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POTENTIAL FOR ADAPTATION OF DOUGLAS-FIR AND COMMON BEECH PROVENANCES TO CLIMATE CHANGE

ABSTRACT

of a Dissertation
for obtaining “Doctor of Sciences” degree

Professional field: 6.5. Forestry
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Rewievers: Acad. Alexander Haralanov Alexandrov, DSc
Prof. Petar Zhelev Stoyanov, PhD
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The dissertation contains a total of 199 pages, 55 figures, 32 tables and 10 appendices. The list of used literature includes a total of 355 titles, of which 56 are in Cyrillic and 299 in Latin.

The dissertation defense will be held on 23.03.2020 at 13.00 in the hall of “Acad. Mako Dakov", Building A of the University of Forestry in Sofia at 10 Kliment Ohridski Blvd at an open meeting of a scientific jury approved by Order No. ZPS - 636/28.11.2019 of the Rector of the University of Forestry with the following members:

Chairperson:

Prof. Petar Zhelev Stoyanov, PhD – University of Forestry

Members:

Acad. Alexander Haralanov Alexandrov, DSc – Forest Research Institute – BAS
Corr. Memb. Prof. Ivan Alexandrov Iliev, DSc – University of Forestry
Prof. Nikolina Penkova Tzvetkova, PhD – University of Forestry
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The materials for the defense are available to those interested in the Dean’s office of the Faculty of Forestry, Room № 222, Building A of the University of Forestry in Sofia at 10 Kliment Ohridski Blvd., and on the University website (www.ltu. bg)

I. INTRODUCTION

The Earth's climate has experienced changes by getting colder at one time and warmer at another. In the distant past, these changes had taken place over hundreds of years. The last 130 years have been characterized mainly by a period of warming, leading to an increase in the average global temperature by 1°C (IPCC 2014). If this trend continues in the future, the ability of forests to adapt to the changing conditions can be seriously affected. The adaptation potential of tree species to climate change can be assessed through provenance tests. These experiments are established by cultivation of selected provenances of a particular tree species under the same conditions. The provenances are adapted to the climate of the seed source, and their ecological plasticity is assessed under the climatic conditions in the site of the provenance test. The difference between the climate of the seed source and that of the experiment site can be considered as experimentally simulated climate change. This methodological approach is an opportunity to analyze, model and predict the response of tree species to climate change.

The present dissertation aims to investigate Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and common beech (*Fagus sylvatica* L.) provenances. These tree species have similar ecological requirements: they prefer slightly moist to moist, medium rich to rich habitats and high air humidity. A substantial part of the Douglas-fir plantations established in Bulgaria are located in the beech forest belt and grow successfully in these surroundings, including in mixed with common beech stands.

The first experiments with Douglas-fir provenances in Bulgaria began about 30 years ago, and with common beech - more than 40 years ago. Previous studies were related to the investigation of species' individual traits, but species' response to the climatic conditions of the sites in which they were introduced has not been evaluated to the present moment.

The current climate change, the provenance tests' potential and the still under-explored ecological plasticity of Douglas-fir and common beech have determined the objective of this study.

II. OBJECTIVE AND TASKS

The objective of this study is to evaluate the potential for adaptation of Douglas-fir and common beech provenances to climate change through provenance tests.

The following important tasks can be specified to accomplish the formulated objective:

1. To investigate how the transfer of Douglas-fir and common beech provenances under different climatic conditions compared to that of their native stands will affect the species' main phenological traits.
2. To assess the reliability of the survival of the provenances as a criterion for their adaptation to new conditions.
3. To investigate the growth by main biometric indicators of the provenances as a sign of their adaptive potential to climate change.
4. To make an attempt to model the height growth of the Douglas-fir and common beech provenances on the basis of main climatic indicators.
5. To study the possibility of beech provenances' transfer from the warmer and drier climate in Bulgaria to a more humid and cooler climate in Central Europe (Germany).
6. To evaluate the mechanical stability of Douglas-fir as an indicator of resistance to damage by some abiotic factors.
7. To evaluate the productivity of Douglas-fir provenances under the conditions of Northwestern Bulgaria.

III. EXPERIMENTAL SITES AND METHODS

III.1. Experimental sites

Douglas-fir provenance test in Petrohan Training and Experimental Forest Range (TEFR).

The provenance test was established in the spring of 1990, with 55 Douglas-fir provenances from the USA: 27 continental, 22 from the Western Cascade Range, and 6 from the Pacific coast. Most provenances originated from the states of Washington and Oregon, but the test also included a provenance from each of the states of Montana, Arizona and New Mexico, as well as the ‘Bulgarian’ provenance[1] Kazanlak (Table 1).

Table 1. Data for Douglas-fir provenances in Petrohan

Provenance			**Seedzone**	**Geographical**		**Altitude, m**
Provenance group	**Name, number**	**Code**		**latitude N**	**longitude W**	
1	**2**	**3**	**4**	**5**	**6**	**7**
CONTINENTAL						
Montana	Whitefish 3	W	Montana	48.5	114.5	1050
New Mexico	Alamogordo 55	A	840	33.0	105.8	750
Washington	Greenwood 1	G	612	49.0	119.0	1350
	Keremeos 2	K	600	49.0	120.0	750
	Naches 13	N	641	46.5	121.3	1050
East Cascade Range Oregon	Parkdale 14	P14	661	45.5	121.5	1650
	Parkdale 15	P15	661	45.5	121.7	1500
	Parkdale 16	P16	661	45.5	121.5	1350
	Parkdale 17	P17	661	45.5	121.5	1200
	Parkdale 18	P18	661	45.5	121.5	1050
	Parkdale 19	P19	661	45.5	121.5	900
	Parkdale 20	P20	661	45.5	121.5	750
	Warm Springs 33	WS33	662	45.0	121.5	667
	Warm Springs 32	WS32	662	45.0	122.0	900
	Santiam Pass 38	SP38	675	44.3	121.6	1125
	Crescent 47	C47	681	43.3	121.8	1650
	Crescent 48	C48	681	43.3	122.0	1500
East Oregon	Bates 21	B21	863	45.0	118.5	1667
	Bates 22	B22	863	45.0	118.5	1500
	Bates 23	B23	863	45.0	118.5	1333
	Canyon City 35	CC35	892	44.5	119.0	1500
	Canyon City 36	CC36	892	44.5	119.0	1350
	Canyon City 37	CC37	892	44.5	119.0	1650
Coastal Range South Oregon	Crater Lake 49	CL	501	42.7	122.5	1200
	Medford 50	MF50	501	42.5	122.5	1050
	Medford 51	MF51	502	42.6	122.8	900

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[1] This provenance is accepted as ‘Bulgarian’ because it originates from the first Douglas-fir plantation in Bulgaria.

Provenance			**Seedzone**	**Geographical**		**Altitude, m**
Provenance group	**Name, number**	**Code**		**latitude N**	**longitude W**	
1	**2**	**3**	**4**	**5**	**6**	**7**
WESTERN CASCADE RANGE						
Washington	Newhalem 4	NH4	402	48.5	121,5	667
	Newhalem 5	NH5	402	48.5	121.5	500
	Darrington 6	DR6	403	48.0	121.5	1167
	Darrington 7	DR7	403	48.0	121.5	1000
	Darrington 8	DR8	403	48.0	121.5	833
	Monroe 9	MR	411	47.8	121.3	525
Oregon	Idanha 24	I24	452	45.0	122.0	1050
	Idanha 25	I25	452	45.0	122.0	1200
	Idanha 26	I26	452	45.0	122.0	1050
	Idanha 27	I27	452	45.0	122.0	900
	Idanha 28	I28	452	45.0	122.0	1333
	Idanha 29	I29	452	45.0	122.0	750
	Idanha 30	I30	452	45.0	122.0	750
	Idanha 31	I31	452	45.0	122.0	750
	Santiam Pass 39	SP39	473	44.3	121.8	1500
	Oakridge 40	O40	472	44.0	122.0	1667
	Oakridge 41	O41	472	44.0	122.0	1500
	Oakridge 42	O42	473	44.0	122.0	1333
	Oakridge 43	O43	482	44.0	122.0	900
	Oakridge 44	O44	482	43.8	122.5	1350
	Oakridge 45	O45	482	43.8	122.5	1200
	Oakridge 46	O46	472	43.8	122.5	1500
PACIFIC COAST						
Washington	Bremerton 10	BM10	222	47.7	123.0	600
	Bremerton 11	BM11	222	47.7	123.5	450
	Moclips 12	MC	12	47.5	124.0	600
Oregon	Toledo 34	T	53	44.6	123.8	150
	Brookings 52	BR52	82	42.0	124.5	833
	Brookings 53	BR53	82	42.0	124.5	667
INTRODUCED						
Bulgaria	Kazanlak	KZN		42.7	25.3E	750

The provenance test was established in an east-facing flat terrain at an altitude of 600 m a.s.l., latitude 43.1898 N and longitude 23.1464 E. The soil is Orthic Luvisol (FAO), mixed sandy and clayey, slightly stony and very deep. The site is slightly moist, medium rich to rich. Three-year-old seedlings were planted in a 2x2 m plot design.

Douglas-fir provenance test in Berkovitza Forest Enterprise (FE)

The provenance test was established in the spring of 2006 with 29 provenances, of which 20 from Germany (Bavaria, Rhineland Palatinate and Lower Saxony), 6 from the USA and 3 from Bulgaria (Table 2). The trial was located at the top of a northeast-facing slope with a gradient of 8° and altitude of 850 m a.s.l., latitude 43.2193 N and longitude 23.0902 E. The soil is Cambisols (FAO), mixed sandy and clayey, friable, slightly stony, deep, on subsoils schists.

The habitat is slightly moist to moist, medium rich to rich. The planting was carried out with 2-years-old seedlings in a 2x2 m plot design.

Table 2. Data for Douglas-fir provenances in Berkovitza

No	Country/Province (State)	Provenance code	Provenance name	Altitude, m	Latitude, E	Longitude N
	Germany					
1	Bavaria	M	Münnerstadt	300-310	10.20	50.22
2	Bavaria	L	Lohr	440-455	9.50	50.00
3	Bavaria	SF	Schweinfurt	380	12.23	50.05
4	Bavaria	SS	Stadtsteinach	490-600	11.57	50.22
5	Bavaria	SB	Schnaittenbach	480-500	11.97	49.50
6	Bavaria	GH	Griesbach	460-510	13.22	48.45
7	Bavaria	FS	Freising	420	11.75	48.40
8	Bavaria	SS1	Stadsteinach	550-650	11.52	50.17
	USA					
9	Washington	MN	Mineral, Wa	533	122.17W	46.70
10	Washington	DR1	Darrington, Wa	381	121.58W	48.37
11	Washington	DR2	Darrington, Wa	381	121.75W	48.33
12	Washington	DR3	Darrington, Wa	381	121.55W	48.33
13	Washington	DR4	Darrington, Wa	381	121.58W	48.37
14	Washington	FO	Forks, Wa	838	124.22W	48.08
	Germany					
15	Rhineland Palatinate	KL	Kaiserslautern	280-310	7.77	49.42
16	Rhineland Palatinate	OS	Osburg	565-590	6.75	49.75
17	Rhineland Palatinate	MY	Mayen	410-500	7.00	50.28
18	Rhineland Palatinate	D	Daun	560-620	6.68	50.17
19	Rhineland Palatinate	SCHL	Schneifel	530	6.50	50.25
20	Rhineland Palatinate	GS	Gerolstein	520-550	6.50	50.25
21	Rhineland Palatinate	KLW	Kaiserslautern W	280-310	7.77	49.42
22	Lower Saxony	OL	Oldendorf	180	9.45	51.93
23	Lower Saxony	MD	Münden	300	9.77	51.32
24	Lower Saxony	OLSP	Oldendorf (SPl)	290	9.42	51.85
25	Lower Saxony	ALH	Ahlhorn	30	7.97	52.90
26	Lower Saxony	SEG	Segeberg	40	10.12	53.93
27	Bulgaria	SM	Smiljan	950	21.77	41.63
28	Bulgaria	KZN	Kazanlak	750	25.43	42.63
29	Bulgaria	NEV	Nevestino	650	22.77	42.20

Common beech provenance tests

Three provenance tests in the regions of Vidin, Varbitza and Kipilovo Forest Enterprises with 5 German and 3 Bulgarian common beech provenances were established in the autumn of 2009 and in the spring of 2010 (Fig. 1). The planting was carried out with 2-years-old seedlings in a 2x1 m plot design. In Vidin and Varbitza all eight beech provenances were included. In Kipilovo, only four beech provenances, Silberbach, Ebersdorf, Berkovitza and Petrohan[2], were planted.

