Wh·m^{-3};

- the total energy $Q_{\text{v-total}} = Q_{\text{v-fw}} + Q_{\text{v-bw}}$ changes from 0 to 70.25 Wh·m^{-3} during the time from 2.92nd h to 17.00th h of the freezing process. From the 17.00th h to 30.00th h the energy $Q_{\text{v-total}}$ is equal to $Q_{\text{v-bw}}$.

By applying the suggested approach for the computation of Qv-fw and Qv-bw during our simulations with the mathematical model, we observed good conformity between the calculated and experimentally determined changes in the temperature field during the freezing of logs from different wood species with different moisture contents.

The overall *RSME* for the studied four characteristic points in the logs does not exceed 5% of the temperature ranges between the initial and the end temperatures of the logs subjected to freezing. This proves the suitable adequacy of the model as well as the correctness of the suggested approach.

The validation of the model with curvilinear change in the temperature of the freezing air medium will allow us, in the future, to solve the model (mutually connected with other our model of the logs' defrosting process) with curvilinear changing of the climate temperature (Deliiski 1988) over many winter days and nights. It will also allow for scientific calculations based the temperature distribution, icing degrees, and different energy characteristics of logs for each desired moment.

The approach for the computation of the specific energies of the internal heat sources in logs subjected to freezing suggested in this paper could be further applied in the development of analogous models; for example, for the calculation of the temperature fields and the energy consumption during the freezing of different wooden and other capillary-porous materials.

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REFERENCES

CHUDINOV, B.S. (1966): Teoreticheskie issledovania teplofizicheskih svoystv i teplovoy obrabotki dreveciny [Theoretical Research of Thermo-physical Properties and Thermal Treatment of Wood]. Dissertation for DSc., SibLTI, Krasnoyarsk, USSR (in Russian)

CHUDINOV, B.S. (1968): Teoria teplovoy obrabotki drevesiny [Theory of Thermal Treatment of Wood]. Nauka, Moscow, USSR, 255 p. (in Russian)

DANTZIG, J. (1989): Modelling Liquid-solid Phase Changes with Melt Convection. International Journal for Numerical Methods in Engineering 28 (8): 1769–1785. https://doi.org/10.1002/nme.1620280805

DELIISKI, N. (1977): Berechnung der instationären Temperaturverteilung im Holz bei der Erwärmung durch Wärmeleitung. Teil 1: Mathematisches Modell für die Erwärmung des Holzes durch Wärmeleitung [Calculating the unsteady-state distribution of temperature during conductive heating of wood. Part 1: Mathematic model conductive heatingof wood]. Holz Roh- und Werkstoff 35 (4): 141−145. (in German)

DELIISKI, N. (1988): Thermische Frequenzkennlinien von wetterbeanspruchten Holzbalken [Thermal frequency characteristics of weathered wooden beams]. Holz als Roh- und Werkstoff 20 (2): 59–65. (in German) https://doi.org/10.1007/BF02612530

DELIISKI, N. (2004): Modelling and Automatic Control of Heat Energy Consumption Required for Thermal Treatment of Logs. Drvna Industrija 55 (4): 181–199.

DELIISKI, N. (2009): Computation of the 2-dimensional Transient Temperature Distribution and Heat Energy Consumption of Frozen and Non-frozen Logs. Wood Research 54 (3): 67−78.

DELIISKI, N. (2011): Transient Heat Conduction in Capillary Porous Bodies. In Ahsan A. (ed) Convection and Conduction Heat Transfer. InTech Publishing House, Rieka: 149–176. https://doi.org/10.5772/21424

DELIISKI, N. (2013a): Computation of the Wood Thermal Conductivity during Defrosting of the Wood. Wood research 58 (4): 637–650.

DELIISKI, N. (2013b): Modelling of the Energy Needed for Heating of Capillary Porous Bodies in Frozen and Non-frozen States. Lambert Academic Publishing, Scholars' Press, Saarbruecken, Germany, 116 p.

DELIISKI, N. (2013c): Modelling of the Energy Needed for Melting of the Ice in Frozen Wood above the Hygroscopic Diapason. Wood Design and Technology, Vol.2, No.1, p.42–52, Ss.Cyril and Methodius University – Skopje.

DELIISKI, N. – DZURENDA, L. (2010): Modelling of the Thermal Processes in the Technologies for Wood Thermal Treatment. TU Zvolen, Slovakia, 224 p. (in Russian)

DELIISKI, N. – BREZIN, V. – TUMBARKOVA, N. (2015a): Modelling of the 1D Convective Heat Exchange Between Logs Subjected to Freezing and to Subsequent Defrosting and the Surrounding Environment. Acta Silvatica et Lignaria Hungarica 11 (1): 77–88. https://doi.org/10.1515/aslh-2015-0006

DELIISKI, N. – DZURENDA, L. – TUMBARKOVA, N. – ANGELSKI, D. (2015b): Computation of the Temperature Conductivity of Frozen Wood during its Defrosting. Drvna Industrija 66 (2): 87–96. https://doi.org/10.5552/drind.2015.1351

DELIISKI, N. – TUMBARKOVA, N. (2016): A Methodology for Experimental Research of the Freezing Process of Logs. Acta Silvatica et Lignaria Hungarica 12 (2): 145–156. https://doi.org/10.1515/aslh-2016-0013

DELIISKI, N. – TUMBARKOVA, N. (2017): An Approach and an Algorithm for Computation of the Unsteady Icing Degrees of Logs Subjected to Freezing. Acta Facultatis Xilologiae Zvolen 59 (2): 91–104.

EFIMOV, S.N. (1985): Temperaturnaya zavisimost tepla kristallizacii vody [Temperature Dependence of the Heat of Water Crystallization]. Engineering-Physical Journal of the Institute of Physic-Technical Problems of the Nord, Siberian Department of the Academy of Sciences of USSR, Yakutsk, 49(4): 658–664. (in Russian)

HADJISKI, M. – DELIISKI, N. (2015): Cost Oriented Suboptimal Control of the Thermal Treatment of Wood Materials. IFAC-PapersOnLine 48–24 (2015): 54–59. https://doi.org/10.1016/j.ifacol.2015.12.056

HADJISKI, M. – DELIISKI, N. (2016): Advanced Control of the Wood Thermal Treatment Processing. Cybernetics and Information Technologies, Bulgarian Academy of Sciences 16 (2): 179–197. https://doi.org/10.1515/cait-2016-0029

HRČKA, R. (2017): Model in Free Water in Wood. Wood Research 62 (6): 831–837.

HU, H. – ARGYROPOULOS, S. (1996): Mathematical Modelling of Solidification and Melting: A Review. Modelling and Simulation in Materials Science and Engineering 4: 371–396. https://doi.org/10.1088/0965-0393/4/4/004

KHATTABI, A. – STEINHAGEN, H.P. (1992): Numerical Solution to Two-dimensional Heating of Logs. Holz als Roh- und Werkstoff 50 (7-8): 308–312. https://doi.org/10.1007/BF02615359

KHATTABI, A. – STEINHAGEN, H.P. (1993): Analysis of Transient Non-linear Heat Conduction in Wood Using Finite-difference Solutions. Holz als Roh- und Werkstoff 51 (4): 272–278. https://doi.org/10.1007/BF02629373

KHATTABI, A. – STEINHAGEN, H.P. (1995): Update of "Numerical Solution to Two-dimensional Heating of Logs". Holz als Roh- und Werkstoff 53(2): 93–94. https://doi.org/10.1007/BF02716399

MIHAILOV, E. – PETKOV, V. (2010): Cooling Parameters and Heat Quantity of the Metal During Continuous Casting of Blooms. International Review of Mechanical Engineering 4 (2): 176–184.

NIKOLOV, S. – VIDELOV, CH. (1987): Manual for Wood Drying. Zemizdat, Sofia, 394 pp.

PAHI, S. (2010): Understanding specific latent heat. Lesson 4.3 – Understanding thermal latent heat. Bidang Sains dan Matematik

PERVAN, S. (2009): Technology for Treatment of Wood with Water Steam. University in Zagreb (in Croatian)

POŽGAJ, A. – CHOVANEC, D. – KURJATKO, S. – BABIAK, M. (1997): Štruktúra a vlastnosti dreva [Structure and Properties of Wood]. 2nd edition, Priroda a.s., Bratislava, 485 p. (in Slovakian)

ROGERS, R.R. – YAU, M. K. (1989): A short Course in Cloud Physics (3rd ed.). Pergamon Press, ISBN 0-7506-3215-1.

SALCUDEAN, M. – ABDULLAH, Z. (1988): On the Numerical Modelling of Heat Transfer during Solidification Processes. International Journal for Numerical Methods in Engineering 25: 445–473. https://doi.org/10.1002/nme.1620250212

SHUBIN, G.S. (1990): Sushka i teplovaya obrabotka drevesiny [Drying and Thermal Treatment of Wood]. Lesnaya Promyshlennost, Moskow, URSS, 337 p. (in Russian)

STAMM, A. J. (1964): Wood and Cellulose Science. Ronald Press, New York.

STEINHAGEN, H.P. (1986): Computerized Finite-difference Method to Calculate Transient Heat Conduction with Thawing. Wood Fiber Science 18 (3): 460–467.

STEINHAGEN, H.P. (1991): Heat Transfer Computation for a Long, Frozen Log Heated in Agitated Water or Steam – A Practical Recipe. Holz als Roh- und Werkstoff 49 (7-8): 287–290. https://doi.org/10.1007/BF02663790

STEINHAGEN, H.P. – LEE, H.W. (1988): Enthalpy Method to Compute Radial Heating and Thawing of Logs. Wood Fiber Science 20 (4): 415–421.

TREBULA, P. – KLEMENT, I. (2002): Drying and Hydro-thermal Treatment of Wood. Technical University in Zvolen, Slovakia, 449 p. (in Slovakian)

VIDELOV, CH. (2003): Sushene i toplinno obrabotvane na darvesinata [Drying and Thermal Treatment of Wood]. University of Forestry in Sofia, Sofia, 335 p. (in Bulgarian)

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Wild Boar (*Sus scrofa*) Home Range and Habitat Use in Two Romanian Habitats

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Abstract – During our research we utilized data provided by GPS collars to compare the spatial patterns of wild boars living in lowland and high-hilly regions. Five wild boars were fitted with GPS Plus (Vectronic) type collars. The two aforementioned investigated habitat areas were as follows: a high-hilly hunting ground from the foot of the Bodoc Mountains (Covasna County), and the meeting point of Olt and Danube rivers in the southern part of the country (Teleorman County). The average daily wild boar activity varied between 2.9 and 3.1 km in the lowlands and between 3.6 and 4.9 km in the higher situated habitats. The average daily movement area calculated with the minimum convex polygon method was between 60.3 and 112.5 ha/day in the lowlands and between 113.5 and 125.2 ha/day in the high-hilly regions. The movement area of the wild boars calculated with the MCP method varied between 1,060 and 1,2001 hectares in lowlands and between 8,689 and 9,463 hectares in higher altitudes. Our data proved inadequate at testing whether or not large carnivores affect wild boar activity patterns. Habitat use analysis produced interesting results: even in a very diverse habitat, every collared individual preferred green forests. We found negative preference for agricultural fields in both habitats.

wild boar / habitat use / GPS collars / large carnivores / home range

Kivonat – A vaddisznó (*Sus scrofa*) otthonterülete és élőhely-használata két romániai élőhelyen. A tanulmányban a szerzők bemutatják a vaddisznó élőhely-használatának jellemzőit egy síkvidéki és egy dombvidéki-középhegységi jellegű élőhelyen Romániában, GPS-nyakörvek segítségével. Öt vaddisznó példányt jelöltünk meg GPS-nyakörvvel (Vectronic). A vaddisznók napi átlagos aktivitása síkvidéken 2,9–3,1 km, dombvidéken 3,6–4,9 km között változott. A napi átlagos otthonterület nagysága (Minimum Convex Poligon, MCP módszerével számolva) 60,3–112,5 ha (síkvidék) és 113,5–125,2 ha (dombvidék) között alakult. Az éves átlagos otthonterület nagysága 1 060 és 12 001 ha (síkvidék) és 8 689–9 463 ha (dombvidék) között változott. Az élőhelyhasználat tekintetében negatív preferenciát találtunk mindkét vizsgálati területen a mezőgazdasági művelés alatt álló területekre vonatkozóan.

vaddisznó / élőhelyhasználat /GPS nyakörv / nagyragadozók / otthonterület

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1 INTRODUCTION

Farmers and foresters in many European countries consider wild boars (*Sus scrofa*) as pests by due to the perceived or real agricultural damage they cause. Schlageter (2013) concluded that numerous studies have provided extensive evidence for a drastic increase in wild boar populations in Europe over the last few decades. Multiple factors have favoured this continent-wide growth trend; among these are the reproductive rate of wild boars, which is the highest rate of all ungulates (Briedermann 1971), global climate change (e.g. Melis et al. 2006), and the increasing availability of foods of human origin such as crops (Geisser – Reyer 2005) or supplemental feeding (Cellina 2008). Increased population sizes are associated with problems including damage to agricultural crops, grassland, and woodland (Focardi et al. 2000, Gómez et al. 2003, Schley – Roper 2003, Calenge et al. 2004, Geisser – Reyer 2005, Schley et al. 2008, Varga – Kása 2011). The amount and severity of damage are strongly related to wild boar population density (Spitz – Lek 1999, Schley et al. 2008). Compensation payments amount to millions of Euros annually (Calenge et al. 2004, Schley et al. 2008, in countries like France (Klein et al. 2000), Luxembourg, and Hungary (Varga – Kása 2011) where damage to agriculture is generally compensated.

According to data provided by the Ministry of Environment, Water and Forests of Romania (MEWF 2016), wild boar population dynamics show increasing growth trends in Romania as well, but the real damage level caused by game species is underestimated because of the ambiguity surrounding the legislative and bureaucratic procedures of damage compensation. According to government decision 1679/2008, compensation requests must be formulated within 24 hours after the damages have occurred. Damage caused by game species are not compensated unless a landowner can prove that damage prevention activities had been undertaken beforehand. Bureaucracy, short deadlines, ambiguous responsibilities, and delayed compensations have resulted in a relatively small number of damage compensation requests. The first state compensations for crop and livestock damage caused by wildlife were paid in 2014. The equivalent of 184,167 Euro (4.4215 Ron = 1 Euro) was paid for 369 cases that occurred in the period of 2012–2014, and this was damage caused mainly by brown bear (*Ursus arctos*) and grey wolf (*Canis lupus*), both large carnivores (MMSC 2014). Official data relating to damages induced by wild boar do not exist at the national level. Currently, landowners and hunting associations try to manage the damages through intense prevention activities and by increasing the number of legally harvested boar both during and outside the limits of the hunting season.

Wild boar habitat selection has been evaluated in different contexts. For example, Boitani et al. (1994) found that boars selected uncultivated fields versus cultivated fields and used them according to the availability of forests. Thurfjell et al. (2009) also found avoidance of cultivated areas and a preference for forests (mainly deciduous forests), water, and open areas. Preference for wetlands has been reported in several areas (Dardaillon 1986; Meynhardt 1986; Thurfjell et al. 2009). The less frequent utilization of cultivated lands has been explained by the fact that they offer scant food resources when the soil is ploughed and become attractive only during the short season for grains and corn (Boitani et al. 1994); nevertheless, preference for agricultural fields, in addition to positive preference of deciduous forest and forest meadows has been found in other places such as Poland (Fonseca 2008).

Wild boar movement ecology varies among contexts. In general, disturbance by humans or natural enemies and widely distributed food resources necessitate larger home ranges (Schlageter 2013). Several studies investigated the influence of hunting on home range sizes (Maillard – Fournier 1995, Sodeikat – Pohlmeyer 2002, 2003, Baubet et al. 2004, Keuling et al. 2008b, Scillitani et al. 2010, Saïd et al. 2012). The effect of resource distribution has also been well-studied (e.g., Keuling et al., 2008a). The impacts of predators as natural enemies can be direct (lethal), but can also include other risk effects (Schmitz 2008, Creel 2011). Currently, it is increasingly recognised that indirect, non-lethal predator impacts could be even more significant than direct lethal effects (Schmitz et al. 1997, Creel – Christianson 2008). In habitats with a high predator species density, direct encounters can occur despite various behavioural responses (i.e., increasing vigilance, altering group size, retreating to safe habitats) ungulates employ to reduce predation risk (e.g., Dehn 1990, Sih 1997, Hunter – Skinner 1998, Brown et al. 1999, Brown – Kotler 2004, Creel – Winnie 2005). These direct encounters, as well as the frequency and strength of anti-predator responses, remain undetected even with the use of advanced GPS technology (Creel et al. 2013), but long term tracking should reveal some activity patterns induced by predators, should they exist.

According to the best and most complete large-scale assessment of large carnivore population estimates available in 2014 (Chapron et al. 2014), large carnivore population sizes in Europe were as follows: brown bear – 17,000; grey wolf – 12,000; Eurasian lynx (Lynx lynx) – 9,000 individuals. Of these, about 35% of bears (6,000 individuals), 21% of wolves (2,300–2,700 individuals), and 15% of lynxes (1,200 – 1,500) were found in Romania. Covasna County hosts the highest ungulate and large predator densities as well. In 2012, the following average large carnivore densities on 10,000 hectares were estimated: bear – 17.55; wolf – 4.59; and lynx – 2.03 (Boronia et al. 2012). In the case of bears, these average densities can be higher than 35 individuals per 10,000 ha at the local game management unit level.

Covasna County also had the most large carnivore damage reports (128 from a total of 902 cases) in 2012. At the national level, the requirements of G.D. 1679/2008 were only met in 71 of the 902 cases; thereby, damage compensation could only be requested in these 71 instances (Boronia et al. 2012). More than 40% (29 out of 71 cases) of properly documented damage compensation requests were from Covasna County.