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[2] Please note that the same names of Berkovitza and Petrohan may refer to both experiment sites and provenance names in this work.

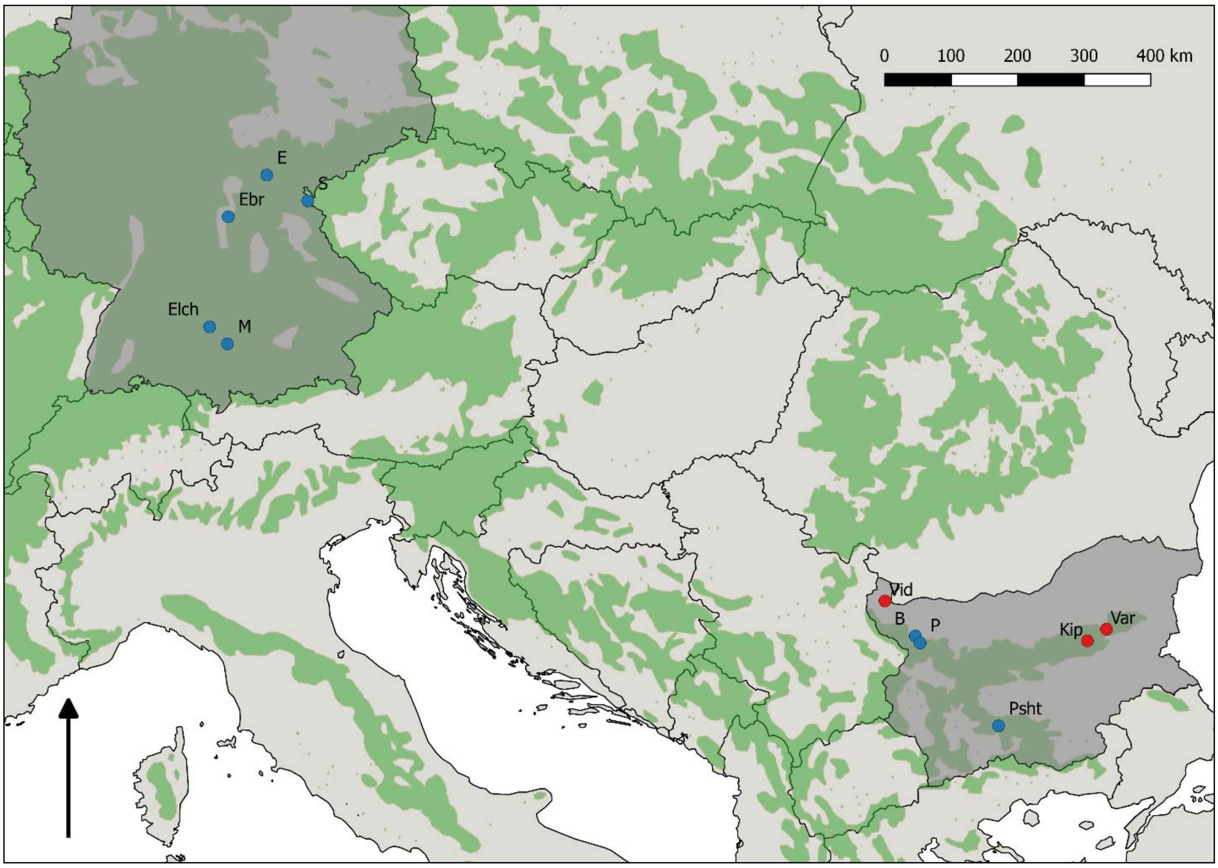


Fig. 1. Distribution of common beech in Central and South-Eastern Europe (green), Germany and Bulgaria (dark grey), locations of provenances (blue): Elchingen (Elch), Silberbach (S), Ebersdorf (E), Mindelzell (M), Ebrach (Ebr), Peschtera (Psht), Berkovitza (B), Petrohan (P) and studied sites (red): Vidin (Vid), Varbitza (Var) and Kipilovo (Kip). Map data: EC.Europa.EU/Eurostat; species distribution map: www.EUFORGEN.org/species.

The provenance test in Vidin was located in a northeast-facing flat terrain, at an altitude of 200 m a.s.l, latitude 43.89 N and longitude 22.72 E. The soil type was chernozems. The habitat is slightly moist, rich.

The provenance test in Varbitza was located in a northwest-facing flat terrain, at an altitude of 350 m a.s.l., latitude 42.98 N and longitude 26.62 E. The soil is Orthic Luvisol (FAO). The habitat is slightly moist to moist, medium rich to rich.

The provenance test in Kipilovo was located in a northeast-facing flat terrain, an altitude of 500 m, latitude 42.88 N and longitude 26.22 E. The soil is Orthic Luvisol (FAO). The habitat is slightly moist, medium rich to rich.

III.2. Methods of the study

III.2.1. Phenological and morphological traits of the seedlings of the investigated provenances

A. Douglas-fir

For the 29 Douglas-fir provenances in Berkovitza Forest Nursery, the following phenological phases and morphological traits were investigated: onset of needle unfolding (bud burst), needle coloring, terminal bud formation, and shoot hardening. The study included 50 seedlings (2 replications x 25 plants) per provenance. The methodology of Kleinschmit et al. (1974) was applied.

B. Common beech

The phenophases of leaf unfolding and leaf coloring of seedlings of 7 common beech provenances in Berkovitza Forest Nursery and of 8 beech provenances in the provenance test in Varbitza were monitored. Observations in Berkovitza were made during the second vegetation period after the seeds sowing (2009), and in Varbitza - in the fourth (2013) and the seventh (2016) year after trial establishment. The methodology of Forstreuter (2002) was applied.

III.2.2. Evaluation of survival, growth and mechanical stability

The survival rate was determined in all provenance tests during the first 3 years after establishment. In the Douglas-fir provenance test at Petrohan, the survival rate was recorded at the end of each growing period for 8 years (until 1997), as well as on the 14th (2003) and the 17th (2006) year after trial establishment. In the provenance test in Berkovitza, the survival rate was recorded also on the 6th (2011) and the 11th (2016) year after trial establishment. For the beech provenance tests in Varbitza and Kipilovo, the survival rate was assessed at the end of each growing period for 8 years (until 2017).

The average height of the provenances in all provenance tests was determined as follows:

- in the provenance test in Petrohan - at 24 years of age;
- in the provenance test in Berkovitza - in the 11th year after establishment in the plots in which a survival rate of over 50% had been calculated;
- in the beech provenance tests in Vidin, Varbitza and Kipilovo - at the end of the first 3 vegetation periods after establishment; only in the provenance tests in Varbitza and Kipilovo - from the fourth to the eighth year;

The average height for all provenance tests was calculated as the arithmetic mean of the measured heights of each provenance.

The average diameter at breast height was determined only for the Douglas-fir in the provenance tests in Petrohan (at 24 years of age) and in Berkovitza (at 11 years of age). A standard biometric method was applied.

The stem volume was calculated only for the Douglas-fir in the provenance tests in Petrohan at 24 years of age according to the formula:

$V = G.HF$, m^3,

where:

G – the total basal area of trees in the provenance (m^2),

HF – height form factor for Douglas-fir plantations (Ferezliev 2012).

The mechanical stability was calculated only for the Douglas-fir in the provenance test in Petrohan. The coefficient of collective mechanical stability was determined as the ratio of average height (m) to average diameter at breast height (cm) for each provenance (Mayer and Ott 1991).

III.2.3. Climatic indicators used in results' analysis and model development

The following climatic indicators were included in the results' analysis and model development for Douglas-fir provenances: mean annual temperature (MAT), average annual minimum temperature (AAMT), mean coldest month temperature (MCMT), mean warmest month temperature (MWMT) – Wang et al. (2006), continentality index (Ic, which is the difference between MWMT and MCMT, Chakraborty et al. 2015, Wang et al. 2016, Rivas-Martinez et al. 2017), mean annual precipitation (MAP).

The main climatic indicators used in the results' analysis for the common beech provenances are the Ellenberg's climate quotient and the ecological distance.

The Ellenberg's climate quotient EQ (Ellenberg, 1988) for each trial and each provenance was calculated according to the formula:

$$EQ = 1000\frac{T_{07}}{P_{ann}},$$ where

T_{07} - the mean annual temperature of the warmest month (July), °C;

P_{ann} – the mean annual precipitation, mm.

The ecological distance ΔE was calculated using the formula:

$\Delta E = X_t – X_o$,, where:

Xt - the average value of the *EQ* of the respective provenance test (Vidin, Varbitza and Kipilovo)

Xo - the *EQ* of the respective beech provenance (Matyas et al., 2009)

III.2.4. Statistical processing of results

The statistical processing was carried out with the R package stats and agricolae (de Mendiburu 2017, R Core Team 2018) and the results were visualized with the graphical functions in the R package ggplot2 (Wickham 2016). The following statistical analyses were used:

Analysis of variance (ANOVA)

Single-factor ANOVA and two-factor ANOVA.

Multiple comparisons methods: Tukey's test and Duncan's criterion.

The variance homogeneity check was performed with the Fligner-Killeen test (Molle 2012). The non-parametric criterion of Games-Howell was also applied (Peters 2017, 2018).

Regression analysis

The following regression models were developed:

A. Single linear regression model

B. Parabolic regression model

C. Generalized Linear Model - GLM – this model in R was presented with different functions from several libraries. A glm (R Core Team 2018) feature with link options was applied to the Poisson family of functions from the R stats library (R Core Team 2018), as developed by Thomas (2015).

D. Nonlinear Logistic Model – it was applied to the average date of the different phenophases. The model was built with the SSlogis function of the R-package stats (R Core Team 2018) with self-starting values. Once model adequacy was established, the inflection point coincided with the predicted average value.

ABC analysis

This model classifies the provenances into three non-overlapping groups and allows a clearer interpretation of the observed variation. The algorithm of the method was presented by Ultsch and Lötsch (2015) and its program implementation in the R language by Thrun et al. (2017).

Correlation analysis

Spearman correlation coefficient (Molle 2012)

IV. RESULTS AND DISCUSSION

IV.1. Douglas-fir provenances

IV.1.1. Evaluation of phenological and morphological traits

The investigation involved a total of 29 German, American and Bulgarian Douglas-fir provenances in Berkovitza Forest Nursery during the 2005 growing period (the second year after sowing). The following phenophases were monitored: bud burst, terminal bud formation and shoot hardening. Needle coloring was also evaluated.

The progress of bud burst phenophase by provenance group is presented in Fig. 2. The earliest bud burst was determined for the Bavarian provenances (BY), with an average date of onset of phenophase on the 113th Julian day (April 23). This group includes provenances proven to be continental (Stadtsteinach and Schnaittenbach), and the continental provenances are characterized by early development (Jestaedt 1980; Popov 1990; Malmqvist et al. 2017; Konnert and Bastien 2019).

The latest development was shown by the American provenances - with an average date of onset of this phenophase on the 117th Julian day (April 27). These are mainly coastal provenances and ones from the area between the Pacific coastal mountain range and the Western Cascade Range in Washington state, which, according to Jestaedt (1980), Günzl (1986), and Popov (1990), have late flushing (leaf unfolding).