Spatial requirements for wild boar has been reported to range from between a few hundred hectares to up to 3,500 ha (McIlroy 1989; Saunders – Kay 1996; Fischer et al. 2004) being that within the same populations there are more boars than sows (e.g., 3,500 ha, SD = ±2200 ha vs. 1100 ha, SD = ±520 ha in boars and sows, respectively Saunders – Kay, 1996; see also Massei et al. 1997 and Keuling et al. 2008a) including areas with different levels of hunting pressure (Saïd et al. 2012). One of the most extreme home range values reported is from Janeau – Spitz (1984) who reported an annual spatial requirement of 4,000–6,000 ha for sows and 12,000–15,000 ha for boars. Reported differences in annual home range areas can be explained by habitat-related factors such as food availability or disturbances. On the other hand, daily home ranges between 6 and 75 ha have also been reported (Janeau – Spitz 1984; McIlroy 1989; Massei et al. 1997). Daily average distance covered ranged between 2.5 and 26.7 km for boars, and between 2 and 9 km for sows (Douaud 1983; Podgórski et al. 2013).

The first legal regulation of the dimensions of game management units in Romania was drafted in 1923 (Cotta – Bodea 1969). Dimensions were already linked to altitudinal zone at that time. The smallest hunting areas could have 100 ha in lowland regions and 1,000 ha in mountain regions. Currently in Romania, law 407/2006 for Game Protection and Hunting regulates the dimensions of hunting units. These dimensions are 5,000 ha in lowlands, 7,000 ha on hills, and 10,000 ha in mountain regions, but the question of how these dimensions are adequately adapted to the focal species remains unknown. According to law 407/2006, the game management unit boundaries must be defined to ensure greater wildlife stability within them. This stability can be accomplished if spatial requirements for normal activities such as food gathering, mating, and nurturing the young are met.

In the present study, we examined spatial utilization patterns and, partly, the evolution of population dynamics trends of wild boar and large predators in two different regions of Romania to address the following questions:

1. Are the game management unit dimensions defined by law properly correlated with wild boar spatial requirements?
2. Are there any differences between activity patterns in the presence or absence of large predators?
3. Does a high preference for agricultural areas exist and does this lead to major crop damage?

2 MATERIALS AND METHODS

2.1 Study area

We chose two different habitat types regarding habitat quality, climate, and the presence of predators. One area was the high-hilly hunting ground of the Bodoc Mountains (mean altitude of 650 m a.s.l; 20,403 ha; Covasna County, Romania). The average temperature during the year is quite low (7.7 ºC), and the number of snowy days is higher when compared to the second study area. This area is characterized by mixed forests (*Fagus sylvatica, Carpinus betulus, Quercus petraea*). Cover types in this mountain area were broad-leaved forests (39.6%), arable lands (37.8%), pastures (19.4%), and artificial surfaces (3.2%). Brown bear, grey wolf, and Eurasian lynx occur in this area. The second study area, a flatland hunting ground with a total area of 24,500 was situated in Teleorman County, at the confluence point of the Olt and Danube Rivers (S Romania). This region is warmer (mean multiannual temperature 11.5 ºC) and broad-leaved forests occupied only 21.0% of the area, while arable lands occupied 50.3%, pastures 26.9%, water bodies 1.4%, and artificial surfaces 0.4%, respectively. As opposed to the previously mentioned hunting ground, all three top predator species are absent and the largest carnivore species in the area are golden jackals (*Canis aureus*). The disturbance caused by hunting is similar in both hunting grounds.

2.2 Population dynamics of wild boar and predator species

Stock assessment and hunting bag data for game species are available on the official Ministry of Environment, Waters, and Forests site (MEWF 2016). In Romania, there are some major differences between stock assessment data provided by hunting associations and population estimates made by some NGOs with various monitoring methods. For example, in 2012 hunting associations ‘had counted’ 9,220 bears while NGOs ‘had estimated’ 6,166 individuals. Therefore, to study trends in population dynamics, we processed only the hunting bag data for wild boars and golden jackal on lowlands. In the case of large predators, estimations made by NGOs are available only at the county level. The stock assessment data provided by hunting associations were reduced by the proportion of differences between data for Covasna County provided by hunting associations and NGOs.

2.3 Crop damage complaints

The number of crop damage complaints and the number of wild boars removed because of these conflicts were processed at the hunting association level.

2.4 Wild boar trapping and monitoring

2.4.1 Capture methods and anaesthesia

To capture wild boars, we used a single one corral type trap placed in traditional feeding sites. These feeding places were situated between resting places and natural feeding locations and their main purpose was to prevent crop damage. We bait the traps all year long regardless of the intention to capture. Boars began using the traps as feeding places almost immediately.

Before capture days, we armed the clasp mechanism. In 4 out of 5 attempts, we captured sows with piglets. Individuals unfitted with GPS collars were transported in a wild boar enclosure. Thus, we succeeded in capturing a sow or piglet in one trap day, whereas the capture of a male took five nights. Wild boars were immobilized using Stresnil® (40 mg Azaperon/ml) applied dose (Fournier et al. 2014): 20mg/50 kgbw; Domosedan® (10 mg/ml Medetomidin) applied dose: 10 mg/50 kgbw; Zoletil® (Tiletamin+Zolazepam 125 mg + 125 mg/5 ml) applied dose: 120 mg/50 kgbw (average induction time: 3’4’’, individuals slept after an average 4’45’’, average time of immobilization: 37’37’’, doses ranged from 6.8 to 9.2 mg/kgbw). Animals recovered from anaesthesia after an elapsed time of 185 minutes. We cannot confirm any unusual secondary effects.

2.4.2 Animal collaring and monitoring

We used GPS Plus collars, version number 10.0.5.12279, Vectronic Aerospace GmbH and utilized information from 5 wild boars (*Table 1*). In the high-hilly hunting ground, the collared individuals were 1 four-year-old boar (AM1_11699) and 1 six-year-old sow (AF1_11702). In the typical flatland and river-flats hunting ground, we captured and fitted 3 individuals with GPS collars: two yearlings, a male (SAM1_09777) and female (SAF1_11699), and a 5-year-old boar (AM2_11701).

2.5 Data analysis

Home range sizes were calculated using the Minimal Convex Polygon (MCP) method (Kie et al. 1996; Burgman – Fox 2003; Nilsen et al. 2008), and the Kernel Home Range (KHR) method (Worton 1987; Worton 1989; Laver – Kelly 2008), considering the 90% probability rate of finding (relocating) the animal in the area. In Kernel Density Estimation (KDE), a Kernel distribution (i.e. a three-dimensional hill or kernel) is placed on each telemetry location. Hill height is determined by the distribution bandwidth, and many distributions and methods are available (e.g. fixed versus adaptive, univariate versus bivariate bandwidth). The commonly used KDE with plug-in bandwidth selection frequently experienced problems: the home range polygons generated appeared unrealistic and fragmented. However, with the development of GPS technology to track animals in near real time, estimators of home range and movement have developed concurrently. Therefore, we also used a new method based on Brownian Bridge Movement Models (BBMM), which is based on two assumptions: (1) location errors correspond to a bivariate normal distribution and (2) movement between successive locations is a random conditional on the starting and ending location (Horne et al. 2007). Normally distributed errors are common for GPS data and 1 h between locations likely ensured that movement between successive locations was random (Horne et al. 2007). We estimated home range sizes using the BBMM method for 90% intensity of use.

GPS coordinates were transformed with Quantum GIS software into a Romanian Stereo70 projection system for subsequent analyses. Further analyses were carried out with Microsoft Excel, Arc View 3.2, and R software.

Habitat characteristics of wild boar home ranges were calculated from the habitat structure of the estimated home ranges using the MCP method. We used the Corine Land Cover 2000 habitat map with a 100 m resolution compiled by the European Environment Agency (EEA) to calculate the proportion of the following land covers within home ranges: artificial surfaces (CLC code = 112, 121, 131), arable fields (CLC code = 211, 213, 241), pastures and grasslands (CLC code = 231, 321), forest and semi-natural forested areas (CLC code = 311, 313, 324), and water bodies (CLC code = 511). Next, we correlated the cumulative incidence frequency occurring in the particular habitat types to the number of total GPS locations. To determine the wild boar habitat preference, we used the Ivlev-index (electivity index) (Ivlev, 1961). We calculated the Ivlev’s electivity index for each of the above mentioned habitat types as follows:

Iv = (N2 – N1) / (N2 + N1), where N1 was the proportion of a given habitat available within a home range and N2 was the proportion of locations within this habitat.

3 RESULTS

We analysed 19,266 valid positions (mean per individual: 3,853; range 737–5,076). *Table 1* lists the identifiers of the five examined individuals, the examination periods, and the number of all positions of each individual.

Table 1. Number of collars, sex and age of wild boars, study period, and number of fixes received

Collar ID	Lowlands			High hills	
	SAM1_09777	SAF1_11699	AM2_11701	AF1_11702	AM1_11699
Sex	Male	Female	Male	Female	Male
Age	1 year	1 year	5 years	6 years	4 years
Study period (dd.mm.yyyy)	30.10.2013– 31.05.2014	09.11.2013– 31.05.2014	06.06.2013– 04.01.2014	24.03.2013– 05.01.2014	08.03.2013– 24.08.2013
Fixes (n)	5,076	4,803	4,660	737	3,990

There was continuous and unimpeded data transmission from 4 individuals. The adult sow from the high hilly habitat marked as AF1_11702 was tracked for a total of 288 days. Unfortunately, in this period, there were only 31 days when the GPS positions could be transmitted due to the lack of GSM signal coverage. Further data collection directly from the collar was impossible because it was lost.

3.1 Population dynamics

During the 2014/2015 hunting season, 25,750 wild boars were harvested in Romania, while in 2004/2005, bagged game amounted to 10,714 individuals. These data show a 2.4-fold increase in 10 years. In the lowlands (Teleorman County), the hunting bag data increase was 2.64-fold (187 to 494) for the same period. At the high-hilly Covasna County site, hunting bag data also increased, but only by a moderate 1.71 rate (500 to 856). At the hunting association level, comparable data are only available since the 2010/2011 hunting season because of some changes in game management organizations. The high-hilly hunting association from the Bodoc Mountains has a stable hunting bag with an insignificant increase rate of 1.1 in 4 years (60 to 66). Ten wild boars were removed in the lowlands study area during the 2010/2011 hunting season, while in the 2014/2015 season the hunting bag reached 168 harvested individuals, which translates to a 16.8-fold increase in 4 years.

National hunting bag data for golden jackal shows a 4.9-fold increase in the period from 2007 to 2015. At the county level (Teleorman County), the rate of increase was 8.17-fold in the 2007–2013 period (from 41 to 335). There was no jackal removal at the studied hunting association level in 2007. The first 2 jackals were harvested in 2008, and this number increased to 78 in the 2012/2013 hunting season.

According to data published by Chapron et al. (2014), compared to the 1950–1970s reference period, the population sizes of large carnivores in Romania increased as follows: >1.5-fold in the case of wolves, >2-fold in the case of lynxes, and >5-fold in the case of bears. The distribution range of these species had also increased in Carpathians: >2-fold in the case of wolf, and >1.5-fold in the cases of lynxes and bears. At the Bodoc Mountains, which is the part of Covasna County that hosts the highest densities of ungulates and large predators, the hunting association 'had counted' 70 bears, 7 wolves, and 11 lynxes in an area of 20,403 ha in 2012 (MEWF 2016). At the county level in the same year, NGOs 'had estimated' smaller population sizes with 39.08% for bears, 28.57% for wolves and 60.52% for lynxes (Boronia et al. 2012). Hunting association data reduced by the proportion of the differences between the data for Covasna County provided by the hunting associations and the NGOs results in the following large carnivore densities at 10,000 ha for the Bodoc Mountains: 20.58 for bears, 2.45 for wolves, and 2.12 for lynxes.

3.2 Crop damages

Until 2015, the hunting season for wild boar opened on August 01. Hunting was forbidden from February to July, but crop damage complaints usually started to appear from the end of April or the beginning of May. The fields of some landowners in the Bodoc Mountains are more exposed to damages regardless of the crop cultivated. The number of complaints at the hunting association level is quite small, under 10 every year, and the damaged area varies between 5 and 30 hectares. As a consequence of the complaints, the hunting association receives permission to authorise wild boar removals within the annual hunting quota limit. From the 60 individuals harvested annually, the number of removals related to crop damages in the summer period is increasing; in 2015 this number reached 20 specimens.

No wild boars were removed for crop damage in Teleorman County in the summer period before the start of the 2015/2016 hunting season. Only verbal complaints were made and, thus, remained unregistered. Nevertheless, the almost 17-fold increase in hunting bags in 4 years could only occur through an increase in hunting pressure. The stock assessment data also shows increasing trends, which could be a more plausible explanation for the evolution of such hunting bag data. Written damage complaints appeared in 2014 when 200 ha of maize owned by 4 landowners were destroyed. An earlier start to the hunting season was permitted in 2015 based on the damage complaints registered in 2014. In the period of May–July 2015, 30 wild boars were removed in relation to crop damages.

3.3 Spatial ecology: Home range and Brownian motion

Using the MCP method, wild boar home range size ranged from 1,060 to 12,001 ha. Habitat related differences in home range sizes were not found. However, adult animals showed the higher values. On the other hand, estimates using the KHR 90% varied between 115 and 1,410 ha. The smallest estimates with this method were for a young boar from the lowland hunting ground, whereas the biggest was detected in the case of an adult sow from the high-hilly habitat. Finally, the BBMM 90% method showed a home range size ranging from 235 to 940 ha (*Table 2*). The Brownian motion home range estimates have shown similar age-group related patterns as the MCP method.

Table 2. Home range size values using the MCP 100%, KHR 90% and by BBMM 90% methods

Collar ID	Lowlands			High hills	
	SAM1_09777	SAF1_11699	AM2_11701	AF1_11702	AM1_11699
MCP to.st.p. (ha)	1,060	6,231	12,001	8,689	9,463
KHR 90% (ha)	114.9	385.5	704.0	1410.3	351.3
BBMM 90.0 (ha)	235.3	443.3	655.5	940.3	475.0

The mean daily home ranges calculated with the MCP method varied between 60.3 and 125.2 ha per day with a maximum of 3,752 ha (*Table 3*).

Table 3. Daily home range (ha) minimum, maximum, and standard deviation of mean

Collar ID	Lowland			High hills	
	SAM1_09777	SAF1_11699	AM2_11701	AF1_11702	AM1_11699
N (day)	214	201	197	31	169
Mean	60.3	109.7	112.5	113.5	125.2
Min	3.2	0.2	0.4	0.1	0.1
Max	294.0	2146.6	1,169.6	844.5	3,752.6
SD	56.3	224.9	167.9	164.5	392.4

The mean daily travel distance of the studied wild boars ranged between 2,887 m and 4,948 m, (*Table 4*). Longer average daily distances as well as shorter minimal daily distances were found in the high hills. The distances between the first and last point in the trajectory appear to be individual characteristics without any connection to the habitat type or the age of the wild boar. Maximum displacement seems to be age related.

Table 4. Basic dataset for Brownian Bridge Movement Models (BBMM)

Habitat ID	Lowlands			High hills	
	SaM1_09777	SaF1_11699	AM2_11701	AF1_11702	AM1_11699
MeanLDay*	2,887	3,149	3,135	4,948	3,576
MinLDay*	333	332	436	66	172
MaxLDay*	17,860	14,075	9,315	15,165	37,483
DisplMtrs*	1,047	4,980	2,109	11,318	1,804
MaxDisplMtrs*	5,605	9,703	19,474	16,309	6,106

* *MeanLDay*: The mean daily distance; *MinLDay*: The min daily distance; *MaxLDay*: The max daily distance; *DisplMtrs*: The distance between the first point in the input trajectory and the last point in the trajectory; *MaxDisplMtrs:* The maximum displacement between any two points in the trajectory.

3.4 Habitat use

Wild boars used forests as main habitats (47–88%) in both study areas (*Table 5*). We found preference or use according to availability of these habitat categories. Water bodies were avoided. We found avoidance of artificial surfaces in most cases, but the male from the high-hilly habitat has shown signs of urbanization. Regarding the use of agricultural areas, we noted avoidance in the lowlands and neutral use in higher altitudes. We have to mention that neutral preference was experienced in the mountainous area and, on the other hand, during the growing period of the agricultural crops. The negative preference values were found in the November–May period, outside the growing time of the cultivated plants.

Table 5. Ivlev's electivity indexes and percentage of use of different habitat types

Type of habitat	Lowlands						High hills			
	SAM1_09777		SAF1_11699		AM2_11701		AF1_11702		AM1_11699	
	%	Iv	%	Iv	%	Iv	%	Iv	%	Iv
Arable land	30.94	–0.24	7.62	–0.74	16.43	–0.51	2.31	–0.88	8,80	–0.62
Pastures, grasslands	0	–1.00	4,48	–0.71	26.16	–0.01	29.04	0.20	27.25	0.17
Artificial surfaces	0	–1.00	0.04	–0.82	0	–1.00	0	–1.00	16.80	0.68
Broad-leaved forests	67.76	0.53	87.77	0.61	57.41	0.46	68.65	0.27	47.15	0.09
Water bodies	1.3	–0.04	0	–1.00	0	–1.00	–	–	–	–

4 DISCUSSION

Although our results are partial, we can state that the home range calculated with the MCP method far exceeds the values published in former studies (McIlroy 1989, Saunders – Kay 1996, Massei et al. 1997, Fischer et al. 2004, Keuling et al. 2008a).

The daily home ranges also exceed the previously published values (McIlroy 1989, Massei et al. 1997). With the exception of the young male marked SAM1_09777 that was characterized with the smallest annual home range, the average daily home range seems to fit with values published by Janeau – Spitz (1984).

In the meantime, the average daily distances covered partially fit the values stated in France (Douaud 1983), but are shorter than those in Poland (Podgórski et al. 2013). There are considerable differences in the home range of boars of differing ages living in the same habitat. As we can see in the Table 2, the home range of the young boar is far smaller. The difference in the results between the young and the old boar persist when calculated with all methods. Since the MCP method also takes the farthest positions into consideration, this draws our attention to the fact that old boars sometimes roam for great distances. The home ranges of the two marked sows are more or less similar; however, in this case too, the younger individual's home range is smaller. In the higher hunting ground, against all expectations, neither the average daily distance covered nor the home range is larger. Here we marked one sow AF1_11702, and one boar AM1_11699. Considering that the disturbance level in this hunting ground is higher due to the large number of top predators (bear, wolf, and lynx), it was assumed that the home range of the wild boar would be bigger. Thus far, the data does not show considerable differences between the daily home ranges of the two boars marked in different habitats, nor in average daily distances covered. Despite the small number of collared individuals in an area that probably contains the highest density of large carnivores in Europe, it is reasonable to assume that predators should affect the activity patterns of wild boars. However, we did not find any sign of predator impacts. Our partial results are different in many respects from the former study results; for example, in respect to the daily home ranges, as well as in respect to the annual home ranges calculated with the minimum convex polygon method.