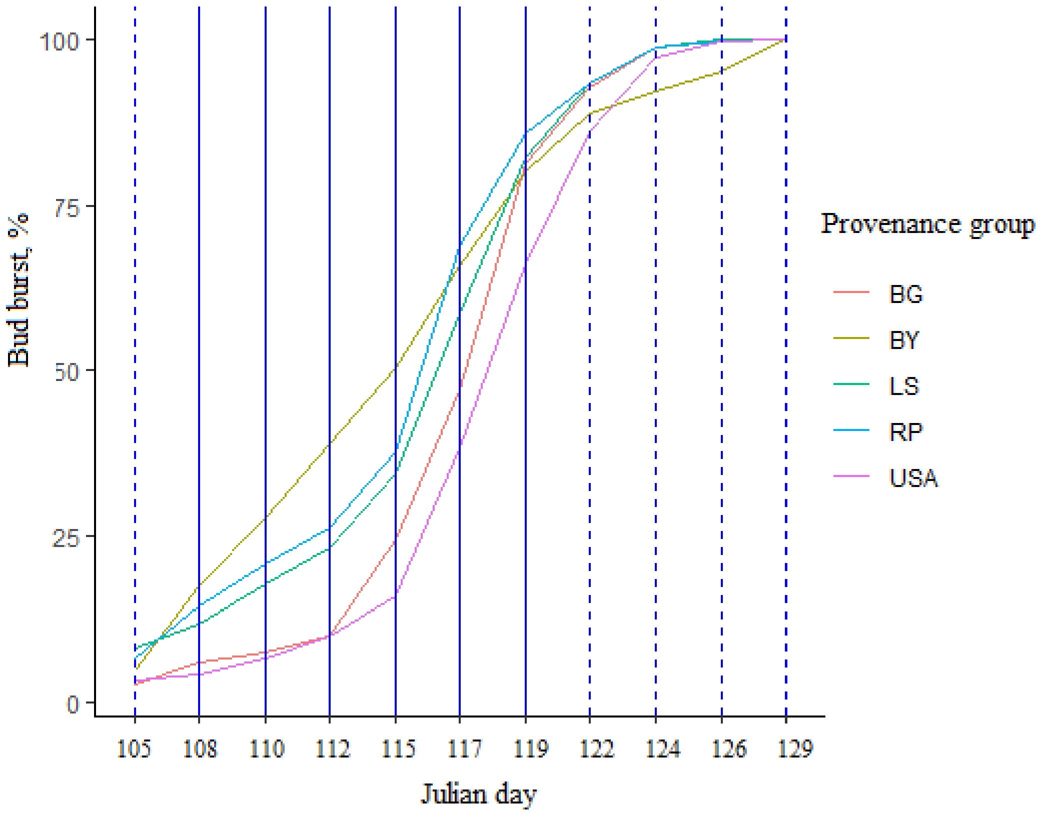


Fig. 2. Bud burst progress for the provenance group in Berkovitza Forest Nursery in 2005

Note: Bulgaria (BG), Bavaria (BY), Lower Saxony (LS), Rhineland Palatinate (RP) and USA. Blue continuous line shows a statistically significant influence of the factor “provenance group”on the phenophase on the respective Julian day with *p* <0.001, and the dashed line - no statistical significance.

The assessment of needle coloring of the different provenances (Fig. 3) shows that no seedlings with gray-green needle coloring were registered, and those with yellow-green coloring occured only in 8 provenances and accounted for only 2–8%. Most of the seedlings observed (24 provenances, which is more than 50%) were green. For the provenances Griesbach (GH), Stadtsteinach (SS1), Nevestino (NEV), 22–32% of the plants had blue-green color, and for provenances Lohr (L), Darrington (DR3), Schneifel (SCHL) and Kaiserslautern W (KLW) more than half of the plants were light green. Blue-green coloring is a needle characteristic of the Douglas-fir continental variety, and a green color – of the coastal variety, but there is evidence (Jestaedt 1980) that the green needle coloring predominates in the Douglas-fir continental variety provenances.

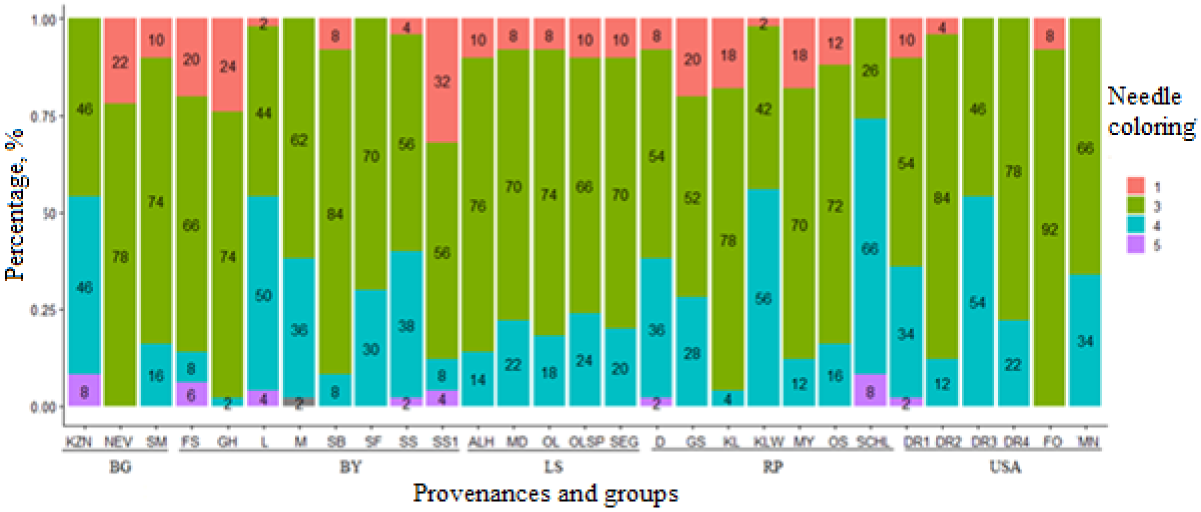
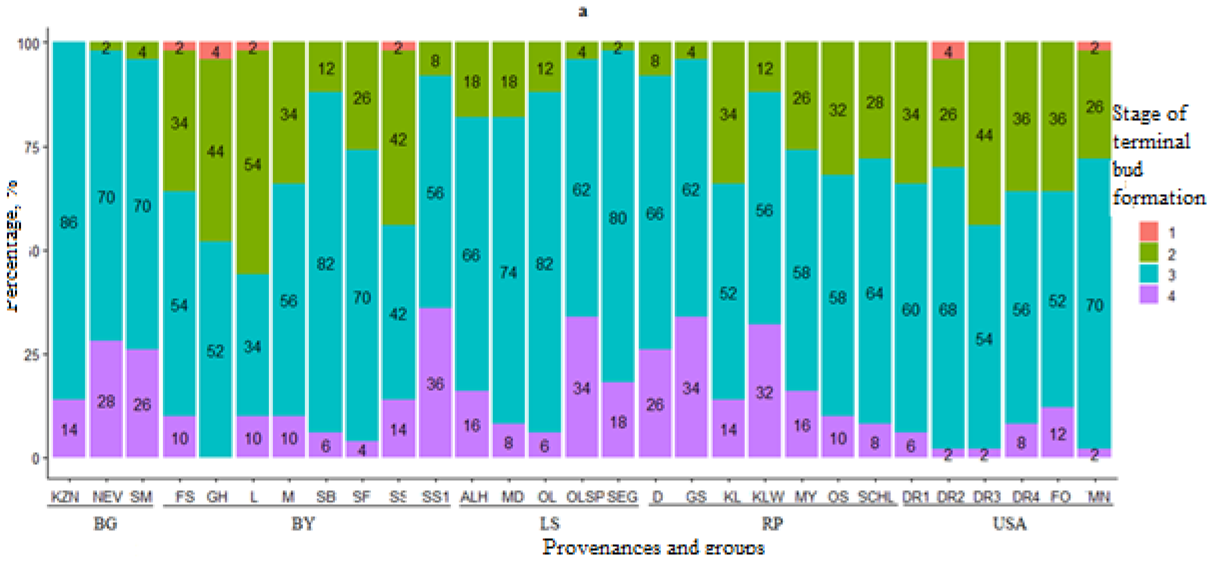


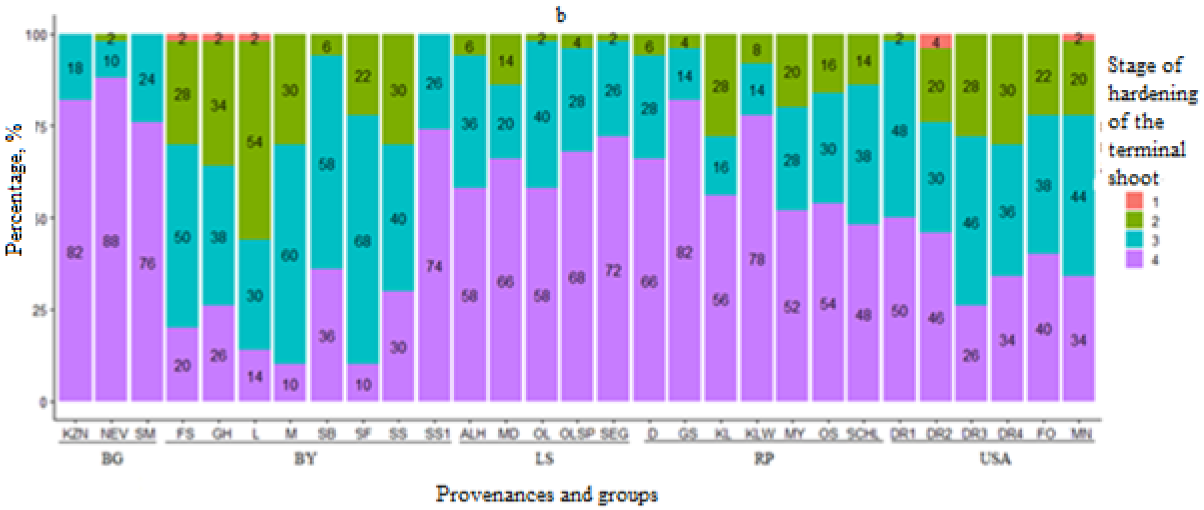
Fig. 3. Percentage (%) of needle coloring of Douglas-fir provenances:
1 – blue-green, 2 – gray-green, 3 – green, 4 – light green, 5 – yellow-green

By mid October, in most provenances, over 50% of the seedlings had reached stage 3, i.e. “developed” terminal bud, with almost all provenances showing seedlings with well-developed terminal buds (Fig. 4a). The stage of ”slightly developed” was less frequent, and only in single seedlings of 6 provenances the terminal bud was ”undeveloped”.

Bulgarian provenances and some provenances from Bavaria, Rhineland-Palatinate and Lower Saxony had well-hardened terminal shoots (over 70%), shown in Fig. 4b. The stage 3 of ”slightly hardened” shoot was observed in all provenances, with a small part of the provenances having ”not hardened” to ”slightly hardened” terminal shoots and only a few individuals being completely “not hardened”. By mid October, the provenances had not yet reached the final stage of a fully-developed terminal bud and hardening. This can be explained by the relatively high average diurnal temperature at the beginning of October 2005, which was around and above 10ºC.



1 – undeveloped; 2 – slightly developed; 3 – developed; 4 – well-developed



1 – not hardened; 2 – not hardened to slightly hardened; 3 - slightly hardened; 4 – slightly hardened to hardened

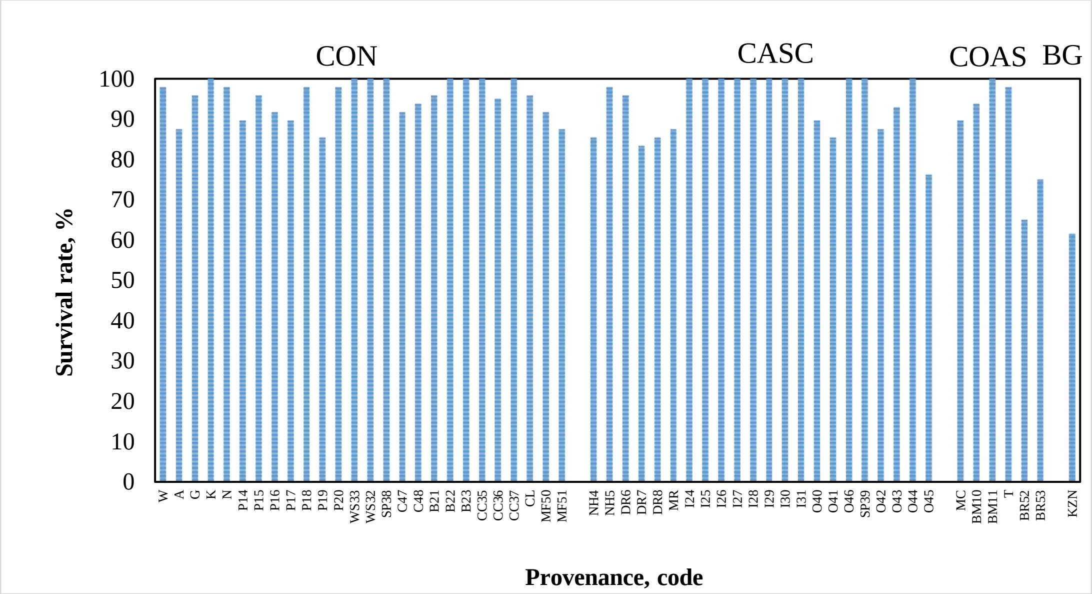
Fig. 4. Completion of Douglas-fir provenances vegetation: **a** – terminal bud formation, **b** – hardening of the terminal shoot

IV.1.2. Survival

The average survival rate of the Douglas-fir provenances at Petrohan in the third year after planting (1992) was above 85%. It was the highest for the continental provenances, followed by the provenances in the Western Cascade Range and the lowest for the coastal provenances (Fig. 5).

At 17 years of age (2006), in part of the continental provenances - Greenwood (G), Keremeos (K), Whitefish (W), Alamogordo (A), Bates (B21, B22, B23), Canyon City (CC35, CC36, CC37) - a marked increase in losses was observed, which may be associated with the disease diagnosed in 2004 and caused by the fungal pathogen *Rhabdocline pseudotsugae*, resulting in the fall of 4-, 3- and even 2-year-old needles and loss of growth, as well as loss of trees.

1992



2006

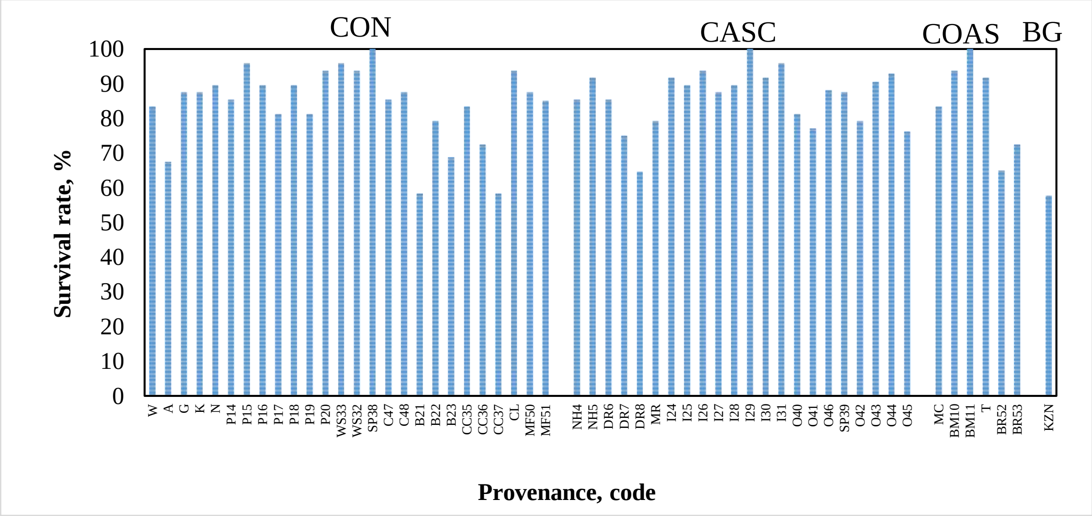
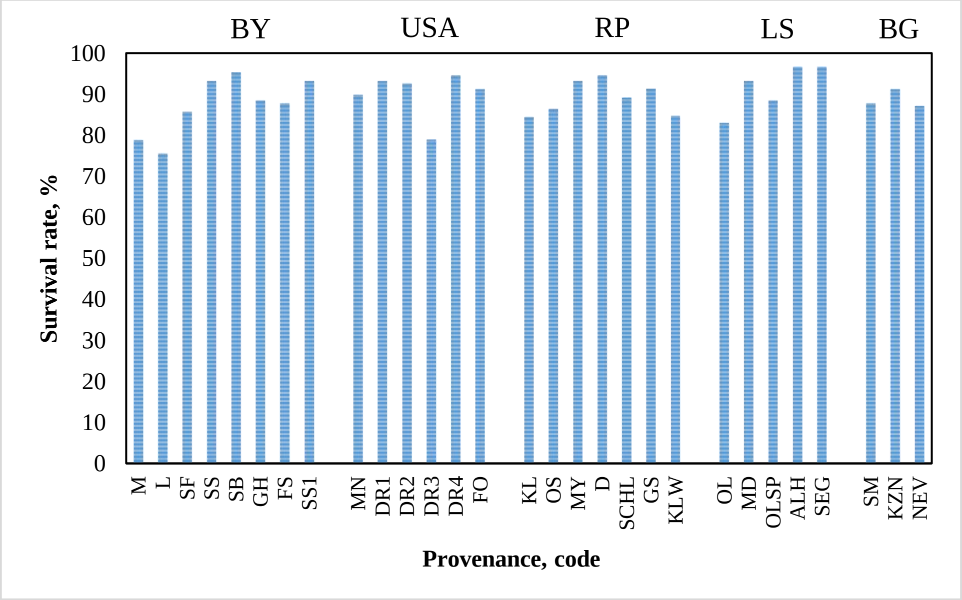


Fig. 5. Survival rate of the Douglas-fir provenances in the 3th (1992) and the 17th (2006) year after establishment in Petrohan

Note: CON – continental, CASC – Western Cascade Range, COAS – coastal, BG – Bulgaria

In the provenance test in Berkovitza, the survival in the first year (2006) was relatively high and was around and above 90% (Fig. 6). In the 11th year (2016) significant losses were found in most parts of the trial and survival was 65.7% or about 30% lower than that recorded five years earlier. The main cause was ice damage due to rainfall at the beginning of December 2014 and the below zero temperatures during the night after it. This caused the whole aboveground part of the plants to freeze, and, under the weight of the ice, some of them fell down or were partially uprooted, and others broke at different heights from the base of the tree. Some of the provenances also suffered losses due to the lush development of competitive vegetation, most often aspen, and in some places common hornbeam and birch.

2006



2016

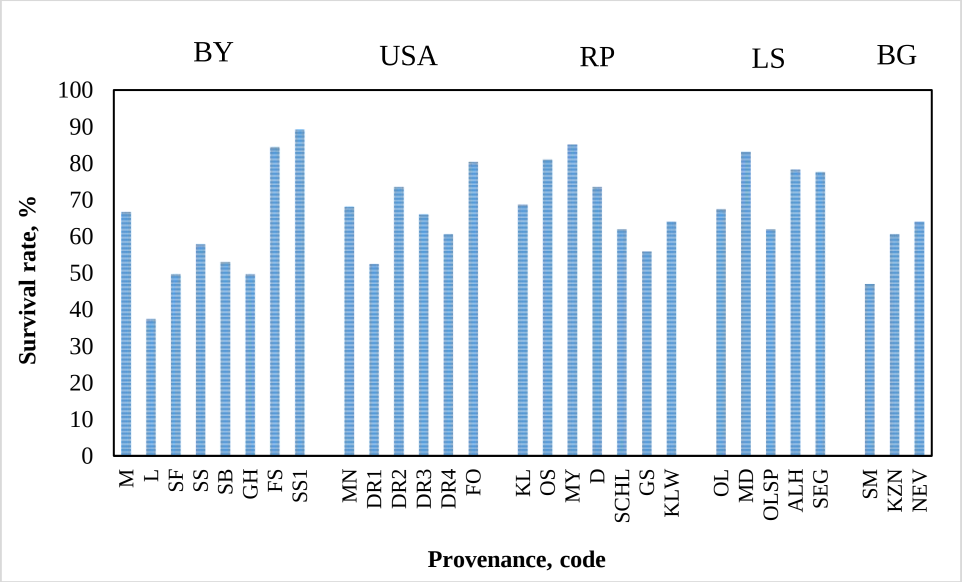


Fig. 6. Survival rate of the Douglas-fir provenances in the 1st (2006) and 11th (2016) year after establishment in Berkovitza

Note: BY – Bavaria, RP – Rhineland Palatinate, LS – Lower Saxony, BG – Bulgaria

IV.1.3. Height growth

Height growth in the 11th year after establishment was analyzed in the provenance test in Berkovitza. Due to the significant overlap of height variation intervals, ABC analysis was applied, in which the total number of measured heights was divided into three intersecting classes - high (class A), medium (class B) and low (class C) values (Fig. 7). The provenance average height distribution within the three classes shows that 11 provenances were the fastest growing, and these were included into class A with the highest values of average height. There were 7 provenances with moderate height growth, which were classified in class B, and 7 provenances were relatively slow growing and were included into class C with the lowest values of average height.

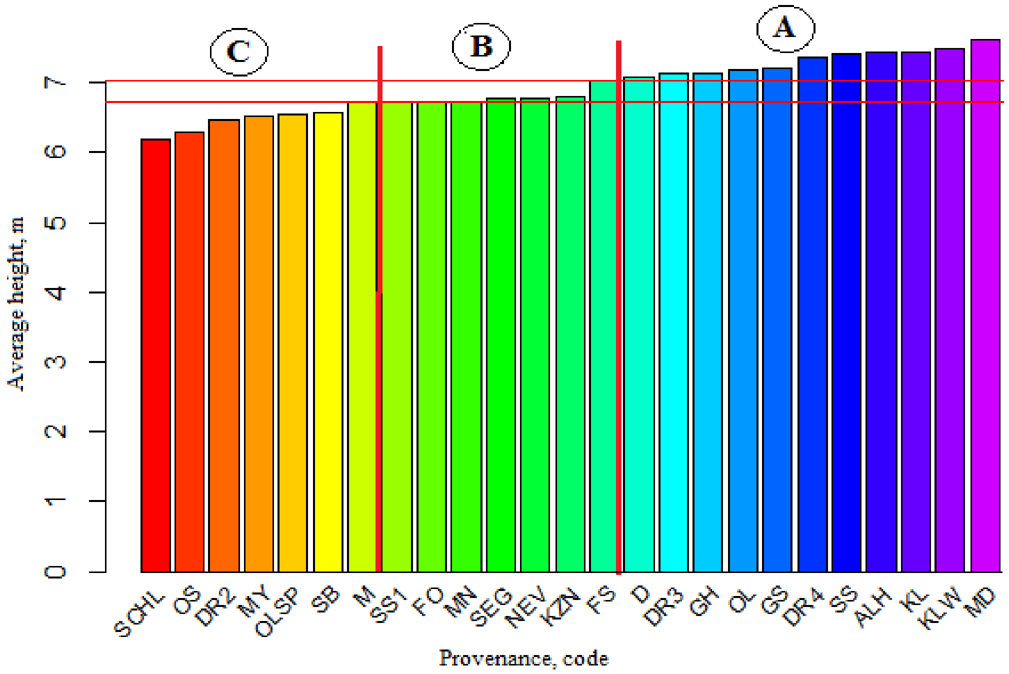


Fig. 7. Distribution of Douglas-fir provenances in Berkovitza in three classes (A, B and C) according to their average height

In Petrohan, the height growth in the 24th year after establishment was also assessed by the application of the ABC analysis (Fig. 8). The provenance average height distribution within the three classes shows that 24 provenances were the fastest growing, and these were included into class A with the highest values of the average height. With moderate height growth, there were 17 provenances, which were classified in class B, and 13 provenances were relatively slow growing and were included into class C with the lowest values of the average height. Particularly impressive, with the highest average height (20 m), was Darrington (DR6) from the Western Cascade Range in Washington State. It was followed by 4 provenances: Newhalem

(NH5), Monroe (MR) and Darrington (DR7) from the same group and the coastal Bremerton (BR11), having approximately the same average height - 17.9 - 18.0 m. Of all 13 provenances included in class C, the lowest height belonged to the provenances Alamogordo (A), Keremeos (K), Greenwood (G), Whitefish (W), Bates (B21, B22, B23) and Canyon City (CC35, C36, CC37). They retained their position as the slowest growing, which had also been shown in previous studies involving the same provenance test.