Regarding the first question concerning the proper correlation of legislated hunting unit dimensions and wild boar spatial requirements, we can state that the smallest dimension for game management units is 5,000 hectares, which is the minimum size that ensures greater species stability. The whole home range of wild boar calculated with methods that exclude the positions without any connection to the normal activities of the animal such as food gathering, mating, and caring for young, do not exceed 3,000 hectares either in the lowlands or in the higher altitudes. In the Carpathians, wild boar population growth and associated crop damage issues seem to be under control. Therefore, the crop damages can be handled appropriately at actual legal hunting unit levels. In the context of harsh climatic conditions and large carnivores, higher harvest rates or expanded hunting seasons could threaten the highly adaptive wild boar. Smaller hunting unit dimensions are not recommended because of the spatial requirements of the other sympatric ungulate and large carnivore communities.

Wild boar populations have become overabundant in lowland areas. The population was underutilised for years; therefore, previously used hunting methods and quotas would prove ineffective at managing the population. These areas provide comfortable climatic conditions, a lack of natural enemies, and a high proportion of accessible agricultural fields under crop; thus, the following management solutions are recommended: increasing the harvest rate through the implementation of minimal hunting quotas; an open, year-round hunting season; removal of females outside the breeding season; a higher harvest rate for juveniles (Keuling et al. 2013, Massei et al. 2015); large scale application of damage prevention methods; and, finally, simplifying and enforcing the damage compensations systems. The abovementioned management solutions require more human resources and smaller areas of responsibility for proper implementation. Smaller game management units of at least 3000 hectares could accomplish greater wild boar stability and reduce management requirements. If the spatial requirements of species of interest, such as wild boars, are smaller than the legal hunting unit dimensions, crop damage issues can become manageable because the hunting revenues and the crop damage compensation costs are generated through the same game management units.

Due to the small number of collared individuals, as well as age and sex related differences in wild boar spatial ecology, we admit that the effect of large carnivores on activity patterns could not be tested. We can only state that annual home ranges of wild boars living in the studied habitat types are similar. Based on our results, we could not conclude whether the activity patterns of wild boar are affected or unaffected by presence of large predators.

In terms of habitat use and the preference of agricultural areas, our main finding is that crop damage prevention efforts are unnecessary during the period from November to May because wild boar display avoidance and neutral use of agricultural areas during this period. Concerning the point of habitat preference, we can state that there is a lower interest in open field areas with reduced coverage. In some cases we experienced total avoidance of these areas; conversely, covered and dense green forest areas were preferred. Our results regarding the preference of deciduous forests fit with other European publications (Fonseca 2008, Thurfjell et al. 2009). Also, there is an inconsistency in the preference of agricultural lands under crop. Random use or negative preference of agricultural fields was found in other studies as well (Boitani et al. 1994, Thurfjell et al. 2009). The cause probably lies in the examination period. This could be the justification of keeping the function in GPS collars on the boars, and this is why we need to make detailed interpretations of the data collected during various seasons.

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REFERENCES

BAUBET, E. – BRANDT, S. – VASSANT, J. – GENDNER, J. P. – KLEIN, F. (2004): Can wild boar be surveyed using GPS? Memoirs of National Institute of Polar Research. Special issue 58: 188–195.

BOITANI, L. – MATTEI, L. – NONIS, D. – CORSI, F. (1994): Spatial and activity patterns of wild boars in Tuscany, Italy. Journal of Mammalogy 75 (3): 600–612. https://doi.org/10.2307/1382507

BORONIA, V. – IONESCU, O. – IONESCU, G. (2012): Studiu privind estimarea populaţiilor de carnivore mari şi pisică sălbatică din România (Ursus arctos, Canis lupus, Lynx lynx şi Felis silvestris) în vederea menţinerii într-o stare favorabilă de conservare şi pentru stabilirea numărului de exemplare din speciile strict protejate care se pot recolta în cadrul sezonului de vânătoare 2012–2013 [Study on estimating populations of large carnivores and wild cats (Ursus arctos, Canis lupus, Lynx lynx and Felis silvestris) from Romania in order to maintain a favorable conservation status and to determine the number of individuals of the strictly protected species that can be harvested during the 2012-2013 hunting season.] Carpathian Wildlife Foundation and subcontractors: National Institute for Research and Development in Forestry and Transilvania University of Brașov - Faculty of Silviculture and Forest Engineering for Ministry of Environment and Forests. (in Romanian)

BRIEDERMANN, L. (1971): Zur Reproduktion des Schwarzwildes in der Deutschen Demokratischen Republik. Tagungsbericht der deutschen Akademie für Landwirtschaftswissenschaften Berlin 113: 169–186.

BROWN, J. S. – KOTLER, B. P. (2004): Hazardous duty pay and the foraging cost of predation. Ecol. Lett. 7: 999–1014. https://doi.org/10.1111/j.1461-0248.2004.00661.x

BROWN, J. S. – LAUNDRÉ, J. W. – GURUNG, M. (1999): The ecology of fear: optimal foraging, game theory, and trophic interactions. Journal of Mammalogy 80 (2): 385–399. https://doi.org/10.2307/1383287

BURGMAN, M. A. – FOX, J. C. (2003): Bias in species range estimates from minimum convex polygons: implications for conservation and options for improved planning. Animal Conservation 6 (1): 19–28. https://doi.org/10.1017/S1367943003003044

CALENGE, C. – MAILLARD, D. – FOURNIER, P. – FOUQUE, C. (2004): Efficiency of spreading maize in the garrigues to reduce wild boar (*Sus scrofa*) damage to Mediterranean vineyards. European Journal of Wildlife Research 50 (3): 112–120. https://doi.org/10.1007/s10344-004-0047-y

CELLINA, S. (2008): Effects of supplemental feeding on the body condition and reproductive state of wild boar *Sus scrofa* in Luxembourg. Brighton: University of Sussex. https://doi.org/10.13140/2.1.5077.6642

CHAPRON, G. – KACZENSKY, P. – LINNELL, J.D.C. – VON ARX, M. – HUBER, DJ. – ANDRÉN, H., et al. (2014): Recovery of large carnivores in Europe's modern human-dominated landscapes. Science 348: 1517–1519. https://doi.org/10.1126/science.1257553

CREEL, S. (2011): Toward a predictive theory of risk effects: hypotheses for prey attributes and compensatory mortality. Ecology 92: 2190–2195. https://doi.org/10.1890/11-0327.1

CREEL, S. – CHRISTIANSON, D. (2008): Relationships between direct predation and risk effects. Trends in Ecology & Evolution 23 (4): 194–201. https://doi.org/10.1016/j.tree.2007.12.004

CREEL, S. – WINNIE, J.A. (2005): Responses of elk herd size to fine-scale spatial and temporal variation in the risk of predation by wolves. Anim. Behav. 69: 1181–1189. https://doi.org/10.1016/j.anbehav.2004.07.022

CREEL, S. – WINNIE, J.A. – CHRISTIANSON, D. (2013): Underestimating the frequency, strength and cost of anti-predator responses with data from GPS collars: an example with wolves and elk. Ecol. Evol., 3: 5189–5200. https://doi.org/10.1002/ece3.896

COTTA, V. – BODEA, M. (1969): Vînatul Romăniei [The hunting in Romania]. Editura Agrosilvica, Bucuresti (in Romanian)

DARDAILLON, M. (1986): Seasonal variations in habitat selection and spatial distribution of wild boar (*Sus Scrofa*) in the Camargue, Southern France. Behavioural Processes 13 (3): 251–268. https://doi.org/10.1016/0376-6357(86)90088-4

DEHN, M.M. (1990): Vigilance for predators: detection and dilution effects. Behav. Ecol. Sociobiol. 26: 337–342. https://doi.org/10.1007/BF00171099

DOUAUD, J. F. (1983): Utilisation de l'espace et du temps et ses facteurs de modulation chez le sanglier, *Sus scrofa*, en milieu forestier ouvert (Massif des Dhuits, Haute-Marne (Doctoral dissertation) [Time and space use and its modulation factors of wild boar, *Sus scrofa*, in an open forest area]. (in French)

FISCHER, C. – GOURDIN, H. – OBERMANN, M. (2004): Spatial behaviour of the wild boar in Geneva, Switzerland: Testing the methods and first results. Galemys 16: 149–155.

FOCARDI, S. – CAPIZZI, D. – MONETTI, D. (2000): Competition for acorns among wild boar (*Sus scrofa*) and small mammals in a Mediterranean woodland. Journal of Zoology 250 (3): 329–334. https://doi.org/10.1017/S095283690000306X

FONSECA, C. (2008): Winter habitat selection by wild boar *Sus scrofa* in southeastern Poland. European Journal of Wildlife Research 54 (2): 361–366. https://doi.org/10.1007/s10344-007-0144-9

FOURNIER, P. – FOURNIER-CHAMBRILLON, C. – MAILLARD, D. – KLEIN, F. (2014): Zoletil® immobilization of Wild boar (*Sus scrofa* L.). Journal of Mountain Ecology 3:134–136.

GEISSER, H. – REYER, H.U. (2005): The influence of food and temperature on population density of wild boar *Sus scrofa* in the Thurgau (Switzerland). Journal of Zoology 267 (1): 89–96. https://doi.org/10.1017/S095283690500734X

GÓMEZ, J.M. – GARCIA, D. – ZAMORA, R. (2003): Impact of vertebrate acorn and seedling predators on a Mediterranean Quercus pyrenaica forest. Forest Ecology and Management 180 (1): 125–134. https://doi.org/10.1016/S0378-1127(02)00608-4

HORNE, J. S. – GARTON, E. O. – KRONE, S. M. – LEWIS, J. S. (2007): Analyzing animal movements using brownian bridges. Ecology 88: 2354–2363. https://doi.org/10.1890/06-0957.1

HUNTER, L.T.B. – SKINNER, J.D. (1998): Vigilance behaviour in African ungulates: the role of predation pressure. Behaviour 135: 195–211. https://doi.org/10.1163/156853998793066320

IVLEV, V. S. (1961): Experimental ecology of the feeding of fishes. – Yale University Press, New Haven

JANEAU, G. – SPITZ, F. (1984): L'espace chez le sanglier (*Sus scrofa scrofa* L.): occupation et mode d'utilisation journalier [Space use of wild boar (*Sus scrofa scrofa* L.): Activity and daily habitat use]. Gibier Faune Sauvage, 1: 73–89. (in French)

KEULING, O. – STIER, N. – ROTH, M. (2008a). Annual and seasonal space use of different age classes of female wild boar *Sus scrofa* L. European Journal of Wildlife Research 54 (3): 403–412. https://doi.org/10.1007/s10344-007-0157-4.

KEULING, O. – STIER, N. – ROTH, M (2008b). How does hunting influence activity and spatial usage in wild boar *Sus scrofa* L.? European Journal of Wildlife Research 54: 729–737. https://doi.org/10.1007/s10344-008-0204-9

KEULING, O. – BAUBET, E. – DUSCHER, A. – EBERT, C. – FISCHER, C. – MONACO, A. – PODGÓRSKI, T. – PREVOT, C. – RONNENBERG, K. – SODEIKAT, G. – STIER, N. – THURFJELL, H. (2013): Mortality rates of wild boar *Sus Scrofa* L. in central Europe. European Journal of Wildlife Research 59 (6): 805–814. https://doi.org/10.1007/s10344-013-0733-8

KIE, J. G. – BALDWIN, J. A. – EVANS, C. J. (1996): CALHOME: a program for estimating animal home ranges. Wildlife Society Bulletin (1973-2006) 24 (2): 342–344.

KLEIN, F. – JAEGER, P. – SAINT-ANDRIEUX, C. - VAN LAERE, G. (2000): Prévention et indemnisation des dégâts forestiers dans différents pays européens [Prevention and compensation of forest damages in different European countries]. Office National de la Chasse, Direction de la Recherche et du Développement & Centre national d'étude et de recherche appliquée Cervidés et sanglier, Paris, 16 pp. (in French)

LAVER, P. N. – KELLY, M. J. (2008): A critical review of home range studies. The Journal of Wildlife Management 72(1): 290–298. https://doi.org/10.2193/2005-589

MAILLARD D. – FOURNIER P. (1995): Effects of shooting with hounds on size of resting range of wild boar (*Sus scrofa* L.) groups in mediterranean habitat. Ibex J. Mt. Ecol. 3:102–107.

MASSEI, G. – GENOV, P. V. – STAINES, B. W. – GORMAN, M. L. (1997): Factors influencing home range and activity of wild boar (*Sus scrofa*) in a Mediterranean coastal area. Journal of Zoological Society of London 242: 411–423. https://doi.org/10.1111/j.1469-7998.1997.tb03845.x

MASSEI, G. – KINDBERG, J. – LICOPPE, A. – GACIC, D. – SPREM, N. – KAMLER, J. – BAUBET, E. – HOHMANN, U. – MONACO, A. – OZOLINS, J. – CELLINA, S. – PODGÓRSKI, T. – FONSECA, C. – MARKOV, N. – POKORNY, B. – ROSELL, C. – NÁHLIK, A. (2015): Wild boar populations up, numbers of hunters down? A review of trends and implications for Europe. Pest Management Science 71 (4): 492–500. https://doi.org/10.1002/ps.3965

MCILROY, J. C. (1989): Aspects of the ecology of feral pigs (*Sus scrofa*) in the Murchison Area, New Zealand. New Zealand Journal of Ecology 12: 11–22.

MELIS, C. – SZAFRAŃSKA, P.A. – JĘDRZEJEWSKA, B. – BARTOŃ, K. (2006): Biogeographical variation in the population density of wild boar (*Sus scrofa*) in western Eurasia. Journal of Biogeography 33 (5): 803-811. https://doi.org/10.1111/j.1365-2699.2006.01434.x

MEWF (2016): Ministry of Environment, Waters and Forests in Romania: http://www.mmediu.ro/categorie/vanatoare

MEYNHARDT, H. (1986): Vaddisznóriport: életem a vaddisznók között. [Wild boar reportage: my life between wild boars]. Gondolat, Budapest (in Hungarian)

MMSC (2014): http://www.mmediu.ro/app/webroot/uploads/files/2014-11-13_ MMSC_a _adus _la_zi _plățile_despăgubirilor_pentru_pagubele_produse_de_speciile_protejate.pdf

NILSEN, E. B. – PEDERSEN, S. – LINNELL, J. D. (2008): Can minimum convex polygon home ranges be used to draw biologically meaningful conclusions? Ecological Research 23(3): 635–639. https://doi.org/10.1007/s11284-007-0421-9

PODGÓRSKI, T. – BAŚ, G. – JĘDRZEJEWSKA, B. – SÖNNICHSEN, L. – ŚNIEŻKO, S. – JĘDRZEJEWSKI, W. – OKARMA, H. (2013): Spatiotemporal behavioral plasticity of wild boar (*Sus scrofa*) under contrasting conditions of human pressure: primeval forest and metropolitan area. Journal of Mammalogy 94(1): 109–119. https://doi.org/10.1644/12-MAMM-A-038.1

SAÏD, S. – TOLON, V. – BRANDT, S. – BAUBET, E. (2012): Sex effect on habitat selection in response to hunting disturbance: the study of wild boar. European Journal of Wildlife Research 58: 107–115 https://doi.org/10.1007/s10344-011-0548-4

SAUNDERS, G. – KAY, B. (1996): Movements and Home Ranges of Feral Pigs (*Sus scrofa*) in Kosciusko National Park, New South Wales. Wildlife Research (23): 711–719. https://doi.org/10.1071/WR9960711

SCHLAGETER, A. (2013): Preventing wild boar *Sus scrofa* damage – considerations for wild boar management in highly fragmented agroecosystems. Doctoral dissertation. University of Basel.

SCHLEY, L. – ROPER, T.J. (2003): Diet of wild boar *Sus scrofa* in Western Europe, with particular reference to consumption of agricultural crops. Mammal review 33(1): 43–56. https://doi.org/10.1046/j.1365-2907.2003.00010.x

SCHLEY, L. – DUFRÊNE, M. – KRIER, A. – FRANTZ, A. C. (2008): Patterns of crop damage by wild boar (*Sus scrofa*) in Luxembourg over a 10-year period. European Journal of Wildlife Research 54 (4): 589–599. https://doi.org/10.1007/s10344-008-0183-x

SCHMITZ, O.J. (2008): Effects of predator hunting mode on grassland ecosystem function. Science 319: 952–954. https://doi.org/10.1126/science.1152355

SCHMITZ, O.J. – BECKERMAN, A.P. – O'BRIEN, K.M. (1997): Behaviorally mediated trophic cascades: effects of predation risk on food web interactions. Ecology 78 (5): 1388–1399. https://doi.org/10.1890/0012-9658(1997)078[1388:BMTCEO]2.0.CO;2

SCILLITANI, L. – MONACO, A. – TOSO, S. (2010): Do intensive drive hunts affect wild boar (*Sus scrofa*) spatial behaviour in Italy? Some evidences and management implications. European Journal of Wildlife Research 56: 307–318. https://doi.org/10.1007/s10344-009-0314-z

SIH, A. (1997): To hide or not to hide? Refuge use in a fluctuating environment. Trends Ecol. Evol. 12:375–376. https://doi.org/10.1016/S0169-5347(97)87376-4

SODEIKAT, G. – POHLMEYER, K. (2002): Temporary home range modifications of wild boar *Sus scrofa* caused by drive hunts in Lower Saxony (Germany). In Proceedings of the 25th Congress of the International Union of Game Biologists and the IXth International Symposium Perdix. E. Hadjisterkotis, editor, 3.–7. September 2001. Lemesos, Cyprus. Zeitschrift für Jagdwissenschaft 48: Supplement: 161–166. https://doi.org/10.1007/BF02192404

SODEIKAT, G. – POHLMEYER, K. (2003): Escape movements of family groups of wild boar *Sus scrofa* influenced by drive hunts in Lower Saxony, Germany. Wildlife Biology 9: Supplement 1: 43–49.

SPITZ, F. – LEK, S. (1999): Environmental impact prediction using neural network modelling. An example in wildlife damage. Journal of Applied Ecology 36 (2): 317–326. https://doi.org/10.1046/j.1365-2664.1999.00400.x

THURFJELL, H. – BAL,L J. P. – ÅHLÉN, P. A. – KORNACHER, P. – DETTKI, H. – SJÖBERG, K. (2009): Habitat use and spatial patterns of wild boar *Sus scrofa* (L.): agricultural fields and edges. European Journal of Wildlife Research 55 (5): 517–523. https://doi.org/10.1007/s10344-009-0268-1

VARGA, Z. – KÁSA, R. (2011): Vadkár. Mezőgazda Kiadó, Budapest.

WORTON, B. J. (1987): A review of models of home range for animal movement. Ecological modelling 38 (3): 277–298. https://doi.org/10.1016/0304-3800(87)90101-3

WORTON, B. J. (1989): Kernel Methods for Estimating the Utilization Distribution in Home-Range Studies. Ecology 70 (1): 164–168. https://doi.org/10.2307/1938423

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Allometric Relationships for Estimation of Above-Ground Biomass in Young Turkey Oak (*Quercus cerris* L.) Stands in Albania

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Abstract – The study objective was the determination of allometric relationships to estimate aboveground biomass in young *Q. cerris* stands growing in various sites in Albania. The equations described here are developed for *Q. cerris* forest stands managed as coppice. The total aboveground biomass of sampled trees varied from 10.67 to 19.71 kg with a stem diameter at 1.3 m (DBH) from 7.65 to 9.7 cm, and height from 5.26 to 7.6 m. Stem biomass comprised, on average, 69.6 %, while branch biomass was 24.3 %, and leaf biomass,6% on the total aboveground biomass of the sampled oak trees. Total aboveground biomass was predicted with the highest accuracy from linear and non-linear regression equations. Total aboveground biomass and the biomass of tree compartments were predicted with a notable accuracy from DBH where the allometric model efficiency exceeded 93%. Biomass expansion factors (BEFs) showed a stronger dependency on diameter at breast height and a weaker relationship with age. The age-dependence relationship found in our study was closely related to site productivity. The variability in aboveground biomass among sampled sites indicated that local site conditions cause this difference. These new equations for *Q.cerris* might be applicable in the framework of the Albanian National Forest Inventory for estimation of carbon accounting from forest ecosystems and will contribute to the sustainable management of oak forests.

Quercus cerris **/ allometric equation / BEFs / tree biomass**

Kivonat – Albániai fiatal csertölgy (*Quercus cerris* L.) faállományok föld feletti biomasszájának meghatározása allometrikus módszerekkel. Albánia különböző területein végrehajtott vizsgálataink során olyan allometrikus kapcsolatokat határoztunk meg fiatal, sarj eredetű cseres (*Q. cerris*) faállományokra, melyek segítségével azok föld feletti biomasszáját lehet megbecsülni. A megmintázott faegyedek föld feletti biomasszája 10,67–19,71 kg között változott, míg a mellmagassági átmérő 7,65–9,70 cm, a magasság pedig 5,26–7,60 m között volt. A teljes biomassza mennyisége a következő részekből tevődött össze: törzs 69,6%, ágak 24,3%, levelek 6%. A föld feletti biomassza mennyiségére a legpontosabb becslést a lineáris és a nemlineáris regressziós egyenletek adták. A teljes föld feletti biomasszát, illetve az egyes farészek ezen belüli arányát jelentős pontossággal meg lehetett határozni a mellmagassági átmérőből, ahol az allometrikus modell pontossága meghaladta a 93%-ot. A biomassza átszámító tényezők (BEF) erősebben függtek a mellmagassági átmérőtől, mint a kortól. Az elemzések során megállapított életkor-függőség szoros kapcsolatot mutatott az adott termőhely termőképességével. A mintákban tapasztalt eredmények változatossága arra utal, hogy a föld feletti biomassza mennyiségében tapasztalt eltérések a helyszínek közötti különbségekre vezethetők vissza. A csertölgyre kidolgozott új egyenletek alkalmazhatók az Albán Nemzeti Erdészeti Felmérés keretében, az erdei ökoszisztémák szén-dioxid-elszámolásának becslése során, illetve hozzájárulnak az ottani tölgyerdők fenntartható kezeléséhez.

Quercus cerris **/ allelometrikus kapcsolatok / BEF / fás biomassza**

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1 INTRODUCTION

Interest in estimating forest biomass for practical and scientific purposes is currently increasing. There are different approaches to calculate biomass and carbon stocks in forests, with most based on forest inventory information as well as on biomass equations, which transform diameter, height or volume data into biomass estimates (Somogyi et al. 2006). Biomass calculations can be obtained by direct and indirect methods. The direct method involves destructive biomass weighing, whereas in the indirect method, regression modelling is used to estimate biomass and carbon stocks from more easily measured tree and stand variables such as diameter at breast height (DBH), tree height (H) and tree age (A). Tree-level variables facilitate the development of biomass equations that are applicable to a wider range of sites and stands and can be used to examine the effects of various factors on stand growth and biomass stocking. The ability of allometric equations to predict aboveground biomass and carbon stocking is not only a matter of statistical tools. The errors made throughout the process of formulating these equations – from the fieldwork and modelling to biomass prediction – should be considered (Picard et al. 2012).

Chave et al. (2005) and Brown et al. (1989) pointed out that errors are caused by various sources such as tree measurement, plot sampling, insufficient number of big trees sampled, diameter intervals, selection of average sample trees in each diameter class, and application of unsuitable models. In addition, accuracy and reliability of biomass models should be assessed not only for individual trees, but also for forest stands taking into account the distribution of trees by diameter classes (Ketterings et al. 2001).

In Albania, information on aboveground biomass and carbon stocking is scarce and relevant estimation methods are not very well known. In contrast, information regarding biomass estimation is more plentiful in other Mediterranean countries. From the review of the studies conducted in Albania, we found one study that provides data on biomass and carbon stocking at national level (Agrotec 2004) and two other studies focused on aboveground biomass estimation for some species growing in natural (Omuri 2006) and artificial stands (Toromani et al. 2011). The first study regarding biomass estimation at the country level was conducted in the framework of National Forest Inventory (Agrotec 2004).Biomass was calculated from the inventoried stand volume per hectare where this value was expanded into aboveground components using biomass expansion factor (BEFs). Due to the lack of information on specific BEFs for Albanian forests, data from other studies was used (Louitat et al. 2000, Lowe et al. 2000, Schulze 2000). Omuri (2006) executed the second research study on forest biomass and BEFs and developed several models to estimate biomass. He determined the BEFs for Austrian pine (*P. nigra* Arn.), Beech (*F. sylvatica* L.) and Birch (*B. pendula* L.) and pointed out that BEFs values vary due to species and age. Thus, in the case of birch, the BEF was 2.1 for the 10 to 20-year age range, 1.4 for Austrian pine in the 20 to 30-year age range and, and 2.3 for beech in 10 to 20-year age range. The third study was conducted by Toromani et al. (2011) in some poplar plantations situated in eastern and central Albania where several allometric equations using tree variables (DBH; squared DBH; H; A) as predictors were developed.

Despite the limited number of published equations, many other forest species growing in Albania are not well represented. Turkey oak (*Quercus cerris* L.) is one of the species lacking biomass-related information. Undoubtedly one of Albania's most important forest species, covering more than 30.8% of the total forest area, Turkey oak grows in Haplic and Chromic Luvisol soil here, in a typical, hilly, Mediterranean climate with a considerable summer drought period (FAO2015). The species is widely distributed all over Albania, from hilly lands along the coastal area to the interior of country. *Q. cerris* is a significant firewood source and is also a fundamental fodder source for wildlife and livestock (mostly sheep and goats). The species also provides habitat for small game species such as Brown hare (*Lepus europaeus* Pallas.), Common blackbird (*Turdus merula* L.), and Grey partridge (*Perdix perdix* Brisson.). No information on the aboveground biomass for Albanian *Q. cerris* forest stands exists, but other Mediterranean countries possess abundant data. Therefore, the aims of this study were: (1) to estimate aboveground biomass of investigated stands, (2) to define the appropriate allometric models for estimation of aboveground biomass using tree variables, and (3) to estimate biomass expansion factors (BEFs) and their dependency. The present study will contribute quantitative data to the current, generally scarce knowledge of this species.

2 MATERIALS AND METHODS

2.1 Study sites

Data used in this study came from measurements carried out in five *Quercus cerris* L. forest stands growing across the country from northeast to central Albania (*Figure 1*).

Instrumental climate records are temporally limited in the studied areas; therefore, the updated CRU TS 3.22 0.5°×0.5°- gridded monthly temperature and precipitation data sets were used (Harris et al. 2014). The climate data in the *Table 1*, were estimated from the database extracted for the region encompassed by the coordinates 40°25’–42°25’N and 19°25’–20°75’E. The *Q.cerris* stands grow under the influence of hilly Mediterranean climate with an average annual temperature from 9.30 °C to 14.46 °C and an annual rainfall ranging from 959 to 1133 mm (*Table 1*). The rainfall is unevenly distributed and the biggest amount falls during the autumn (253 mm) and winter (245 mm). The minimum temperature ranges from –1 to 6.2 °C, while the maximum values vary between 23.7 °C to 30 °C.

Table 1. Site description including location, longitude (long), latitude (lat), altitude above sea level, mean annual temperature (MAT) and mean annual precipitation (MAP) .

Site	Long (°E)	Lat (°N)	Altitude (m)	MAT (°C)	MAP (mm)
Sllove	20°24"16"	41°45'35"	750	9.56	959
Bushtrice	20°25'02"	41°53'34"	780	9.66	1010
Melan	20°28'03"	41°39'17"	850	9.30	1000
Zerqan	20°22"04"	41°30'48"	715	9.85	1008
Paper	19°57'42"	41°04'43"	160	14.46	1133

The oak forest stands grow on moderately deep soils formed during the long-term alteration of the clay bedrocks.

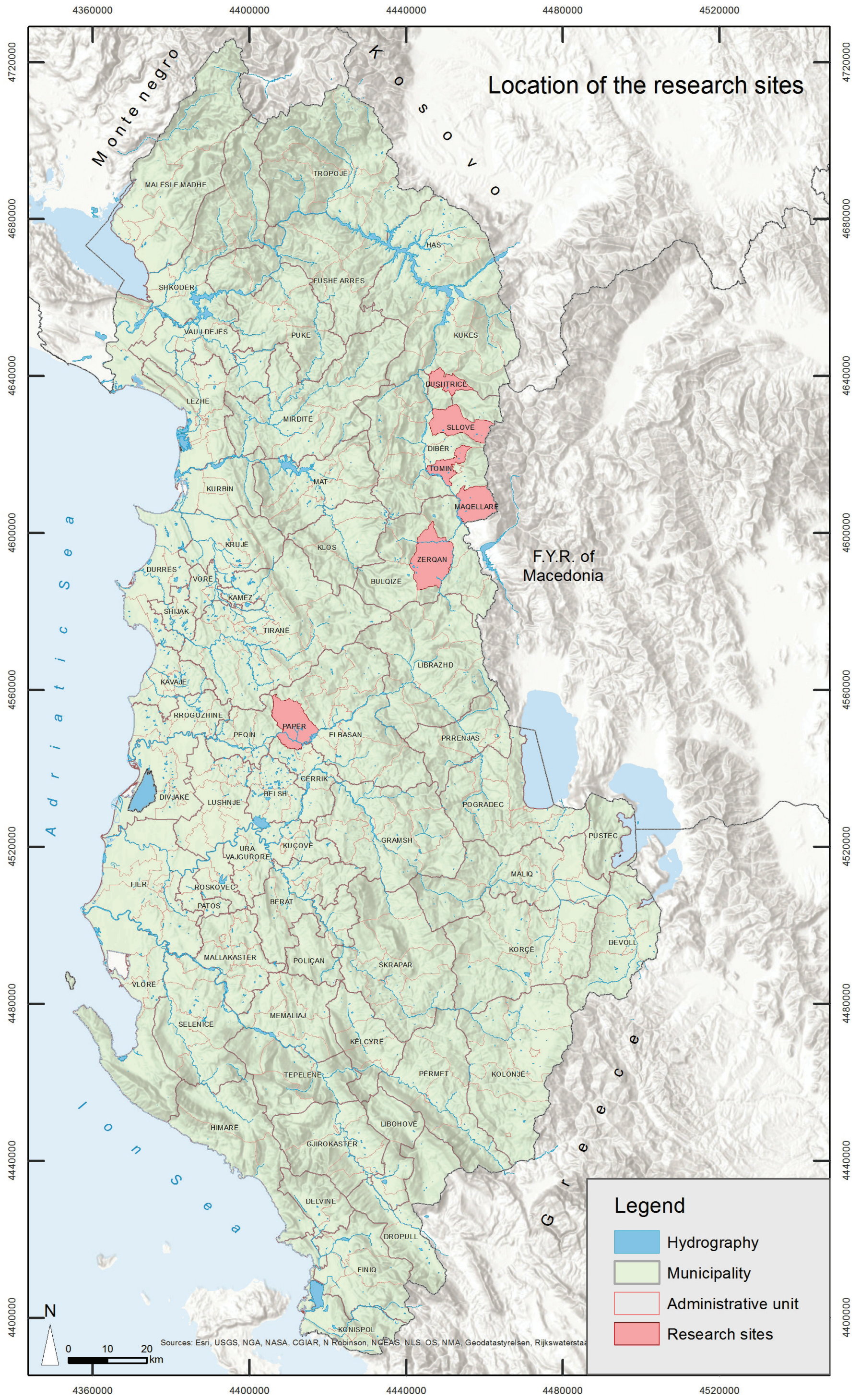

Figure 1. Location of the research sites

2.2 Field data

In each sampled site, five circular sample plots with an area of 200 m^2 (r = 7.98 m) were used to investigate each forest stand (*Table 2*). In total, 1170 trees were measured inside sample plots. The main tree characteristics measured were diameter at breast height (DBH) with a calliper at 1.3 m from the ground, and tree height (H) with a Vertex 4.

Table 2. Dendrometric characteristics of the studied Q. cerris forest stands

Site	Forest parcel	D_{mean}(cm) ± SD	H(m) + SD	Stem number per ha	Age (yr)
Sllove	137b	6.09 ± 1.41	5.86 ± 1.57	5,000	15–20
Bushtrice	109c	4.03 ± 0.95	2.13 ± 0.25	1,500	14–18
Melan	115a	5.28 ± 1.59	5.71 ± 1.11	3,350	10–17
Zerqan	115b	3.46 ± 1.58	4.30 ± 0.84	1,400	13–18
Paper	169a	3.73 ± 2.60	3.70 ± 1.02	450	8–12

SD-standard deviation

A subsample of 50 trees was chosen for biomass estimation. The sampled trees were representative of the DBH range and height in each research site. They were felled at ground level, where DBH, H, A (i.e. counting rings in the stem base) and fresh weight was measured for each biomass compartment. Each sampled tree was cut into three compartments – bole (stem), branches, and foliage – for biomass weighing in the field. Plant roots were not investigated in this study. Each biomass compartment was weighed using an electronic balance with a 100 kg capacity and 100 g precision. A subsample was taken from each biomass compartment of sampled trees to determine dry weight in the laboratory.

Three stem discs, with a thickness from 2 to 3 cm, were extracted from the base, middle, and top part of the stem. The same procedure was applied for branches. In this case, the branch discs were extracted from the top and bottom of the branches. Foliage of sampled trees was completely removed from the branches and was measured. These subsamples were measured in the field and then oven-dried at 70°C until a constant weight was reached. Thus, it was possible to determine the dry/fresh weight ratio of each biomass compartment for respective sampled trees.

In those cases where the stem could not be weighed, the diameter was measured at 1 meter intervals from the bottom to the top of the bole. Bole volume of the tree was calculated using Newton − Riecke's equation (Yavuz 1999). Total aboveground biomass of individual trees was calculated by summing the weights of all biomass pools or compartments.

2.3 Regression analysis

In the analysis we used data derived from field and laboratory measurements of 50 sampled *Q. cerris* individuals. Respective allometric equations between sampled tree variables (DBH, H) and the dry biomass of each compartment were developed. The allometric equations developed were obtained using linear and nonlinear regression without any preliminary transformation of raw data. For all the empirical relationships developed in this study, the predictive variables of dry biomass were DBH, H, or a combination of the two variables. First, the raw data were graphed to visually assess the relationships between aboveground biomass dry weight and predictive tree variables; after this, allometric models were fitted. The best model for each component was chosen based on graphical analysis of residuals and fitting statistics such as coefficient of determination (R^2), root mean square error (RMSE), and model efficiency (MEF) (Gadow et al. 2001). In regression, all these coefficients represent a statistical measure of how well the trend line approximates the observed values.

$$MSE = \frac{1}{n} \cdot \sum_{i=1}^{n} (\check{y}_i - y_i)^2 \quad (1)$$

$$RMSE = \sqrt{MSE} \tag{2}$$

$$MEF = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{3}$$

where: y_i – is the observed value,
$\hat{y}_i$ – is the estimated value,
$\bar{y}_i$ – is the mean observed value.