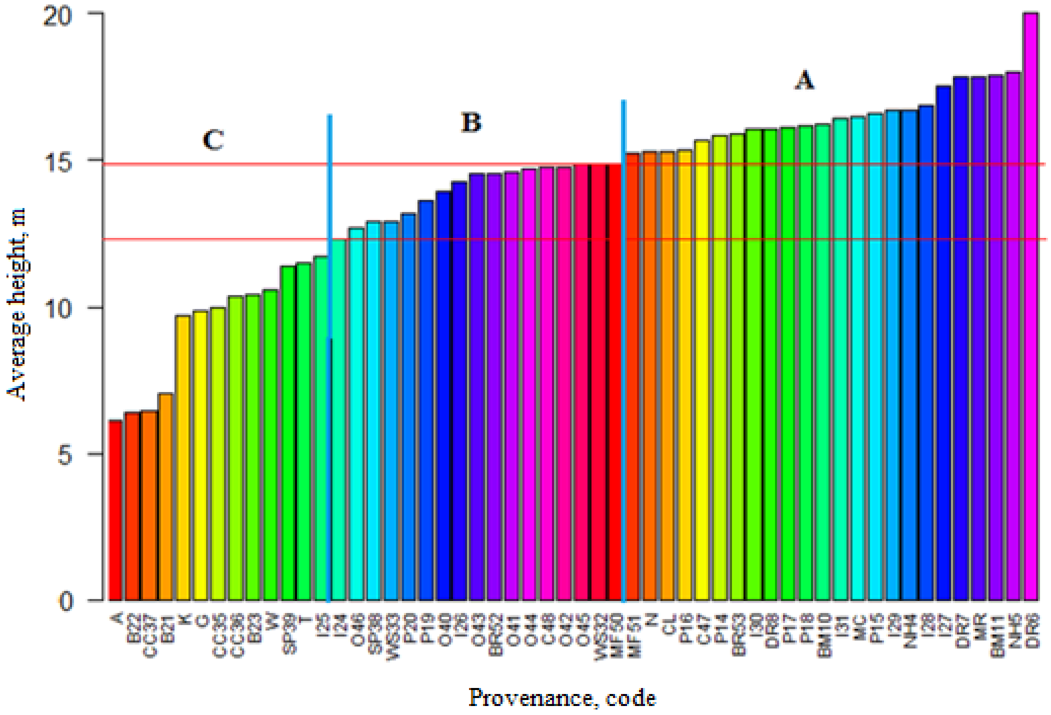


Fig. 8. Distribution of Douglas-fir provenances in Petrohan
in three classes (A, B and C) according to their average height

IV.1.4. Correlations between height growth and main climatic indicators

Regression relationships between the height growth of Douglas-fir provenances in the Petrohan provenance test and main climatic indicators were determined. The first relationship (Fig. 9) is between, on the one hand, the difference in the average height of each provenance at 24 years of age and the average height of the ‘local’ provenance (HD), in this case the provenance Kazanlak, and considered as the dependent variable, and, on the other hand, the difference between the mean minimum temperature of each provenance site and the provenance test site (TD) as the independent variable (Schmidtling 1994, Carter 1996). When the peak of the regression curve is at a point where the difference between the mean minimum temperature of seed source and the planting site is TD = 0, this indicates that the provenances are optimally adapted for growth at locations where the average minimum temperature matches that of the original seed source location.

When the peak is at a point where TD is a negative number, the provenances grow best in warmer locations with a corresponding deviation of 0℃, and when the peak is at a point where TD is a positive number, the provenances grow best at sites which are cooler than their original locations. Here the peak of the regression curve (parabola) for the Douglas-fir provenance test is at TD = -1.66℃, which shows that the optimal growth of Douglas-fir in the studied provenance test was observed for provenances transferred from 1.66℃ colder sites that the provenance test site. All provenances, the relative heights of which was greater than the ordinate's value 0, were higher than the ‘local’ provenance. For the continental group (CON), the transfer to provenance test site was to a warmer climate, with the difference in the mean minimum temperature of the seed source and the planting site being a negative number. The only exception was the provenance Alamogordo from New Mexico, for which the relocation to Bulgaria was with about 10° to the north and in a cooler climate (Tab. 1). For 14 of the continental provenances, their height growth in provenance test conditions was slower than that of the ‘local’ provenance. The other 12 provenances had a better growth than it. For all Western Cascade provenances (CASC), the transfer was to a warmer climate. Under these conditions, most were taller than the ‘local’ provenance. For half of the coastal provenances (COAS), the transfer was to a warmer climate and for the other – to a cooler climate than that of the seed source. They were taller than the ‘local’ provenance, with the exception of the provenance Toledo, which retreats on this indicator to the ‘local’ provenance.

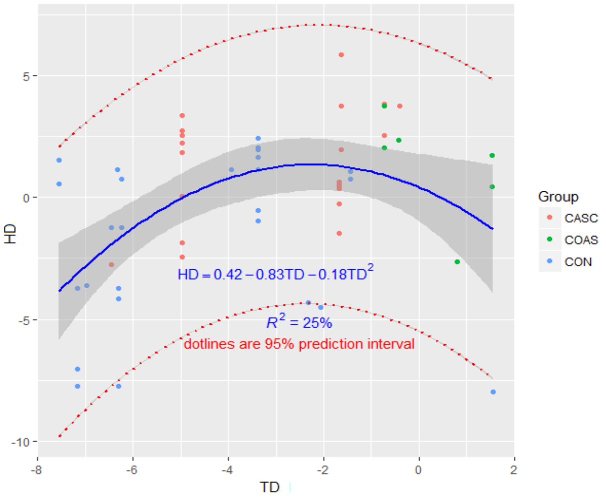


Fig. 9. Correlation between the relative height at 24 years of age (HD) and the difference in the mean annual minimum temperature between the seed source site and the provenance test site (TD).

The regression relationships below involve the above-described dependent variable HD and the transfer distance for some climatic indicators. The transfer distance was calculated as the difference between the relevant climatic indicator of the provenance test site and that of the seed source site - Leites et al. (2012), Lamy et al. (2013).

A regression relationship, represented by a parabolic model (Fig. 10), was established regarding the difference between the temperature of the coldest month of the provenance test site and the seed source site (CTD). The peak of the regression curve of the parabolic model was at CTD = -5.5 ℃, i.e. the optimal height growth was observed for provenances for which the winters of the provenance test site were 5.5℃ colder than the seed source site. This condition corresponds to coastal provenances Bremerton (BM10, BM11) and the continental provenances Medford (MF50, MF51) from Southern Oregon. For all Western Cascades provenances (CASC) and for the coastal (COAS) provenances, the transfer was to colder winters. For most of the continental provenances, the transfer to North-Western Bulgaria was to a colder winter, and only for some of them - to a warmer winter. The transferred to a colder-winter provenances had better height growth than the 'local' provenance compared to those transferred to a warmer winter.

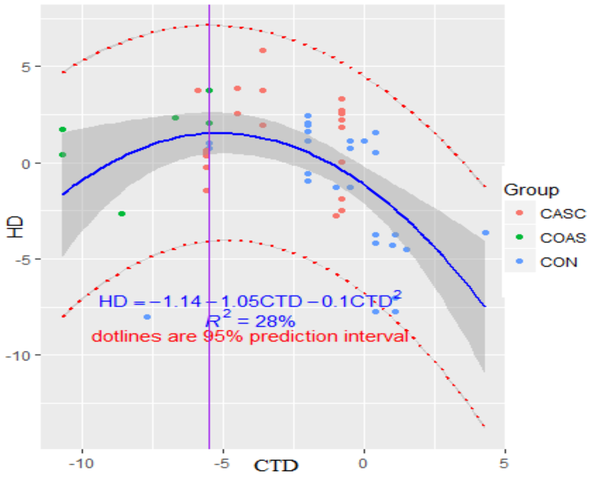


Fig. 10. Correlation between the provenance relative height at 24 years of age (HD) and the difference in the coldest month temperatures between the provenance test site and seed source site (CTD, ℃).

The correlation between the relative height and the difference in the continentality index is presented in Fig. 11 with two regression models – linear (Fig. 11a) and parabolic (Fig. 11b). With increasing the difference in the continentality index (DIc), the relative height (HD) increased, i.e. by transferring to a more continental climate, most provenances grew taller than the ‘local’ one. Particularly noticeable were the differences when transferring the coastal provenances (COAS); however, this did not negatively affect their growth. The optimum height growth was observed when the continentality index was increased by 12.7 towards the seed source site.

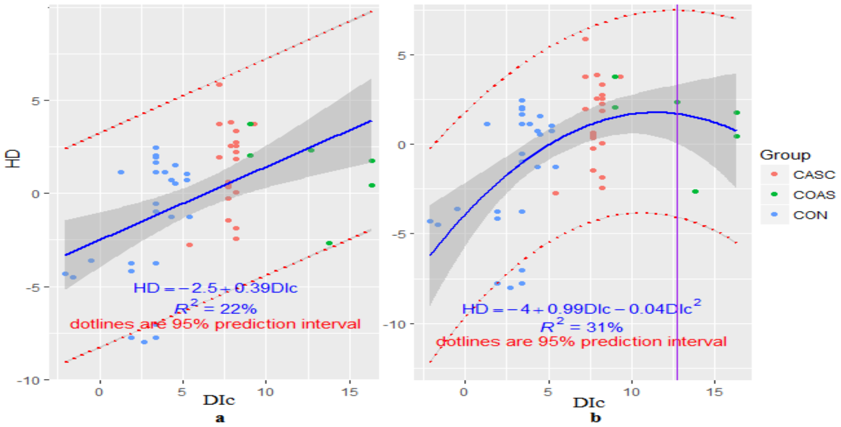


Fig. 11. Correlations (a – linear and b – parabolic) between the relative height at 24 years of age (HD) and the difference in the continentality index of the provenance test site and the seed source site (DIc).

A regression correlation between the relative height and the difference in the mean annual precipitation (DMAP) between the planting site and seed source site is presented with a linear model (Fig. 12). Positive DMAP values indicate that provenances were transferred to more humid conditions. It is obvious that all continental provenances (CON) were transferred to a more humid climate, while coastal (COAS) and Western Cascade provenances (CASC) were moved to significantly drier conditions. Figure 12 shows clustering of provenances, with most continental provenances having a lower height than the ‘local’ provenance. It seems illogical that with increased precipitation in the new location, the provenances did not take advantage of the better humidity conditions, which should have had a positive effect on their height growth. Here, the genetic features of provenances are interfered. Part of the continental provenances refer most likely to *Pseudotsuga menziesii* var. *glauca*, which is characterized by significantly poorer growth than *Pseudotsuga menziesii* var. *menziesii*. Another factor influencing the growth of the continental provenances was their susceptibility to the fungal pathogens *Phaeocryptopus gaeumannii* (Rohde) Petrak and *Rhabdocline pseudotsugae* Syd., which were also found in the planting site, as the more humid conditions of these locations favoured the fungi’s development.

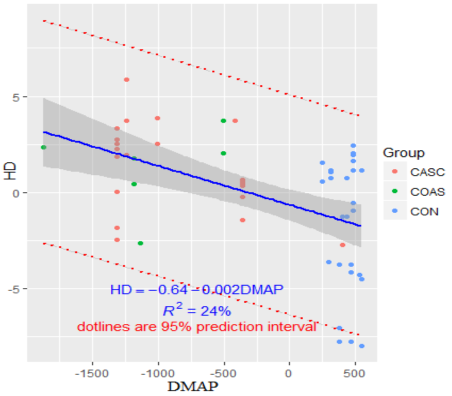


Fig. 12. Correlation of the relative height at 24 years of age (HD) and the difference in the average annual precipitations of the provenance test site and the seed source site (DMAP, mm).

The regression correlation between the relative height (HD) and mean annual temperature (MAT) is presented in Fig. 13. The resulting parabolic model shows that the optimal height growth is characterized by the provenances in sites with an average annual temperature of 9.4°C. This condition corresponds to the provenances of Darrington by Western Cascade Range in Washington State.

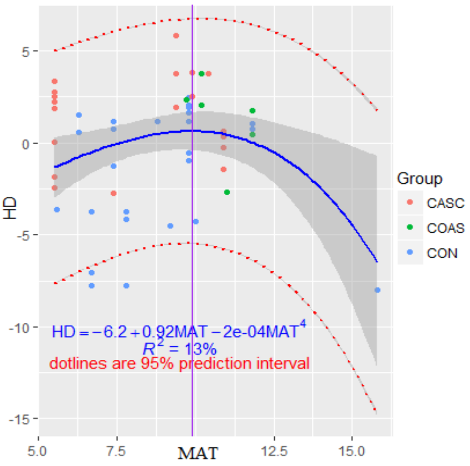


Fig. 13. Correlation between the relative height of the provenances at 24 years of age (HD) and the mean annual temperature (MAT) of the seed source site.

The correlation between height and mean warmest month temperatures is also presented with a parabolic model (Fig. 14). Most provenances (except the continental ones of Alamogordo, Greenwood, Keremeos and Medford) were transferred to a warmer summer compared to that of the seed source site. The peak of the parabolic model was WTD = 5.6ºC, i.e. the growth optimum was for provenances that had been transferred from a 5.6ºC cooler summer compared to that of the provenance test site (Fig. 14). Under these conditions, almost half of the provenances had better growth than the ‘local’ provenance.

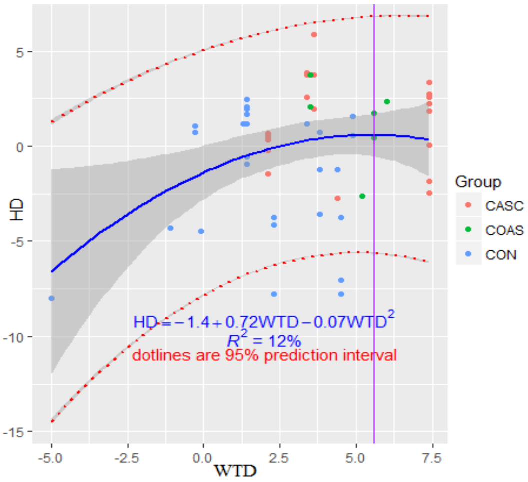


Fig. 14. Correlation between the relative height at 24 years of age (HD) and the difference in mean warmest month temperatures of provenance test site and seed source site (WTD, ºC).

IV.1.5. Breast height diameter growth

Douglas-fir provenance test in Berkovitza

The average diameter of Douglas-fir in the provenance test at 11years of age was 8.7 cm, ranging from 6.4 to 9.6 cm (Fig. 15). The largest average diameter belonged to the provenance Münden (MD) from Lower Saxony and Bavarian Stadtsteinach (SS) - 9.6 cm, and the smallest – to the provenance from Rhineland Palatinate Schneifel (SCHL) - 6.4 cm. The fastest growing-in-diameter provenances were Daun (D) from Rhineland Palatinate - 9.4 cm, the ‘Bulgarian’ provenances Kazanlak (KZN) and Nevestino (NEV) - 9.3 and 9.4 cm and the American Darrington (DR3) - 9.2 cm. The largest variation in mean diameter of about 3 cm was measured for Rhineland Palatinate provenances: from 6.4 cm for the provenance Schneifel (SCHL) to 9.4 cm for Daun (D). For the Bavarian and American provenances, the variation was within 2 cm: from 7.6 cm for Schnaittenbach (SB) to 9.6 cm for Stadtsteinach (SS), and from 7.7 cm for Mineral (MN) and Forks (FO) to 9.2 cm for Darrington (DR3). The slowest growing-in-height provenances Schneifel (SCHL) from Rhineland-Palatinate and Schnaittenbach (SB) from Bavaria were also characterized with the lowest growth in diameter - 6.4 and 7.6 cm respectively.

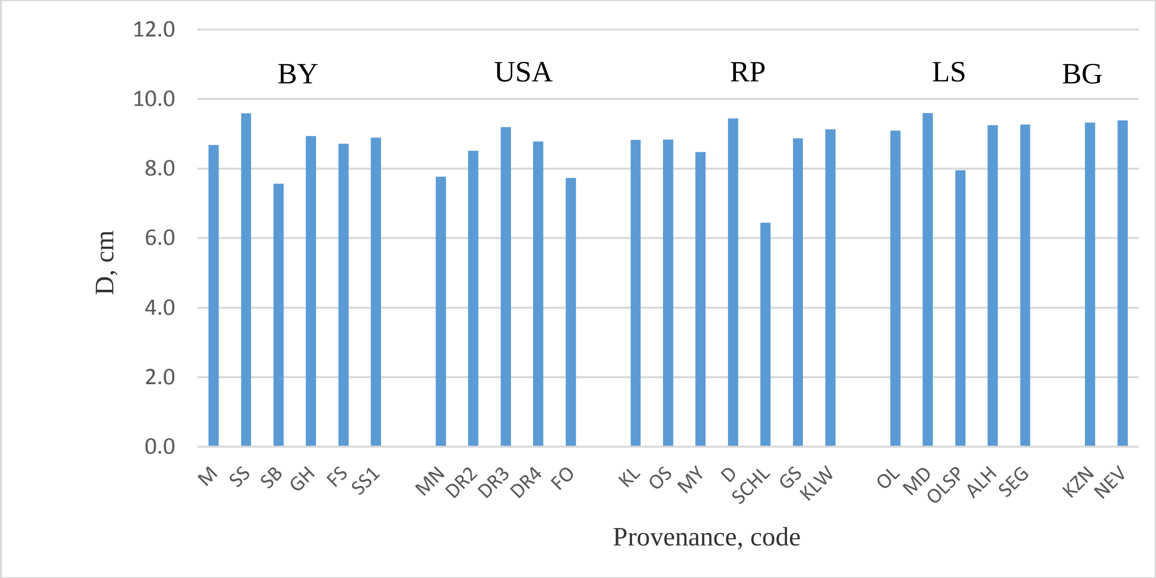


Fig. 15. Average diameter at breast height of the provenances in the provenance test

Douglas-fir provenance test in Petrohan

The largest average diameter at breast height at 24 years of age belonged to the provenance Newhalem (NH4) from the Western Cascade Range - 20.2 cm, and the smallest – to the continental Canyon City (CC37) - 7.6 cm (Fig. 16). The smallest average diameter was that of the continental provenances - 14.8 cm, and the largest - of the coastal provenances - 18.0 cm. An intermediate position was occupied by the provenances from the Western Cascade Range, which had an average diameter of 16.1 cm. The 'local' provenance Kazanlak had an average diameter (18.1 cm) just above the average for the coastal provenances.

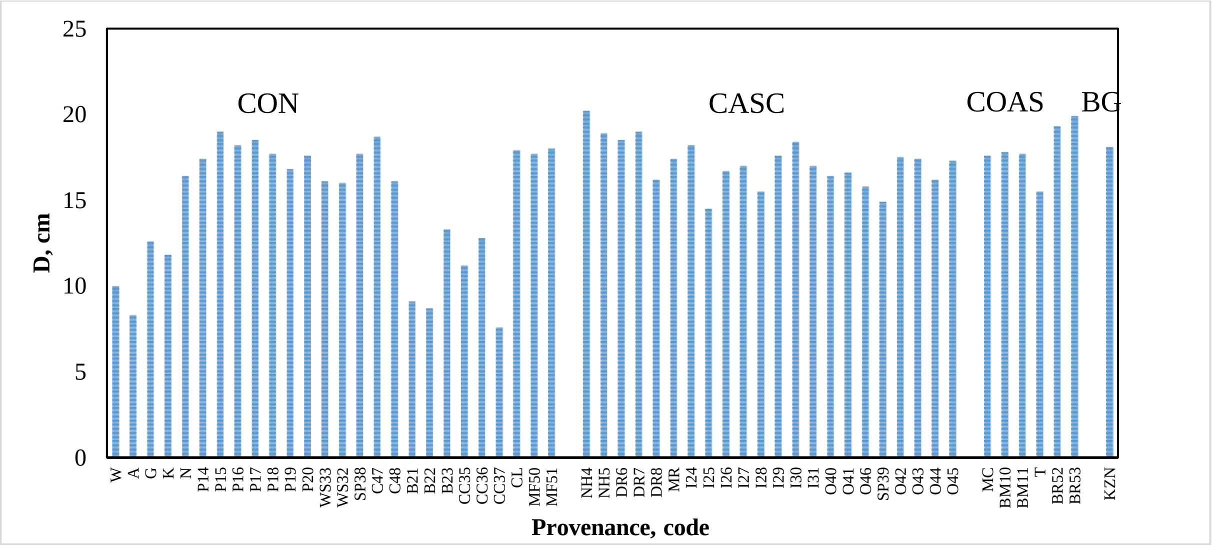


Fig. 16. Average diameter at breast height of the provenances in the provenance test at 24 years of age

IV.1.6. Mechanical stability

The mechanical stability was investigated for the Douglas-fir provenance test in Petrohan. In it, of 54 American and one ‘Bulgarian’ provenances (Fig. 17), at 24 years of age (2011), only 12 provenances had an h/d ratio below 0.8. Of these, 7 were continental provenances - Alamogordo (A), Greenwood (G), Parkdale (P20), Santiam pass (SP38), Bates (B21, B22, B23), i.e. they were characterized by a relatively slower growth. The other 5 included the provenances from the Western Cascade Range: Idanha (I24) and Santiam pass (SP39), the coastal Toledo (T) and Brookings (BR52) and the ‘Bulgarian’ provenance Kazanlak (KZN).

For the other 43 provenances, the risk of damage from abiotic factors was greater. The h/d ratio was particularly high (> 1.0) for the provenances Whitefish (W), Monroe (M), Idanha (I27, I28) and Bremerton (BR11). The susceptibility of most of the provenances to wind damage was observed in the course of 3 years (2015, 2016 and 2018). For the provenances Whitefish (W) and Monroe (M), identified as highly unstable, no damaged individuals were found, but for Idanha (I27, I28) and Bremerton (BR11), which had a particularly high coefficient of collective mechanical stability, almost all individuals were affected. The wind-damaged group also included the provenances Parkdale (P20) and Santiam pass (SP38), which had a coefficient of mechanical stability of 0.75 - 0.73. Although below the critical limit of 0.8, this ratio value may be considered insufficient to ensure mechanical stability.