2.4 Calculation of Biomass Expansion Factor (BEF)

Based on the values of biomass estimated for all tree components, we derived the aboveground dry biomass and dry biomass of tree bole. Biomass expansion factor (BEF) for sampled trees were calculated using the following equation:

$$BEF = \frac{W_{aboveground}}{W_{bole}} \tag{4}$$

where: BEF – biomass expansion factor (dimensionless)
$W_{aboveground} = W_{crown} + W_{tree\ bole}$ (kg)
W_{bole} – tree bole dry weight (kg)

2.5 Statistical analysis to test intra-site variability

Correlation and cluster analysis were used to investigate the similarity and differences between biomass data of sampled trees growing in different stands. This analysis is used to quantify the association between pairs of biomass datasets. For that reason, in correlation analysis to quantify the direction and strength of the association between two data sets, we used the correlation coefficient (r). The sign of the correlation coefficient indicates the direction of the association, while the magnitude of the correlation coefficient indicates the strength of the association. Cluster analysis was used to identify homogeneity and similarity in aboveground biomass datasets of sampled trees among research sites. In order to explore the similarity, we used the hierarchical cluster analysis following these procedure: (i) firstly, we specified the distance measuring method (Squared Euclidean Distance) to calculate the distances between variables; (ii) secondly, we linked the clusters using the Ward method because it uses the F-value (like in ANOVA) to maximize the significance of differences between clusters; (iii) thirdly, we selected the right number of clusters (3 clusters).

3 RESULTS

3.1 Biomass equations

The biomass equations were developed for *Q. cerris* trees, which grow in different sites from northeast to central Albania. Maximum aboveground biomass ranged from 20.82 kg per individual tree in Zerqan to 56.34 kg per tree in Sllove (*Table 3*). Mean aboveground biomass for sampled trees range from 10.67 kg (Zerqan) to 19.71 kg in Sllove.

Table 3. Minimum, maximum, and mean values for diameter at breast height, tree height, and aboveground biomass weight for the sampled Q. cerris trees in the studied sites

Site	Sampled tree number	Diameter at breast height(cm)			Height (m)			Age (years)			Aboveground biomass (kg/tree)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Sllove	10	4.0	15.0	9.00	4.1	10	7.60	11	24	17	6.45	56.34	19.71
Bushtrice	9	4.5	13.5	8.30	3.3	9.4	6.30	10	33	20	3.61	23.45	13.10
Melan	8	2.0	15.0	8.80	2.8	8.5	5.71	11	31	21	1.45	27.10	12.98
Zerqan	11	2.5	14.0	7.65	2.2	10.5	6.02	6	25	15	1.52	20.82	10.67
Paper	12	3.0	30.0	9.69	2.8	9.2	5.26	8	48	19	1.78	53.89	15.75

We also found biomass equations for various aboveground components including stem, branches, and foliage using DBH (*Table 4*), H (*Table 5*) as predictive variables. The biomass models developed were selected through the statistics for bias and precision (R^2, RMSE and MEF) where all parameters were considered significant at the 95% confidence level. In most of the biomass models between DBH and biomass components, the highest model efficiency was attained with the total aboveground biomass exceeding a value of 0.93. Only the biomass model for the Melan site showed the weakest relationship and dependence. Even so, most of the models of stem biomass and aboveground biomass presented efficiency values higher than branches and foliage. Thus, threshold values of model efficiency were respectively 0.74 for stem, 0.63 for branches, and 0.56 for leaves.

In addition, several multiple regression equations were developed using DBH and tree height (H) as well as squared DBH and H as predictor variables of aboveground biomass (*Table 6*).

Table 4. Allometric equations and statistics between biomass compartments and DBH for Q. cerris

Site	Species components	Model	R^2	RMSE	MEF
Sllove	Stem	$DW = 1.9848 \bullet DBH^{0.730}$	0.71	6.74	0.74
	Branches	$DW = 1.04819 \bullet DBH^{0.435}$	0.66	1.52	0.65
	Leaves	$DW = 0.195201 \bullet DBH^{0.493}$	0.56	1.08	0.56
	Whole tree	$DW = 2.428 \bullet \exp^{0.207 \bullet DBH}$	0.96	2.62	0.97
Bushtrice	Stem	$DW = 2.112 \bullet DBH - 7.437$	0.95	1.39	0.95
	Branches	$DW = 0.210 \bullet DBH + 0.665$	0.68	1.40	0.63
	Leaves	$DW = 0.071 \bullet DBH^{0.998}$	0.65	0.2	0.64
	Whole tree	$DW = 2.387 \bullet DBH - 6.691$	0.93	1.80	0.93
Melan	Stem	$DW = 0.282 \bullet DBH^{1.657}$	0.97	3.82	0.76
	Branches	$DW = 0.335 \bullet DBH + 0.263$	0.79	2.15	0.81
	Leaves	$DW = 0.108 \bullet DBH - 0.158$	0.96	0.09	0.96
	Whole tree	$DW = 0.927 \bullet DBH^{1.128}$	0.65	12.3	0.58
Zerqan	Stem	$DW = 1.325 \bullet DBH - 2.604$	0.93	1.28	0.93
	Branches	$DW = 0.346 \bullet DBH - 0.161$	0.89	0.42	0.90
	Leaves	$DW = 0.082 \bullet DBH + 0.002$	0.91	0.09	0.92
	Whole tree	$DW = 1.755 \bullet DBH - 2.762$	0.95	1.45	0.94
Paper	Stem	$DW = 1.489 \bullet DBH - 3.273$	0.97	1.78	0.97
	Branches	$DW = 0.368 \bullet DBH - 0.016$	0.93	0.43	0.93
	Leaves	$DW = 0.115 \bullet DBH - 0.085$	0.95	0.14	0.94
	Whole tree	$DW = 1.973 \bullet DBH - 3.375$	0.98	1.90	0.98

Table 5. Allometric equations and statistics between biomass components and tree height for Q. cerris in studied sites

Site	Species components	Model	R^2	RMSE	MEF
Sllove	Stem	$DW = 0.724 \cdot \exp^{0.359 \cdot H}$	0.93	3.39	0.87
	Branches	$DW = 0.589 \cdot \exp^{0.234 \cdot H}$	0.54	3.78	0.30
	Leaves	$DW = 0.150 \cdot \exp^{0.225 \cdot H}$	0.54	0.79	0.32
	Whole tree	$DW = 1.376 \cdot \exp^{0.320 \cdot H}$	0.86	7.62	0.72
Bushtrice	Stem	$DW = 2.753 \cdot H - 7.452$	0.92	1.82	0.92
	Branches	$DW = 0.296 \cdot H + 0.523$	0.77	0.30	0.76
	Leaves	$DW = 0.186 \cdot \exp^{0.172 \cdot H}$	0.66	0.20	0.59
	Whole tree	$DW = 1.861 \cdot \exp^{0.277 \cdot H}$	0.82	1.80	0.93
Melan	Stem	$DW = 0.162 \cdot H^{2.173}$	0.54	9.12	0.64
	Branches	$DW = 0.334 \cdot H^{1.093}$	0.30	2.34	0.42
	Leaves	$DW = 0.058 \cdot H^{1.209}$	0.35	0.51	0.32
	Whole tree	$DW = 0.417 \cdot H^{1.826}$	0.47	11.9	0.45
Zerqan	Stem	$DW = 1.841 \cdot H - 3.548$	0.97	0.89	0.97
	Branches	$DW = 0.172 \cdot H^{1.44}$	0.85	0.69	0.72
	Leaves	$DW = 0.068 \cdot H^{1.227}$	0.94	0.10	0.89
	Whole tree	$DW = 0.468 \cdot H^{1.689}$	0.95	1.94	0.91
Paper	Stem	$DW = 0.806 \cdot \exp^{0.411 \cdot H}$	0.82	9.64	0.85
	Branches	$DW = 0.230 \cdot H^{1.576}$	0.76	1.55	0.66
	Leaves	$DW = 0.046 \cdot H^{1.779}$	0.75	0.49	0.65
	Whole tree	$DW = 0.443 \cdot H^{2.022}$	0.85	7.45	0.72

Table 6. Multiple regression equations using DBH and H as predictor variables of total dry biomass

Site	Species components	Model	R^2	RMSE	MEF
Sllove	Total aboveground dry weight (biomass)	$DW = -0.839 + 8.43 \cdot DBH - 7.28 \cdot H$ $DW = 10.35 + 0.301 \cdot DBH^2 - 7.28 \cdot H$	0.93 0.96	3.69 2.86	0.94 0.96
Bushtrice	Total aboveground dry weight (biomass)	$DW = -0.36 + 1.41 \cdot DBH + 1.385 \cdot H$ $DW = -3.73 + 0.05 \cdot DBH^2 + 2.02 \cdot H$	0.95 0.97	13.3 1.69	0.91 0.94
Melan	Total aboveground dry weight (biomass)	$DW = 22.2 + 4.63 \cdot DBH - 8.952 \cdot H$	0.53	6.07	0.55
Zerqan	Total aboveground dry weight (biomass)	$DW = -3.56 + 0.69 \cdot DBH + 1.49 \cdot H$ $DW = -3.24 + 0.01 \cdot DBH^2 + 2.19 \cdot H$	0.96 0.96	1.18 1.28	0.97 0.96
Paper	Total aboveground dry weight (biomass)	$DW = - 6.25 + 1.72 \cdot DBH + 1.016 \cdot H$ $DW = - 4.05 + 0.04 \cdot DBH^2 + 2.676 \cdot H$	0.98 0.99	1.48 2.19	0.98 0.99

The statistics of biomass equations developed showed that multiple regression equations are more accurate in the prediction of aboveground biomass than simple regression equations are. In addition, the relationships between dry biomass and predictor variables (squared DBH and H) were stronger than equations using only DBH and H as independent variables. Linear regression of the observed (y-axis) against the predicted values were used to examine how well the models fit the observed data (*Figure 2*).

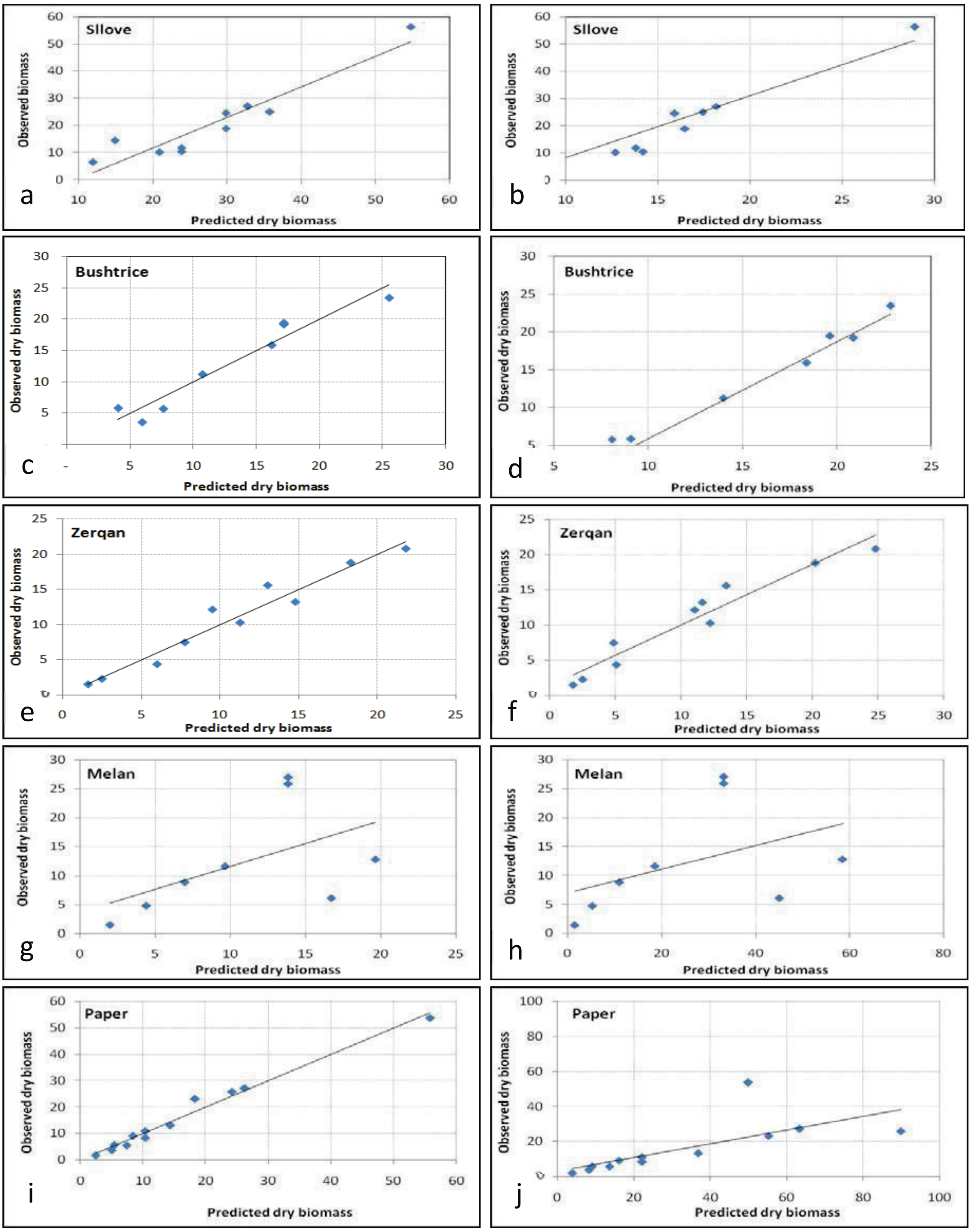

Figure 2. Observed and predicted values of total aboveground biomass (kg) of Quercus cerris L. using DBH (left side) and H (right side) as predictive variables

The partitioning of tree biomass into basic fractions as stem and crown (branches of different sizes and foliage when present) is shown in *Figure 3*. The stem was the biggest fraction ranging from 66.0% in Paper to 72.4 % in Bushtrica. In contrast, sampled trees from Paper had the largest fraction of branch, up to 26.5% of the aboveground biomass, whereas trees from Bushtrica had the lowest value (22.3%). The crown biomass is predominated by branches, which represents 78 to 82 % of the total crown biomass. There is a significant negative relationship between stem biomass and branches ($R = –0.98$; $p < 0.05$) and foliage ($R = –0.93$; $p < 0.05$) biomass. A positive relationship exists between branch and foliage biomass ($R = 0.83$; $p < 0.05$).

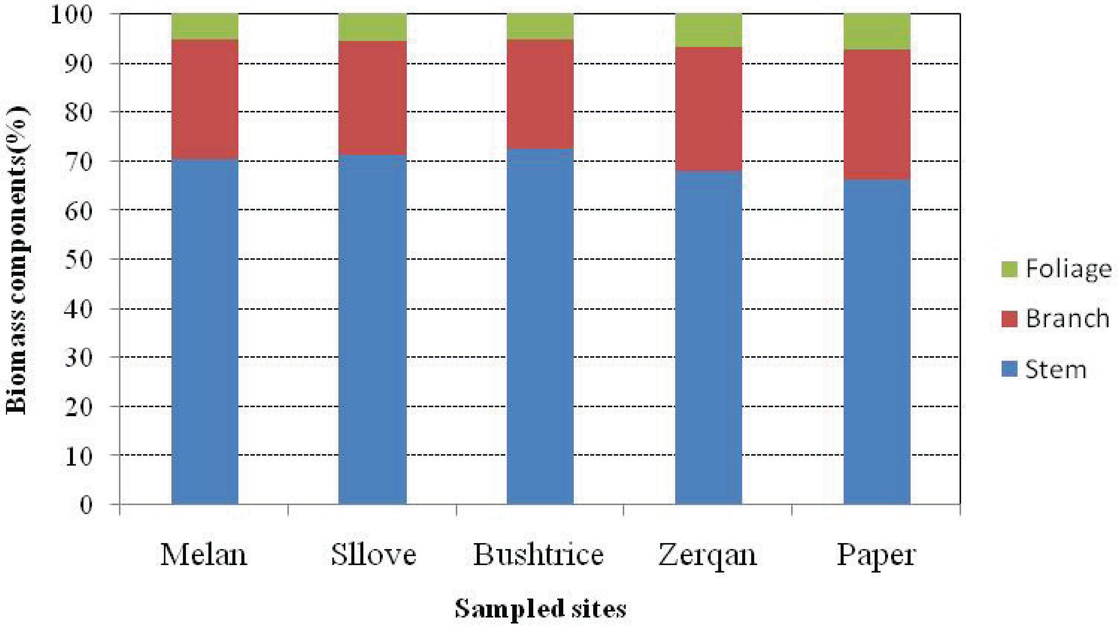

Figure 3. Comparison of biomass partitioning in fractions of sampled tree for the studied sites

3.2 Variation in aboveground biomass among sampled sites

Correlation analysis indicated a significant relationship between Bushtrica aboveground biomass data of sampled trees and those from Zerqan and Paper sites. In other cases, the Pearson's correlation coefficients were not significant, indicating the presence of a difference or lack of association in aboveground biomass data sets between the sampled sites (*Table 7*).

Table 7. Correlation matrix of Pearson's correlation coefficients in aboveground biomass of individual trees among sampled sites

Sites	Pearson's correlation coefficients among sampled sites				
	Melan	Sllove	Bushtrice	Zerqan	Paper
Melan	1.00	0.06	0.33	–0.18	–0.11
Sllove		1.00	–0.53	–0.44	–0.37
Bushtrice			1.00	**0.72**	**0.79**
Zerqan				1.00	**0.72**
Paper					1.00

Bold numbers display the significant correlation values for a threshold value of Pearson's correlation coefficient of $r = 0.576$; $p < 0.05$.

Cluster analysis grouped the research sites into three clusters based on the similarity of the aboveground biomass data of the fifty sampled trees (*Figure 4*). The first and second cluster represent the biomass data of sampled trees from the Melan and Sllove sites respectively. These were different from the biomass data for Bushtrica, Zerqan, and Paper, which were grouped in a common cluster. The cluster analysis corresponds well with the results of the matrix of correlation, emphasizing that the populations of sampled trees from Melan and Sllove are different from other sites.