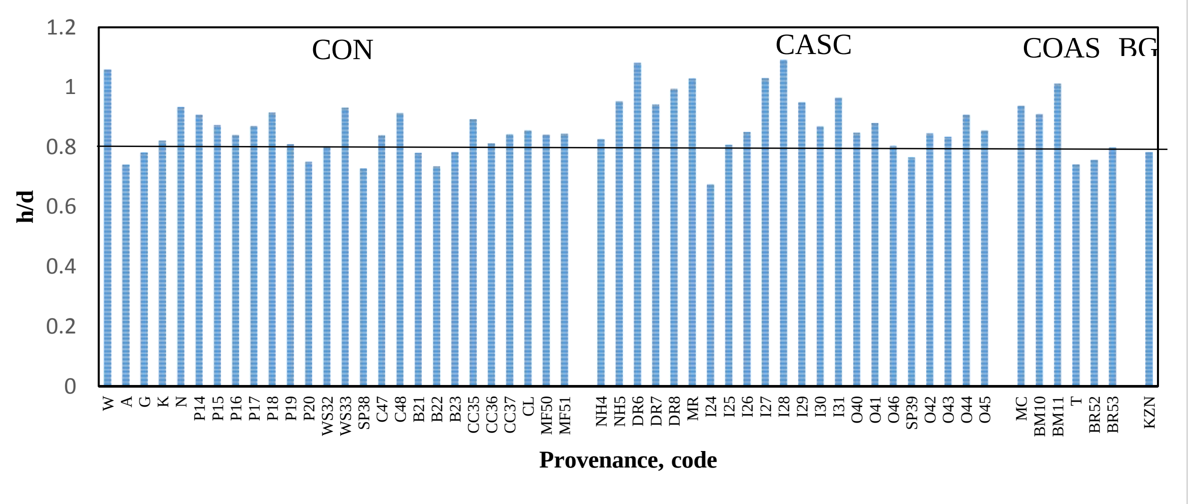


Fig. 17. Collective mechanical stability of 55 Douglas-fir provenances at 24 years of age in the provenance test in Petrohan (CON - continental, CASC - Western Cascade Range, COAS - coastal, BG - Bulgarian)

A correlation between the mechanical stability coefficient (h/d) and the degree of wind damage is presented in Fig. 18.

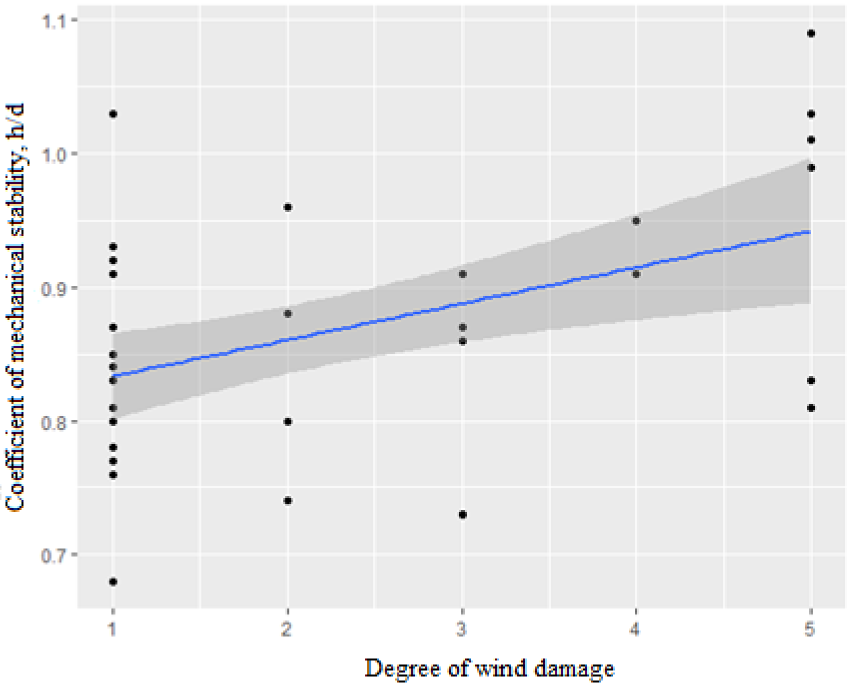


Fig. 18. Correlation between the coefficient of mechanical stability and the degree of wind damage in the Douglas-fir provenance test in Petrohan

IV.1.7. Stem volume and productivity

The average value of the total stem volume was 238.5 m^3/ha, but with a great variation in different provenances (Fig. 19). The largest stem volume was exhibited by the provenance Newhalem (NH5) from the Western Cascade Range - 377.2 m^3/ha, followed by the provenances Darrington (DR6), Idanha (I30) and Parkdale (P15), which had a stem volume above 350 m^3/ha. Other provenances from the top 10 most productive ones included Darrington (DR7), Idanha (I29), Monroe (MR) from the Western Cascade Range, the coastal Bremerton (BM11) and the continental provenances Crescent (C47) and Parkdale (P17).

The smallest stem volume was recorded in the continental provenances Canyon City (CC37) from the Eastern Cascade Range and Alamogordo (A) from New Mexico – 13-17 m^3/ha. These results were expected because the continental provenances were characterized by the smallest growth in height and diameter at breast height. With a relatively small stem volume, in the range of 25-130 m^3/ha, there were further 8 continental provenances: Bates (B21, B22 and B23) and Canyon City (CC35 and CC36) from the middle part of eastern Oregon, Whitefish (W) from the state Montana and Greenwood (G) and Keremeos (K) from the northernmost part of Oregon near the border with Canada.

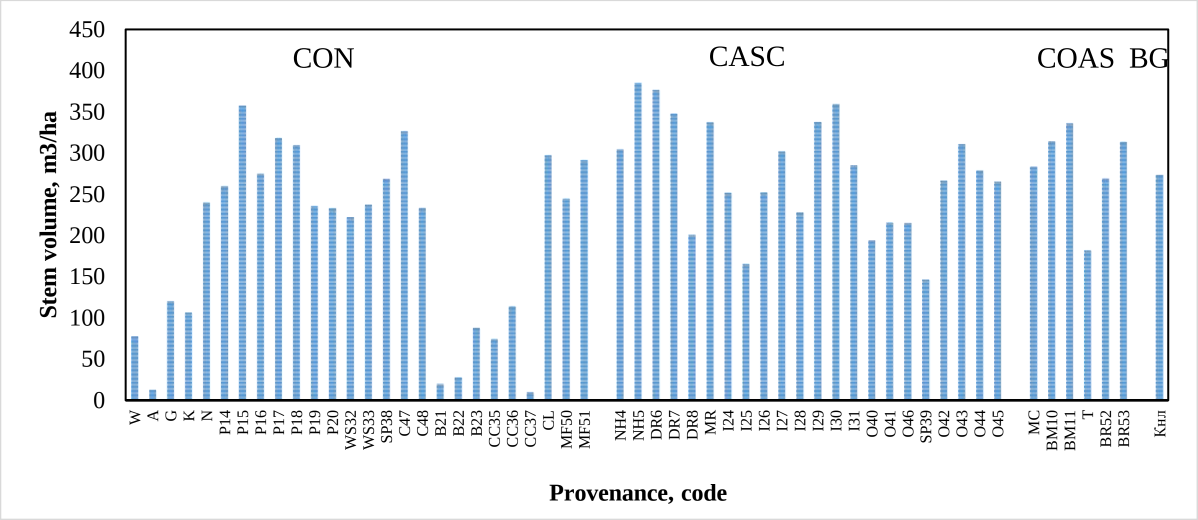


Fig. 19. Stem volume of the Douglas-fir provenances in the provenance test in Petrohan (CON – continental, CASC – Western Cascade Range, COAS – coastal; BG – Bulgarian)

IV.2. Common beech provenances

IV.2.1. Phenological traits

The flushing progress for the tested provenances in the fourth (2013) and the seventh (2016) year after establishment in Varbitza shows (Fig. 20) that the Bulgarian provenances Berkovitza and Petrohan started their development the earliest. The German provenances Ebrach, Elchingen and Mindelzell started later and changed their ranking partially for the observation period, but remained behind the two Bulgarian provenances Berkovitza and Petrohan. The third Bulgarian provenance Peshtera, which comes from high elevation (1300 m), had an intermediate position between the Bulgarian and German provenances.

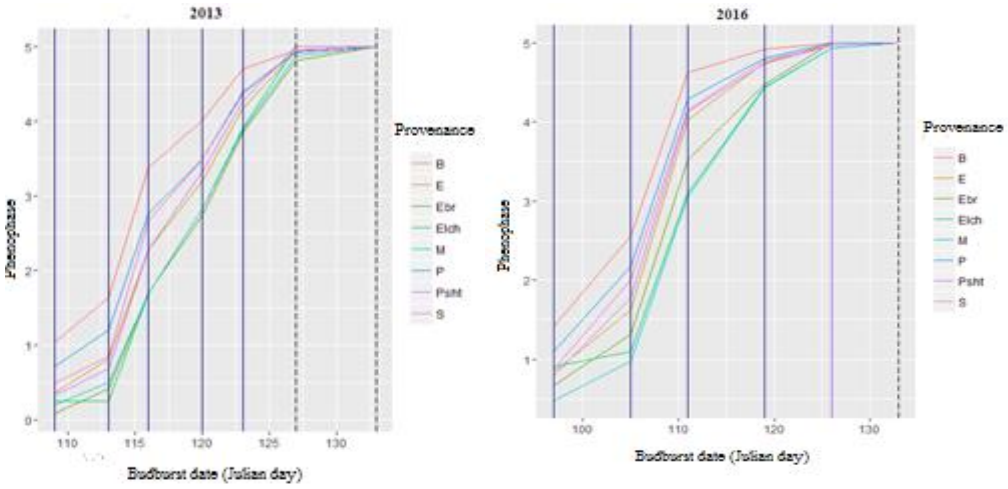


Fig. 20. Leaf unfolding progress of the common beech provenances in 2013 and 2016
Note: B -Berkovitza, E - Ebersdorf, Ebr - Ebrach, Elch - Elchingen, M - Mindelzell, P - Petrohan, Psht - Peshtera and S - Silberbach. Colors and form of vertical lines correspond to the following levels of significance for differences between provenances: *** - 0.001 (dark-blue continuous line); ** - 0.01 (purple, continuous line), not significant (black, long-dashed line).

Leaf coloring in 2013 started earlier in most German provenances (Fig. 21). In 2016, there was no clear grouping of the German and Bulgarian provenances. Leaf coloring began about 10 days later than in 2013. On the one hand, the warmer August and September of 2016 compared to those in 2013 may be responsible for the delay in autumn leaf coloring. On the other hand, the monthly precipitation in August 2016 was 2.5 times higher compared to that in August 2013. That may have improved soil moisture, and together with the high temperatures may have helped to prolong the functional activity of leaves.

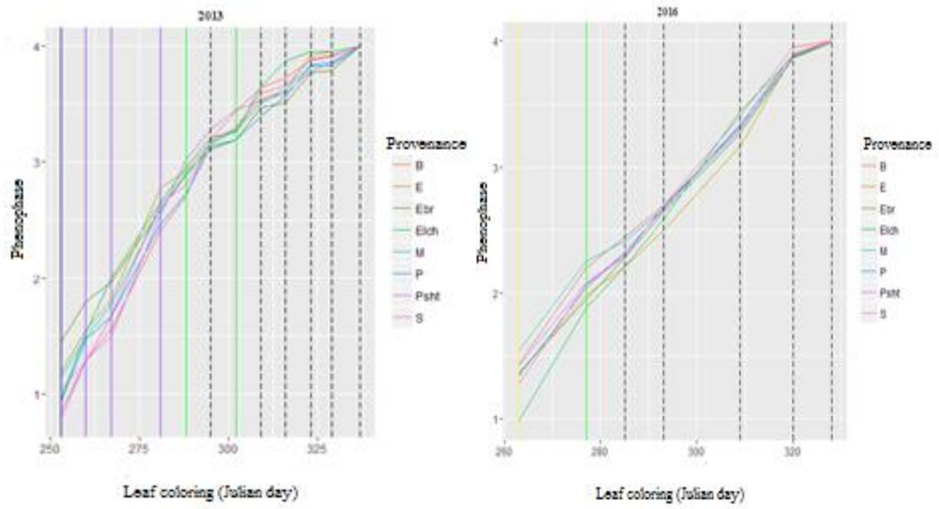


Fig. 21. Leaf coloring progress of the common beech provenances in 2013 and 2016
Note: B - Berkovitza, E - Ebersdorf, Ebr - Ebrach, Elch - Elchingen, M - Mindelzell, P - Petrohan, Psht – Peshtera and S - Silberbach. Colors and form of vertical lines correspond to the following levels of significance for differences between provenances: *** - 0.001 (dark-blue continuous line); ** - 0.01 (purple, continuous line), * - 0.05 (green, continuous line), - 0.1 (yellow, continuous line), not significant (black, long-dashed line).