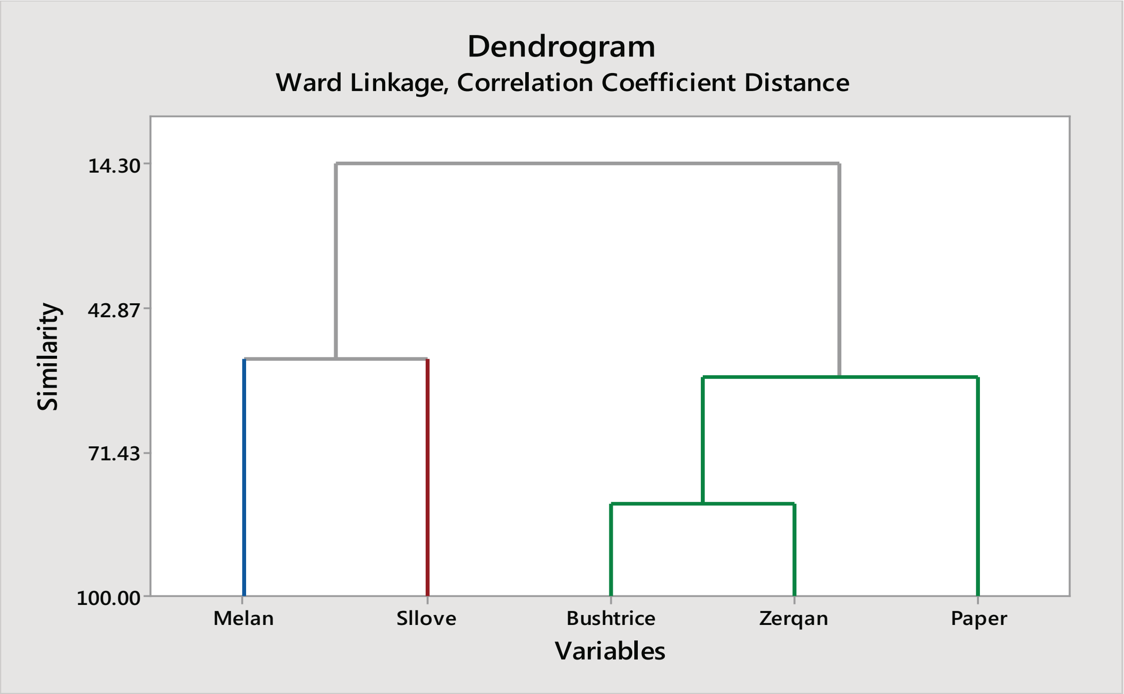

Figure 4. Dendrogram of the studied sites' clustering using the Ward method incorporating the aboveground biomass data of individual sampled trees

The variability in aboveground biomass among sampled sites denoted that difference is site-specific and caused by differences in local site conditions.

3.3 Biomass expansion factors (BEFs)

In the present study, BEFs for *Q. cerris* ranged from 1.2 to 1.97, while the mean value was 1.4. Average BEFs (± SD) for the stem volume conversion into total aboveground biomass were as follows: 1.44 (± 0.25) for Melan, 1.42 (± 0.19) for Sllove, 1.40 (± 0.20) for Bushtrice, 1.47 (± 0.12) for Zerqan and 1.53 (± 0.20) for Paper. The BEFs for this species were age-dependent and the ratio of aboveground biomass to volume over bark decreased as age increased (*Figure. 5*). A similar negative relationship between BEFs and DBH was noted in all sampled sites where BEFs were slightly decreasing with DBH increasing (*Figure 6*). Values of coefficients of determinations for this relationship were much lower than those of allometric biomass models, implying that the relationship of BEFs with tree age is weaker, but statistically significant.

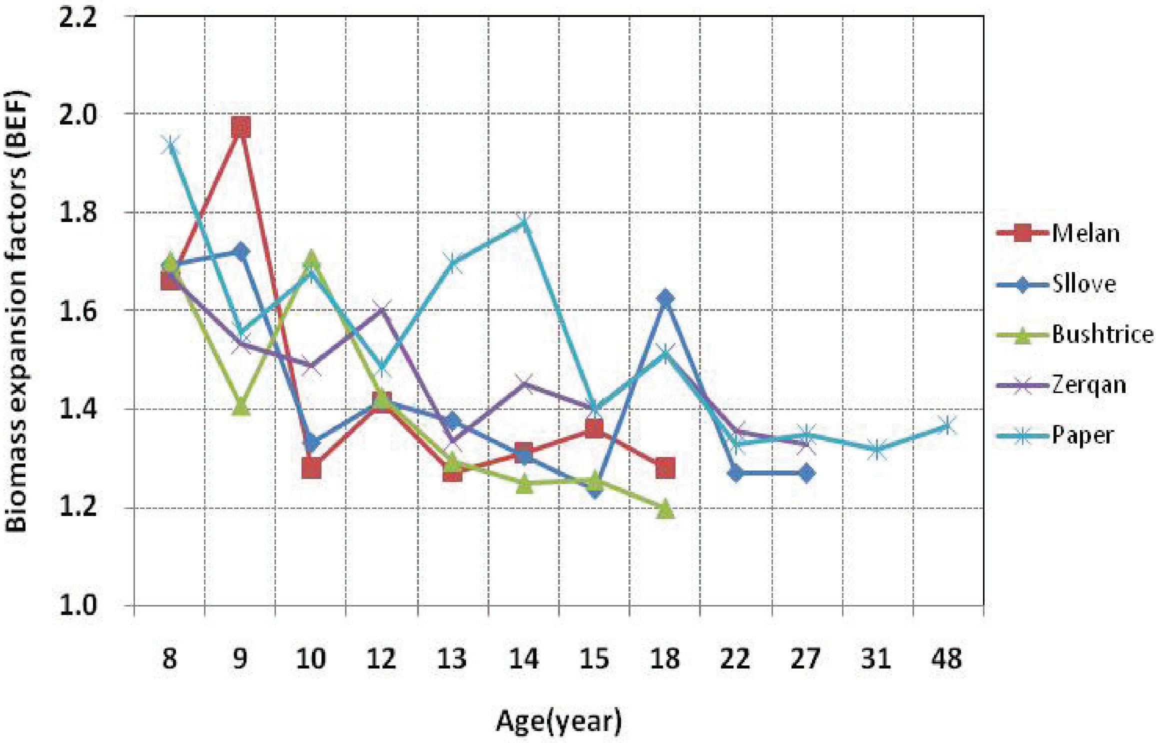

Figure 5. Relationship between biomass expansion factors (BEF) and age for the estimation of the total aboveground biomass

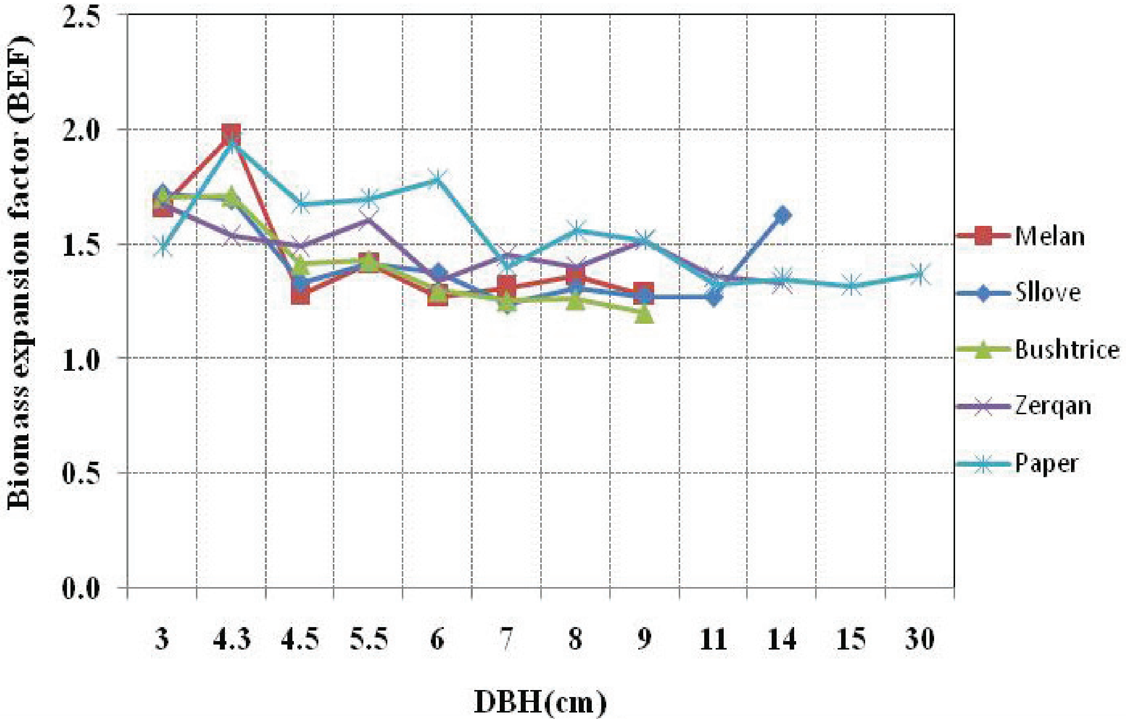

Figure 6. Relationship between biomass expansion factors (BEFs) with bole diameter at breast height (DBH)

The uncertainty of BEFs models developed with DBH and tree age was tested using coefficient of determination (R^2), Relative Standard Error (RSE), and Root Square Mean Error (RMSE) (*Table 8*). The analysis showed that RSE computed from BEF models varied between 4 and 16% by age as well as from 4 to 12% by DBH. In addition, the RSME estimated showed a lower value when BEFs were predicted by DBH and an opposite result was obtained when age was the predictor variable.

Table 8. Coefficient of determination (R^2), relative standard errors (RSE) and Root Mean Square Errors (RSME) of respective models of BEF using DBH and age as predictive variables

Site	Model	R^2	RSE (%)	RSME
Melan	$BEF = 3.622 \cdot Age^{-0.31}$	0.56	4.2	0.06
Sllove	$BEF = -0.026 \cdot Age + 1.881$	0.38	7.8	0.04
Bushtrice	$BEF = 1.909 \cdot \exp^{-0.01 \cdot Age}$	0.63	6.9	0.07
Zerqan	$BEF = -0.016 \cdot Age + 1.722$	0.65	6.1	0.02
Paper	$BEF = 2.522 \cdot Age^{-0.18}$	0.59	16.0	0.14

Site	Model	R^2	RSE (%)	RSME
Melan	$BEF = 2.011 \cdot DBH^{-0.17}$	0.55	4.3	0.06
Sllove	$BEF = 2.041 \cdot DBH^{-0.17}$	0.30	6.9	0.05
Bushtrice	$BEF = 1.964 \cdot \exp^{-0.04 \cdot DBH}$	0.83	11.9	0.03
Zerqan	$BEF = -0.023 \cdot DBH + 1.645$	0.56	5.8	0.02
Paper	$BEF = 2.008 \cdot DBH^{-0.13}$	0.46	8.2	0.04

4 DISCUSSION

The results presented in this article complement tree biomass allometry for *Q. cerris* growing in Albania. New allometric models developed for this species provides a good basis to obtain consistent and accurate biomass estimation. Diameter at breast height and total height are well correlated with aboveground biomass, which are considered as independent variables in all developed biomass models. The use of tree height as an explanatory variable not only affects the accuracy of biomass estimation (Bi et al. 2004, Joosten et al. 2004), but provides the opportunity to compare the developed models in other stands because tree height offers valuable information regarding growth and site conditions (Wirth et al. 2004). For a given DBH and H, there was considerable intra-specific variability and this was greater for the shorter lived components such as foliage and branches than for longer lived components like stems. This finding is consistent with previous studies (Wirth et al. 2004, Saint-André et al. 2005, António et al. 2007, Genet et al. 2011, Xiang et al. 2016, Clough et al. 2016).

The inclusion of squared DBH and tree height as predictor variables in aboveground biomass estimation resulted in a notable improvement of the biomass models, as indicated by the increase of R^2 and reduction of RMSE, improving the precision of the estimations (Antonio et al. 2007). DBH, as one of the many dendrometric parameters, falls into the category of easily measurable ones and is widely used in forest inventory. Allometric relationships between DBH and aboveground biomass or tree components biomass take the form of different functions, i.e. from linear to power or exponential functions with one or many covariates. In presented data, the highest R^2, RMSE and MEF coefficients were found between DBH and total tree aboveground biomass. We noted that stem models showed a greater ability for predicting biomass than models of other biomass components, possessing a higher value of R^2 and model efficiency (MEF) ranging from 64 to 97%.

Many researchers have proposed several models for fitting the relationship between tree variables and aboveground biomass in oak species. Some of these models, found in the international web platform (GlobAllomeTree), were: (i) multiple regression models built by Giurgiu (1974) in Romania for *Quercus* spp., (ii) linear regression equations for *Q. ilex* in Italy (Susmelt et al.1976); (iii) logarithmic models between DBH and aboveground biomass for *Q. coccinea* in United States of America (Martin et al.1998) and *Q. ilex* from Spain (Canadell et al.1988).

In most of the studied sites, the biomass models developed for estimation of branch biomass presented a lower predictive ability. The most representative cases belong to Sllove and Melan sites. The variability observed in this component might be caused from the differences in stand density (*Table 2*) and tree competition (Návar 2009).

Biomass partitioning showed that in *Q. cerris* sampled trees, the stem represents over 65%, implying that this biomass pool is the biggest fraction in the aboveground biomass. *Figure 3* showed that *Q. cerris* allocates 28 to 34% of its aboveground biomass in the crown; these findings are consistent with those reported for other species of the same genus like *Q. ilex* (Canadell – Roda 1991), *Q. suber* and *Q. canariensis* found in other Mediterranean countries (Peinado et al. 2012).

The tree organ-biomass proportions are closely related to age, competition, health status and growing conditions (e.g. Johansson 1999). Specifically, we noted that these proportions changed significantly during the first twenty years of growth from those in 20-year successive period. Thus, stem biomass increases, whereas branches and foliage biomass decrease (*Table 9*). Previous studies have reported that in middle-aged and mature stands, stem biomass increases continuously, whereas branch and leaf mass do not vary much (Kantola – Makela 2006).

Table 9. Variability of tree organ-biomass proportions due to age in oak stands

Site	Biomass proportions (%) by age class					
	0–20 year			21–40 year		
	Stem	Branches	Foliage	Stem	Branches	Foliage
Melan	67	27	6	77.5	18.5	4
Sllove	69	25	6	79	17	4
Bushtrice	66	28	6	80	15	5
Zerqan	68	25	7	75	20	5
Paper	63	29	8	74	20	6
Average value	66.6	26.8	6.6	77.1	18.1	4.8

Concerning the effect of age on BEFs, we found a strong age-dependence increase from the Sllove site ($r = -0.62$; $P < 0.05$) to Zerqan ($r = -0.80$; $P < 0.05$). The significant age-dependence relationship is also closely related with site productivity (all forest stands belong to the fifth production class). Previous studies have reported higher, age-dependent BEFs in broadleaf and conifer forest stands growing on sites with lower productivity (Wirth et al. 2004). This is because trees growing in poor sites are characterized by a higher degree of branches and modification of stem shape (presence of fork etc.), which increases the value of BEF. This age and site dependence of BEF was also reported in earlier studies (e.g. IPCC 2006, Levy et al. 2004). Our results related to the relationship between BEFs and DBH of sampled trees and agreed with those presented by (Teobaldelli et al. 2009). Such trends of BEFs with increasing DBH were found to be under statistical significance ($p < 0.05$). Differences in correlation and cluster analysis between aboveground biomass values of individual *Q. cerris* trees growing in different sites implies that developed biomass models are site-specific. Such differences between biomass models are increasing due to the variability of age, site conditions, and stand density of the studied forest stands; these findings are consistent with those earlier reported finding (Pilli et al. 2006, Teobaldelli et al. 2009). This highlights the risk of applying site-specific biomass equations to stands other than the ones for which the equations were developed.

Recently, the Albanian government has finalised the third National Communication on Climate Change in which the responsible authorities have reported the situation of GHG inventory covering all sources including the five main sectors of energy, industrial processes, agriculture, waste, and land use change and forestry. Estimation of greenhouse gases (GHG) in the framework of GHG inventory as well as the stocking rate of forest resources at the country level requires suitable BEFs and accurate allometric equations. Therefore, allometric equations developed for many other species in Albania, as well as suitable biomass expansion factors for estimating total biomass and carbon stocks at different spatial and temporal scales, are needed.

5 CONCLUSIONS

Allometric equations for estimating aboveground biomass and BEFs from five oak forest stands were developed based on DBH, H and A. The accuracy of estimates of aboveground biomass has been improved by using squared DBH and H as predictor variables. This study emphasizes that, for a given DBH and H, variability in biomass was greater for the short living tree components. The difference tested statistically showed that biomass models developed were site-specific and that this variability increases due to age, site productivity, and stand density.

REFERENCES

AGROTEC (2004): Albanian National Forest Inventory. Final Report. 140 p.

ANTONIO, N. – Tomé, M. – Tomé, J. – Soares, P. − Fontes, L. (2007): Effect of the tree, stand and site variables of the allometry of *Eucalyptus globulus* tree biomass. Canadian Journal of Forest Research 37: 895−906. https://doi.org/10.1139/X06-276

Bi, H − Turner, J − Lambert, M.J.(2004): Additive biomass equations for native eucalypt forest trees of temperate Australia. Trees 18: 467–479. https://doi.org/10.1007/s00468-004-0333-z

BROWN, S. − GILLESPIE, A.J.R. − LUGO, A.E. (1989): Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35: 881−902.

CANADELL, J. − RODA, F. (1991): Root biomass of *Quercus ilex* in a montane Mediterranean forest. Canadian Journal of Forest Research 21: 1771–1778. https://doi.org/10.1139/x91-245

CHAVE, J. − ANDALO, C. − Brown S, − CAIRNS, M.A. − CHAMBERS, J.Q, − EAMUS, D. − FÖLSTER, H. − FROMARD, F. − HIGUCHI, N. − KIRA, T. − LESCURE, J.P. − NELSON, B.W. − OGAWA, H . − PUIG, H. − RIÉRA, B. − YAMAKURA, T. (2005): Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145 (1): 87−99. https://doi.org/10.1007/s00442-005-0100-x

CLOUGH, B.J. − RUSSELL, M.B. − DOMKE, G.M. − WOODALL, C.W. (2016): Quantifying allometric model uncertainty for plot-level live tree biomass stocks with a data-driven, hierarchical framework. Forest Ecology and Management 372: 175–188. https://doi.org/10.1016/j.foreco.2016.04.001

FAO (2015): World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. IUSS Working Group WRB. ISBN 978-92-5-108369-7 (print).

GADOW, K von. − REAL, P. − ALVAREZ-GONZALEZ, J.G. (2001): Modelizacion del crecimiento y la evolucion de los bosques. IUFRO World Series Vol. 12, Vienna.

GENET, A. − WERNSDÖRFER, H. − JONARD, M.. − PRETZSCH, H. − RAUCH, M. − PONETTE, Q. − NYS, C. − LEGOUT, A. − RANGER, J. − VALLET, P. − SAINT-ANDRÉ, L. (2011): Ontogeny partly explains the apparent heterogeneity of published biomass equations for Fagus sylvatica in central Europe. Forest Ecology and Management 261: 1188–1202. https://doi.org/10.1016/j.foreco.2010.12.034

HARRIS, I. − JONES, P.D. − OSBORN, T.J. − LISTER, D.H. (2014): Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset. International Journal of Climatology 34 (3): 623−642. https://doi.org/10.1002/joc.3711

JOHANSSON, T. (1999): Biomass production of Norway spruce (*Picea abies* [L.] Karst.) growing on abandoned farmland. Silva Fennica 33 (4): 261−280.

JOOSTEN, R.. − SCHUMACHER, J. − WIRTH, C. − SCHULTE, A. (2004): Evaluating tree carbon predictions for beech (Fagus sylvatica L.) in western Germany. Forest Ecology and Management 189: 87−96. https://doi.org/10.1016/j.foreco.2003.07.037

KANTOLA, A. − MAKELA, A. (2006): Development of biomass proportions in Norway spruce (*Picea abies* [L.] Karst.). Trees 20: 111−121

KETTERINGS, Q.M. − COE, R. − VAN NOORDWIJK, M. − AMBAGAU, Y. − PALM, C.A. (2001): Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management 120: 199−209. https://doi.org/10.1016/S0378-1127(00)00460-6

LAITAT, E. − KARJALAINEN, T. − LOUSTAU, D. − LINDNER, M. (2000): Introduction: Towards an integrated scientific approach for carbon accounting in forestry–COST E21 workshop on Contribution of forests and forestry to mitigate greenhouse effects. 28-30 September, 2000 Joensuu, Finland – Biotechnology, Agronomy, Society and. Environment 4 (4): 241−251.

LEHTONEN, A. − CIENCIALA, E . − TATARINOV, F. − MAKIPAA, R. (2007): Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic. Annals of Forest Science 64: 133−140. https://doi.org/10.1051/forest:2006097

LOWE, H. − SEUFERT, G. − RAES, F. (2000): Comparison of methods used within Member States for estimating CO_2 emissions and sinks according to UNFCCD and EU Monitoring Mechanism: forest and other wooded land. Biotechnology, Agronomy, Society and Environment 4 (4): 315−319.

OMURI, I. (2006): Studim mbi perllogaritjen e nivelit te sekuestrimit te karbonit ne komunen Shishtavec bazuar ne rigjenerimin e vegjetacionit autokton pyjor dhe menaxhimin e qendrueshem e shumfunksional te pyjeve [A study over the calculations on carbon sequestration level in Shishtavec commune based on the native forest vegetation regeneration and sustainable management and multifunctionality of the forests]. Master Thesis, 71 p. (in Albanian)

PEINADO, R.R. − MONTERO, G. − DEL RIO, M. (2012): Biomass models to estimate carbon stocks for hardwood tree species. Forest Systems 21(1): 42−52. https://doi.org/10.5424/fs/2112211-02193

PICARD, N. − SAINT-ANDRÉ, L. − HENRY, M. (2012): Manuel de construction d´equations allométriques pour l'estimation du volume et la biomasse des arbres. Centre de Coopération Internationale en Recherche Agronomique pour le Développement [Handbook for the development of allometric equations for estimating the volume and biomass of trees. Center for International Cooperation in Agronomic Research for Development]. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 211. (in French)

PILLI, R. − ANDOFILLO, T. − CARRER, M. (2006): Towards a functional and simplified allometry for estimating forest biomass. Forest Ecology and Management 237 (1–3): 583−593. https://doi.org/10.1016/j.foreco.2006.10.004

SAINT − ANDRE, L, M'BOU, A.T. − MABIALA, A. − MOUVONDY, W. − JOURDAN C. − ROUPSARD O. − DELEPORTE, P. − HAMEL, O. − NOUVELLON, Y. (2005): Age-related equations for above- and belowground biomass of a *Eucalyptus* hybrid in Congo. Forest Ecology and Management 205: 199−214. https://doi.org/10.1016/j.foreco.2004.10.006

SCHULZE, D.E. (2000): Carbon and nitrogen cycling in European forest ecosystems. Ecological Studies Vol. 142, Springer Verlag, Berlin/Heidelberg.

SOMOGYI, Z. − CIENCIALA, E. − MAKIPA, A.R. − MUUKKONEN, P. − LEHTONEN, A. − WEISS, P. (2006): Indirect methods of large-scale forest biomass estimation. European Journal of Forest Research 126 (2):197–207.

TEOBALDELLI, M. − SOMOGYI, Z. − MIGLIAVACCA, M. − USOLTSEV, V.A. (2009): Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index. Forest Ecology and Management 257: 1004−1013.

TOROMANI, E. − SANXHAKU, M. − SALLAKU, M. − SHAHO, E. (2011): Biomass production and carbon storage of Populus ×canadensis Guinier I-214 plantations grown at Pogradeci region in Albania, Southern Forests: Journal of Forest Science 73 (2): 91−99. https://doi.org/10.2989/20702620.2011.610877

WIRTH, C. − SCHUMACHER, J. − SCHULZE E.D. (2004): Generic biomass functions for Norway spruce in Central Europe - a meta-analysis approach toward predictionand uncertainty estimation. Tree Physiology 24: 121−139. https://doi.org/10.1093/treephys/24.2.121

XIANG, W. − ZHOU, J. − OUYANG, S. − ZHANG, S. − LEI, P. − LI, J. − DENG, X. − FANG, X. − FORRESTER, D.I. − BAUHUS, J. (2016): Species-specific and general allometric equations for estimating tree biomass components of subtropical forests in southern China. European Journal of Forest Research 135: 963–979. https://doi:10.1007/s10342-016-0987-2

YAVUZ, H. (1999): Comparison of the Centroid Method and Four Standard Formulas for Estimating Log Volumes. Turkish Journal of Agriculture and Forestry 23: 597−602.

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The Effect of the Rate of Longitudinal Compression on Selected Wood Properties

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Abstract – Longitudinal compression of wood and relaxation after compression (held compressed for a while) is called pleating and results in improved bending properties. The examinations conducted on the longitudinal compression of air-dried oak (*Quercus petraea* (Matt.) Liebl.) and beech wood specimens (*Fagus sylvatica* L.) revealed the effects of different compression rates (10, 20, 40, 60 mm/min). The comparison of the various treatment methods showed that the stress in wood specimens during longitudinal compression increases with the rising compression rate. The remaining length reduction due to pleating slightly decreases and the bending modulus of elasticity increases at higher compression rates. The highest deflection of the specimens during the 4-point bending tests lowers with the increasing compression rate, while the change of modulus of rupture is negligible. Taking into account the differences between these results and the industrial effectiveness of the treatment according to the compression rates, it can be stated that a procedure with a higher rate should be preferred.

wood modification / steaming / wood bending / pliability / MoE / MoR

Kivonat – A rostirányú tömörítés sebessége és a fa egyes tulajdonságai közötti kapcsolat. A faanyag hosszirányú összenyomása és az azt követő relaxáció (összenyomva tartás egy ideig) kiemelkedő hajlítási tulajdonságokat eredményez. Légszáraz tölgy (*Quercus petraea* (Matt.) Liebl.) és bükk minták (*Fagus sylvatica* L.) tulajdonságainak változását vizsgáltuk különböző tömörítési sebességek hatására (10, 20, 40, 60 mm/perc). Az eljárások összehasonlítása azt mutatta, hogy a mintákban keletkező feszültség a rostirányú tömörítés sebességének növelésével együtt növekszik. A maradandó hosszváltozás a tömörítés hatására kissé csökken, míg a hajlítórugalmassági modulus növekszik a nagyobb tömörítési sebesség hatására. A minták maximális behajlása a 4 pontos hajlítóvizsgálat során a növekvő tömörítési sebességgel csökken, míg a hajlítószilárdság változása elhanyagolható. Figyelembe véve az eredmények közötti különbségeket és a kezelés ipari hatékonyságát a tömörítési sebesség változásával megállapítható, hogy a nagyobb sebességű tömörítési eljárást célszerű előnyben részesíteni.

famodifikáció / gőzölés / fahajlítás / hajlíthatóság / MoE / MoR

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1 INTRODUCTION

At the beginning of the twentieth century, Hanemann (1917) patented the method of longitudinal compression of wood, and in the 1920s the technology suitable for serial production was also developed (Holzveredelung 1926). With this thermo-hydro-mechanical treatment, wood become more pliable, even in cold conditions, than it would be after only a steaming process. Longitudinally compressed wood can be used to make flexible and lightweight furniture (Anssary 2006), curved handrails with mechanical fastenings or edge bandings with gluing (Deibl et al. 1999), restoration work, vibration-dampened tool handles, custom-shaped tools, and arched picture frames. Longitudinally compressed wood can also be used in the construction, sports equipment, musical instrument, and visual arts industries (Vorreiter 1949). It can be processed with negligible wood waste (Ivánovics 2005, Anssary 2006), and no excessive manufacturing oversize is required. The structure of the compressed wood remains intact during shaping because the grain always follows the arch. According to our present knowledge, longitudinally compressed wood is currently produced in a few places around the world. In Italy, the Candidus Prugger SAS uses a technology patented in 1927, which was further developed by the company (Bátori 2000). In other places, manufacturers such as Compwood Products KFT (Hungary) and Pure Timber LLC (USA) use Compwood equipment developed in Denmark.

This method requires a high-quality hardwood raw material with at least middle-level density. After plasticization – using usually 100 °C saturated steam – the compression ratio is 15–25% of the original length. Following compression, the degree of compression should remain for a while to allow the relaxation of internal stress to further increase the compression effects. These changes slow down after 1 minute of relaxation, but do not cease *(Figure 1)*.

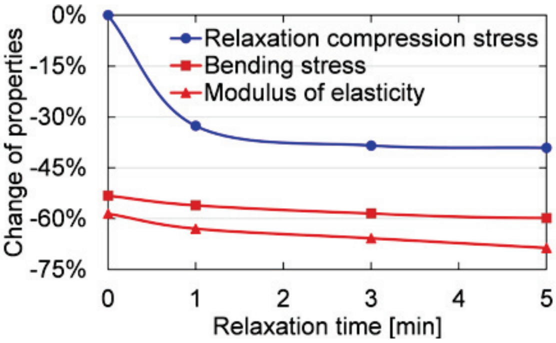

Figure 1. Some changes of oak wood due to 20% longitudinal compression are shown on the left side of the graph as well as the further change of these properties by relaxation (Báder and Németh 2018)

Longitudinal compression and 1-minute relaxation time results in an increase in maximum deflection during 4-point bending tests to 353%, and in a decrease to 37% in bending modulus of elasticity (*MoE*) and to 44% in bending stress at 5 mm crosshead displacement compared to the control specimens (Báder and Németh 2018). This means the process ensures high deformability for wood even with a dramatically decreased bending force. After treatment, the specimen is wet at the beginning, and as long as the moisture content (*MC*, [%]) is high, it can be bent more easily in a cold state when needed (Buchter et al. 1993). Different sources give different minimal moisture contents as a limit of pliability, ranging from 15% (Vorreiter 1949) to 25% (Buchter et al. 1993). During the modification process, the normally smooth cell walls deform (crinkle or buckle, *Figure 2*) (Báder and Németh 2017a). Therefore, this method may practically be called “pleating” (Báder and Németh 2018). While the moisture content is high, the wood is more pliable than it is in a dry condition, but it is always easier than uncompressed wood.

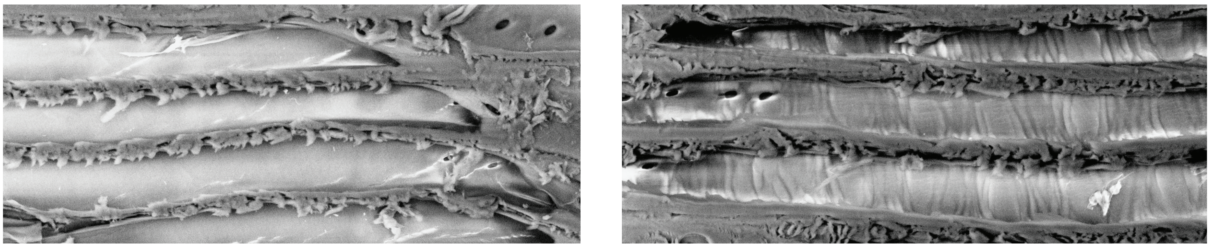

Figure 2. SEM images on radial sections of oak: before (left) and after (right) the longitudinal compression and relaxation treatment (magnification 1000x)

Unfortunately, scientific literature on this wood modification treatment is limited. Some studies contain general information about the technology and certain results (Vorreiter 1949, Heisel and Eggert 1990, Sandberg et al. 2013, etc.). Thorough studies of the physical and mechanical properties of this material are rare, and in many cases, they are found in theses (Bátori 2000, Sadatnejad et al. 2008, Kuzsella 2011, Báder and Németh 2018, etc.). In a previous experiment of Báder and Németh (2017c), applying a low compression rate (3 mm/min) to 200-mm-long specimens resulted in damage to 50% of the specimens. Generally, the fibers of the specimens bent out sideways and were thus unable to pass on the compression force in full length. However, at a compression rate of 6 mm/min, the yield was already 90%. On the other hand, high-speed compression, (for example 100 mm/min), rarely causes faults. However, operator intervention time is proportionally shorter in the event of specimen damage. If the specimen splits as a wedge due to a cross grain, it may damage the compression device. Taking these aspects into consideration, the compression rates have to be between about 6 and 100 mm/min (Báder and Németh 2017c). Further scientific articles relating to longitudinal compression rates were not found. The only sources that mentioned the topic were the book by Buchter et al. (1993) and some student theses (Bátori 2000, Sőregi 2007 and Dienes 2013).

The aim of this study is to determine the differences between the mechanical properties of pleated wood; these differences are caused by significantly different processing rates. This information can be used in the future to make disparate research results more comparable when the research is conducted under dissimilar circumstances. Furthermore, the properties of industrial products manufactured by similar methods will be more predictable.

2 MATERIALS AND METHODS

2.1 Specimen preparation

The raw materials for the experiment were sessile oak (*Quercus petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica L.*) taken from the forests of the Sopron region in Hungary. The dimensions of the untreated, wet specimens determined by the laboratory scale compressing machine were 20×20×200 mm (R × T × L). The requirements for the specimens to be longitudinally compressed were that they be knot and defect-free, precisely sized hardwood cut from a tree with a straight trunk structure and free from cracks and tortuosity with minimal fiber slope (Báder and Németh 2016).

With the exception of the control specimens, steaming at atmospheric pressure was used for the plasticization of wood. After steaming, the specimens were longitudinally compressed in a self-engineered and individually produced device developed to operate in an Instron 4208 (Instron Corporation, USA) universal material testing machine. The workpiece is kept straight during the compression process through the supports on the sides of the machine. An internal temperature in the device of 90 to 100 °C – maintained by a thermostat – was adequate to keep the specimen in plasticized state. All specimens were compressed by 20% compared to their original lengths. To obtain information about the effects of compression rates in the margins and the middle region in the optimal range, the compression rates were set to 10, 20, 40 and 60 mm/min for the 200-mm-long specimens. Each group had 20 specimens of both wood species. After compression, the treated specimens were relaxed for 1 minute. Following the aforementioned treatments, the specimens were conditioned to 20 °C and 65% relative humidity until a constant weight was reached. Specimen *MC* was determined by a weight measurement method after the bending tests were completed. The *MC* relative to net dry weight can be calculated using the mass of the wet wood (m_n [g]) and the mass of the absolute dry wood (m_0 [g]), by the ISO 13061-1 (2014) standard (Eq. 1):

$$MC = \frac{m_n - m_0}{m_0} \cdot 100 \tag{1}$$

2.2 Measurements

Macromechanical experiments were performed with longitudinally compressed wood to acquire the discrepancies that different compression rates initiate. After conditioning, 4-point bending tests were conducted. Based on the method described by Báder and Németh (2018), the specimen height (*h*) was cut back to 12.5 mm, while width (*b*) was left at the original size. For the bending tests, specimens with an average 19.6×12.5 mm^2 (radial × tangential) cross section were used. The average length was 199.4 mm for the control specimens and 190.6 mm for the treated specimens, which resulted in an average 4.4% reduction due to pleating. The position of the annual rings was in vertical direction. An Instron 4208 (Instron Corporation, USA) universal material testing machine was used for 4-point bending tests. The loading rate was 8 mm/min for control specimens, and 20 mm/min for treated specimens according to Hungarian standard MSZ 6786-5 (2004). Tests were halted upon failure when the load dropped with no recovery. Modulus of rupture (*MoR*) with the 4-point bending test was determined by Eq. 2, according to the European standard EN 408 (2010) +A1 (2012).

$$MoR = \frac{3 \cdot F \cdot a}{b \cdot h^2} \tag{2}$$

where *F* is the maximum load, and *a* is the distance between the loading roller and the nearest support roller, which, in this case was 50 mm. The upper span was 50 mm as well. The calculation of *MoE* is based on the work of Báder and Németh (2018), using the increment of the crosshead displacement (Δw) corresponding to the 10% and 25% difference of the maximum load (ΔF) in Eq. 3.

$$MoE = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{12 \cdot I_x \cdot \Delta w} \tag{3}$$

where *L* is the lower span and I_x is the second moment of area. y_{max} is the maximum deflection during the bending test, which came from Eq. 4 (Báder and Németh 2018).

$$y_{\max} = 1.1563 \cdot \frac{F \cdot a \cdot (3 \cdot L^2 - 4 \cdot a^2)}{48 \cdot I_x \cdot MoE_y} - 0.7345 \tag{4}$$

where MoE_y is the bending modulus of elasticity, which belongs to the bending force and the deflection measured at the end of the bending test. Eq. 4, modified with experimental values, is applicable for highly pliable wood materials. After the bending test, the specimens were analyzed visually, and their *MC* was determined by drying the specimens to 0% *MC* in an oven at a temperature of 103±2 °C. As the mechanical properties of wood change with the *MC* , the mechanical properties of the specimens were recalculated to get comparable results at 12% *MC* as described in Eq. 5, according to standard series ISO 13061 (2014).

$$\sigma_{12} = \sigma_u \cdot \left[1 + \alpha \cdot (u - 12)\right] \tag{5}$$

where σ_{12} is the mechanical property at 12% *MC*, σ_u is the examined mechanical property at the *MC* at the time of measurements, u is the *MC* of wood at the time of measurements. α is the coefficient of moisture dependence of mechanical properties, and it has been determined for treated wood specimens as 0.04 for the modulus of rupture and 0.05 for the modulus of elasticity. The equilibrium moisture content at the time of the bending examinations averaged between 9.3% and 9.8% for beech specimens, and between 7.6% and 9.8% for oak specimens.

3 RESULTS AND DISCUSSION

3.1 Physical properties

Several machines have been developed for longitudinal wood compression; some of these are in use today. These machines differ in capacity (both in length and cross-section) and compression technology, which determines the compression rate. Therefore, it is necessary to obtain a universal unit of measurement for the rate of longitudinal compression to make the comparison on laboratory measurements and different industrial scales possible. It seems best to use the relative rate of compression $\left[\frac{m}{m \cdot h}\right]$, as it provides information that is independent of the specimen size (Báder and Németh 2017c). Basic units are used to show how much shortening would occur in a 1-meter-long section of the workpiece during a 1-hour compression process. In other words, it represents the amount of shortening that occurs on the workpiece per unit length over a unit of time. The relative rate of compression described above is independent of the compression ratio. Since the latter is also a significant factor, it is advisable to specify the percentage of shortening relative to the original length. The rate of longitudinal compression is extremely important for both productivity and quality output. Using the relative rate of compression and the data from literature, it can be calculated that industrial equipment working with large raw material cross-sections and lengths compress at a rate of 0.4 to 2.4 $\frac{m}{m \cdot h}$ (Buchter et al. 1993, Bátori 2000, Sőregi 2007, Dienes 2013). The laboratory equipment (Báder and Németh 2017b) can successfully compress small specimens with dimensions of 20x20x200 mm^3 at a rate of 1.8 to 30 $\frac{m}{m \cdot h}$. Further refining these values, according to Báder and Németh (2016), it is recommended to use a productive but safe 9 to 15 $\frac{m}{m \cdot h}$ compression rate that allows a better than 90% yield. In this study, using the unit of measurement of the relative rate of compression, 3, 6, 12 and 18 $\frac{m}{m \cdot h}$ compression rates were used.

During the longitudinal compression process, the compression force increases gradually until the end of the compression phase, and during the following relaxation, it decreases in the first minute by 1/3 compared to the maximum value (Báder and Németh 2018). The results of the examinations show that the maximum compression stress increases with the compression rate, while during relaxation, the decrease of the compression stress gets higher with the increasing compression rate *(Figure 3)*.

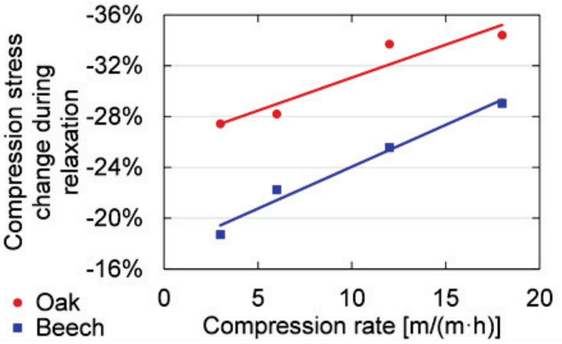

Figure 3. The change of compression stress during 1 minute of relaxation time, as a function of the compression rate

Although the change of compression stress during 1-minute relaxation time of oak and beech wood were similar, the test results for ring-porous oak and diffuse-porous beech wood often showed different tendencies. The coefficient of determination for the remaining length change by pleating is very good in the oak specimens (0.95), but weak in the beech specimens (0.01) *(Figure 4a)*. Based on the results of previous studies (Báder and Németh 2017c), under a certain rate it is not possible to achieve proper compression quality. The lowest compression rate of beech data point seems to be an outlier. Both oak and beech are hardwoods, but they have significantly different structures. Hence, it is likely that oak can already be sufficiently compressed at this rate, but in the case of beech, this rate is still too low for a successful longitudinal compression. If this result is ignored, the coefficient of determination will be 0.83 *(Figure 4b)*. Accordingly, the results of the lowest compression rate of beech will be further illustrated for information purposes only. Furthermore, it is worth noting that the deviation of the results of beech wood is always higher than the deviation of oak results; therefore, oak provides more reliable material properties. Higher remaining length reduction due to pleating indicates an increase in the bending modulus of elasticity (*MoE*) and better pliability, according to Báder and Németh (2018). By increasing compression rate, the length reduction will be lower, which means a decrease in the success of the treatment, as described hereinafter.

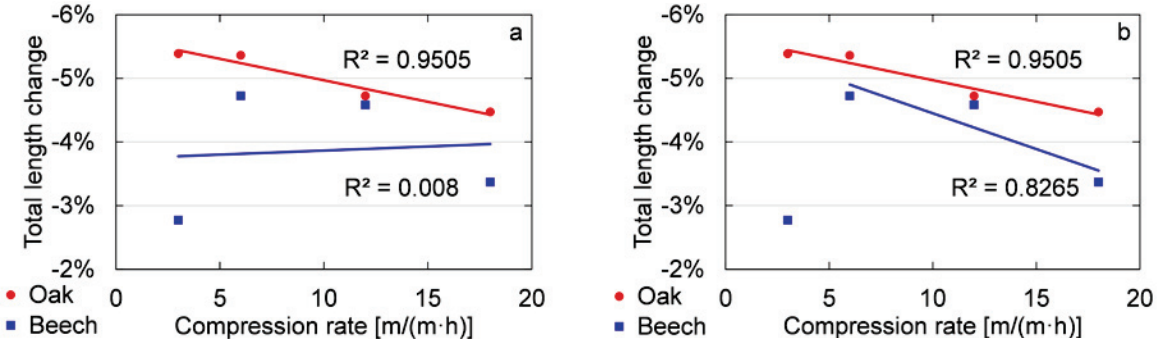

Figure 4. Remaining length change by pleating and conditioning as a function of the compression rate. For the linear trend lines, all the data points were taken into account (a) and the lowest compression rate of beech was not taken into account (b)

3.2 Mechanical properties

Based on the results of Ivánovics (2006) and Kuzsella and Szabó (2006), the average decrease of the modulus of rupture (*MoR*) was 29% for oak and 47% for beech wood due to 20% longitudinal compression. The results of this study were lower, with a 21-25% decrease at a 20% compression ratio and 1-minute relaxation. The difference may be attributed to a dissimilar relaxation process, a different bending test method, and the natural diversity of wood. In *MoR*, a 5% increase for oak and 1% decrease for beech is observable with a 20% compression ratio and 1-minute relaxation time, between 3 and 18 $\frac{m}{m \cdot h}$ compression rates *(Figure 5a)*. These changes are so low that they can be considered negligible. The bending stress during 4-point bending tests behaves the same as *MoR*, but *MoE* has a higher slope for both oak and beech wood *(Figure 5b)*.

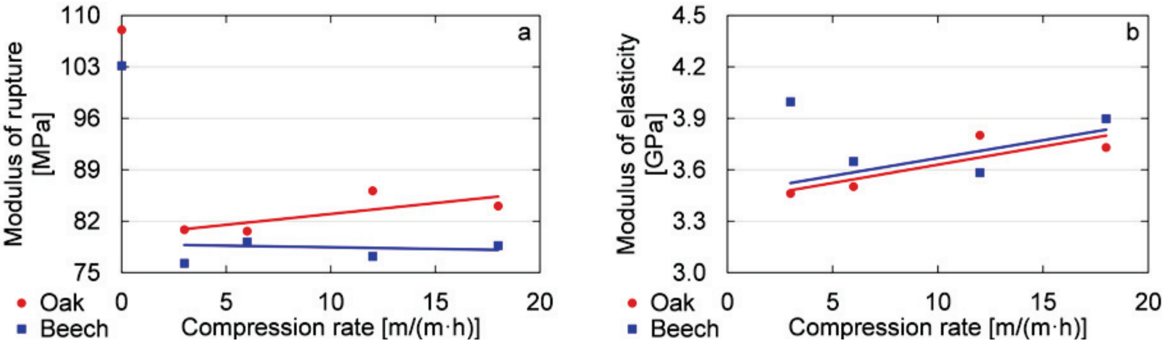

Figure 5. The modulus of rupture (a) and the modulus of elasticity (b) as a function of compression rate

The *MoE* for beech control specimens was 9.2 MPa, and for oak control specimens, it was 9.8 MPa. The decreases of *MoE* were between 58% and 62%, and between 61% and 64%, respectively. These values correlate with the published data (Vorreiter 1949, Ivánovics 2006, Kuzsella and Szabó 2006, Báder and Németh 2017d, etc.). Compared to the control specimens, the increase of *MoE* was about 3% with the change of the compression rate. However, considering only the *MoE* of treated specimens as a function of the compression rate, it is 9% for both wood species. Báder and Németh (2018) found that the *MoE* of oak correlates well inversely with pliability. Accordingly, the decrease of deflection at maximum load during 4-point bending test is 9% between 3 and 18 $\frac{m}{m \cdot h}$ compression rate for oak, and 22% for beech wood. The higher value for the deflection decrease was indicated by the higher change of compression stress during relaxation *(Figure 3)* and the higher length change by pleating *(Figure 4b)*. This property is a result of the characteristics of beech wood. Beech, more than oak, responds differently to the same treatment and changes in circumstances. The deflection at maximum load is between 428% and 334% for beech and between 462% and 422% for oak in the compression rate range that was used, compared to the deflection of the control specimens *(Figure 6)*. The available flexibility is thus high – at least 3–4 times higher because of the pleating. However, with further adjustments for the treatment, at least 2 times higher flexibility is available (Báder and Németh 2018).

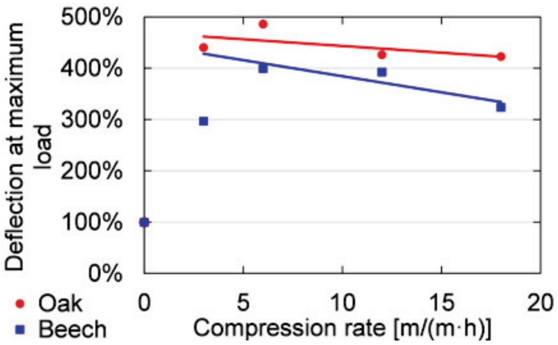

Figure 6. The change of deflection at maximum load during 4-point bending test, as a function of compression rate

Considering the increase in the production speed of compressed wood and, consequently, both the productivity growth and cost reduction as a function of the deterioration of flexibility, higher compression rates are acceptable. Of course, if there is a demand for the highest achievable flexibility, a lower compression rate, higher compression ratio, and much higher relaxation time should be used (Báder and Németh 2018).

4 CONCLUSIONS

In this study, the effect of the compression rate on the mechanical properties of ring-porous oak and diffuse-porous beech hardwoods was investigated. A new unit of measurement, the use of the relative compression rate $\left[\frac{m}{m \cdot h}\right]$ became necessary. It represents the shortening that occurs on the workpiece per unit length over a unit of time. Compression rates between 3 and 18 $\frac{m}{m \cdot h}$ were used. The stress in wood specimens during longitudinal compression increases with the increasing compression rate, and the remaining length reduction is lowered. The specimens were subjected to 4-point bending tests. The change of modulus of rupture is not significant with increasing compression rates as well as the change of bending stress. For both oak and beech specimens, the modulus of elasticity increases by 3% in this range of compression rate. The deflection at maximum load decreases by 9% for oak and by 22% for beech, but still remains very high compared to the untreated wood. If the effectiveness of the treatment according to the compression rates is considered, higher compression rates should be preferred. If a higher flexibility is needed, higher compression ratios and longer relaxation times are more effective.

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REFERENCES

ANSSARY, E.A. (2006): An approach to support the design process considering technological possibilities. PhD Dissertation, University of Duisburg-Essen, Germany, 207 p.

BÁDER, M. – NÉMETH, R. (2016): The solid wood crushing's conditions. In: Proceeding of the Eco-efficient Resource Wood with Special Focus on Hardwoods Conference. Hungary. September 2016, 120 p.

BÁDER, M. – NÉMETH, R. (2017a): Hygroscopicity of longitudinally compressed wood. Acta Silvatica et Lignaria Hungarica 13 (2): 135–144. https://doi.org/10.1515/aslh-2017-0010

BÁDER, M. – NÉMETH, R. (2017b): A faanyagok rostirányú tömörítésének kísérleti körülményei – 1. rész. [Research conditions of the wood's longitudinal compression - Part 1.] Gradus 4 (2): 403–411. (in Hungarian)

BÁDER, M. – NÉMETH, R. (2017c): A faanyagok rostirányú tömörítésének kísérleti körülményei – 2. rész. [Research conditions of the wood's longitudinal compression - Part 2.] Gradus 4 (2): 412–418. (in Hungarian)

BÁDER, M. – NÉMETH, R. (2017d): A faanyagok rostirányú tömörítésének kísérleti körülményei – 3. rész. [Research conditions of the wood's longitudinal compression - Part 3.] Gradus 4 (2): 419–425. (in Hungarian)

BÁDER, M. – NÉMETH, R. (2018): The effect of the relaxation time on the mechanical properties of the longitudinally compressed wood. Wood Research 63 (3): 383-398.

BÁTORI, K. (2000): A fa tömörítése és alkalmazási területei. [Compression and application areas of wood.] Bachelor's thesis, University of West Hungary, Sopron, Hungary, 41 p. (in Hungarian)

BUCHTER, J. – ADELHOEJ, J. – LJOERRING, J. – HANSEN, O. (1993): Introducing Compressed Wood. Danish Technological Institute, Taastrup, Denmark, 32 p.

DEIBL, H.J. – ILLHARDT, J. – WALTER, H.J. (1999): Verfahren zur Herstellung von Halbzeugen aus biegbarem Holz. [Method to produce semi-finished products from bendable wood.] Patent Nr. DE19913775 A1, Deutsches Patent- und Markenamt, Germany, 2 p. (in German)

DIENES, ZS. (2013): Terméktervezés tömörített faanyag felhasználásával. [Product design using compressed wood.] Bachelor's thesis, University of West Hungary, Sopron, Hungary, 58 p. (in Hungarian)

HANEMANN, M. (1917): Holzaufbereitungsverfahren. [Wood treatment processes.] Patent Nr. 318197, Deutsches Reich Reichspatentamt, Germany, 1 p. (in German)

HEISEL, U. – EGGERT, O.TH. (1990): Plastifizierung von Bugholz mit Hochfrequenz oder Wasserdampf. [Plastification of bentwood with high frequency or water vapor.] Die Holzbearbeitung 37 (9): 18–26. (in German)

HOLZVEREDELUNG GMBH. (1926): Verfahren und Vorrichtung zur Herstellung von weichbiegsamen Holz. [Method and device for producing easily bendable wood.] Patent Nr. 458923, Deutsches Reich Reichspatentamt, Germany, 3 p. (in German)

ISO 13061-1 (20149: Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 1: Determination of moisture content for physical and mechanical tests. International Organization for Standardization, Geneva, Switzerland.

IVÁNOVICS, G. (2005) A fa hajlításának technológiája napjainkban. [The technology of wood bending nowadays.] In: Proceedings of the AGTEDU 2005 Conference. Hungary. November 2005, 189–193. (in Hungarian)

IVÁNOVICS, G. (2006): Rostirányban tömörített faanyagok szilárdsági vizsgálata. [Strength test of longitudinally compressed wood.] In: Proceedings of the AGTEDU 2006 Conference. Hungary. November 2006, 171–176. (in Hungarian)

KUZSELLA, L., SZABÓ, I. (2006): A fa tömörítésének hatása a mechanikai tulajdonságokra. [Effect of wood compression on mechanical properties.] In: Proceedings of the XI. Scientific Session of Young Engineers. Romania. March 2006, 233–236 p. (in Hungarian)

KUZSELLA, L. (2011): Rostirányú tömörítés hatása a bükk faanyag szerkezetére és mechanikai tulajdonságaira. [Effect of longitudinal compression on the structure and mechanical properties of beech wood.] PhD Dissertation, University of Miskolc, Hungary, 151 p. (in Hungarian)

MSZ 6786-5 (2004): Testing of wood materials. Determination of static bending strength. Hungarian standard No. 6786-5:2004, Magyar Szabványügyi Testület, Budapest, Hungary.

SADATNEJAD, H., TAJVIDI, M., YOSEFI, H. (2008): اثر فشرده سازي در جهت موازي الياف بر خصوصيات مكانيكي چوب راش. [Effect of longitudinal compression to bulk cell wall on mechanical properties of steamed treated of beach wood.] Iranian Journal of Wood and Paper Science Research 23 (2): 191–199. (in Iranian)

SANDBERG, D., HALLER, P., NAVI, P. (2013): Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products. Wood Material Science & Engineering 8 (1): 64–88. https://doi.org/10.1080/17480272.2012.751935

SŐREGI, R. (2007): Vitorláshajó kabinbelső kialakítása tömörített fa alkalmazásával [Interior design of a sailboat cabin using compressed wood.] Master's thesis, University of West Hungary, Sopron, Hungary, 55 p. (in Hungarian)

VORREITER, L. (1949): Holztechnologisches Handbuch, Band I. Verlag Georg Fromme & Co., Wien. 547 p.

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