A statistically significant correlation was found between the average date of leaf flush and the longitude of provenances (Fig. 22). With an increase in longitude, i.e eastward movement, leaf flush started earlier. The Bulgarian provenances in both studied vegetation periods produced leaves earlier than the German ones.

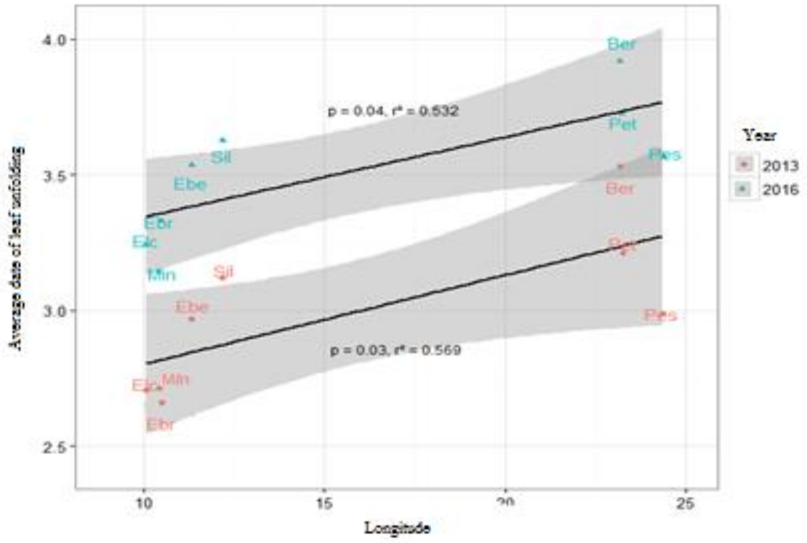


Fig. 22. Relationship between the average date of leaf flushing and longitude

A linear relationship was also found between, on the one hand, the average date of leaf coloring and, on the other hand, the longitude and latitude (Fig. 23). While leaf coloring was inversely proportional to longitude, it was directly proportional to latitude. In other words, further-eastern and southern provenances had later leaf coloring.

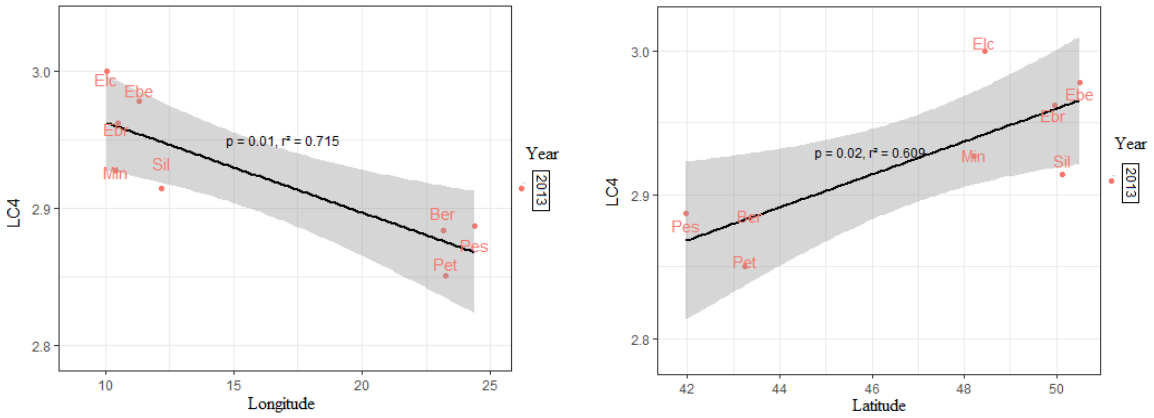


Fig. 23. Relationship between average date of leaf coloring and longitude and latitude

IV.2.2. Survival

At the driest test site in Vidin, tree survival was remarkably low (Fig. 24). After the first growing period, it reached 75.2% for the whole trial, and kept on declining: after the second year it was 47.0% and after the third - 31.3%.

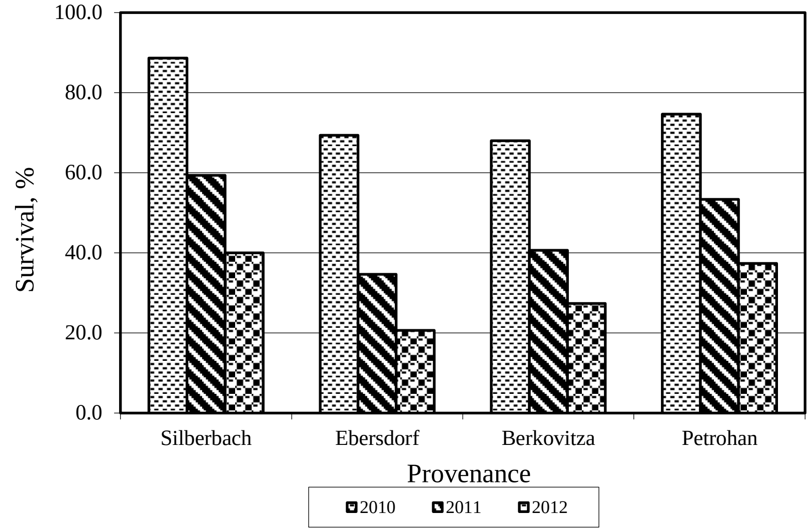


Fig. 24. Survival of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Vidin

The survival of the investigated provenances during the first three years after establishment at the more humid test sites in Varbitza and Kipilovo was relatively high (Fig. 25 and 26).

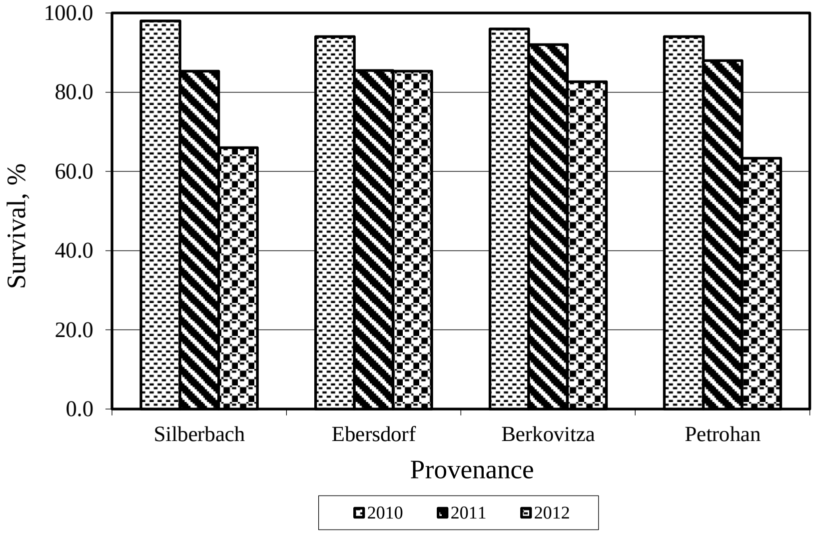


Fig. 25. Survival of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Varbitza

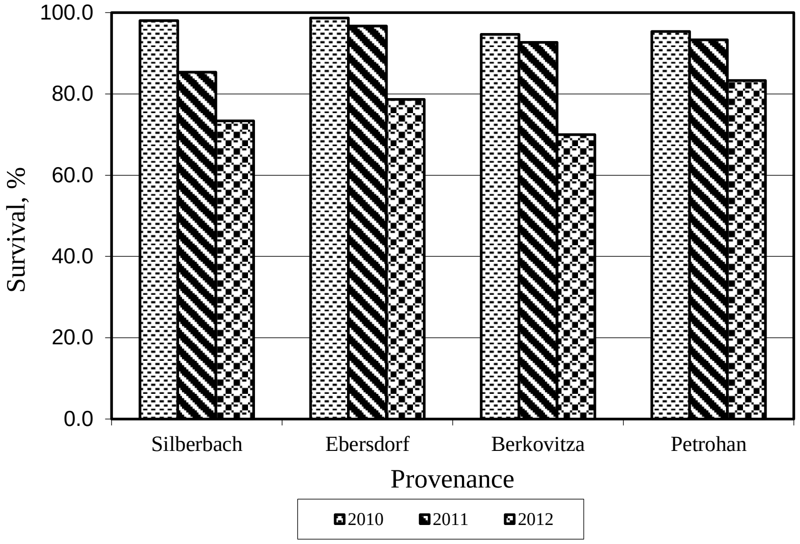


Fig. 26. Survival of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Kipilovo

IV.2.3. Height growth

Until the third year after establishment

In the first year, the Bulgarian provenances had the highest height growth in Vidin (Fig. 27). After the second year, there was a decrease of mean height for the provenances Ebersdorf from 27.4 to 23.4 cm, Berkovitza from 31.8 to 31.0 cm and Petrohan from 34.9 to 30.8 cm (Figure 4). This was due to the high mortality rates.

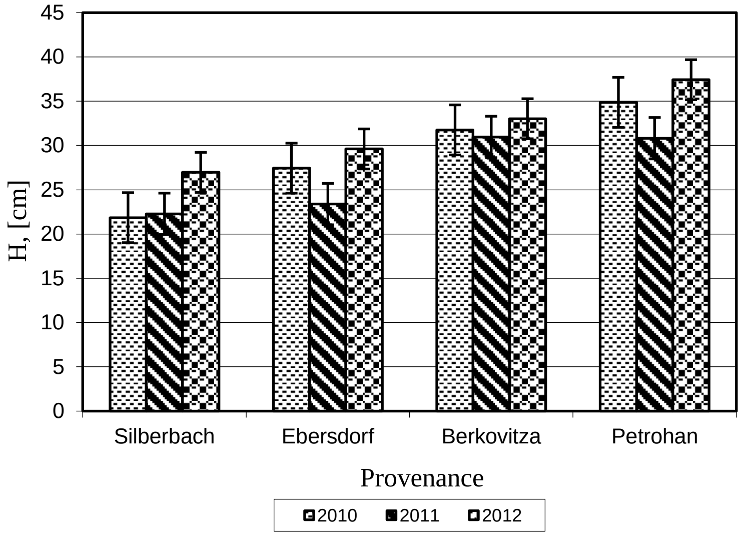


Fig. 27. Average height of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Vidin

In Varbitza, there were no significant differences between the provenances' average height after the first year (Fig. 28). After the second year, the beech provenance from Silberbach was significantly shorter than the others; the provenances Ebersdorf and Berkovitza had approximately the same average height and the highest was the provenance Petrohan. At the end of the third year, the Bulgarian provenances Berkovitza and Petrohan were the highest.

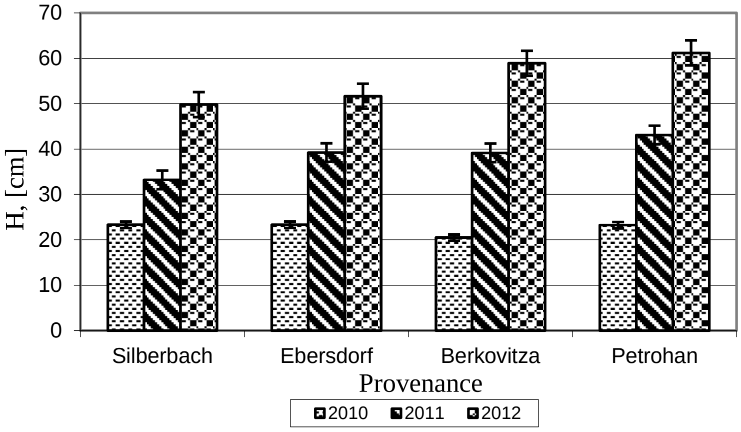


Fig. 28. Average height of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Varbitza

In Kipilovo, the Bulgarian provenance Petrohan had the best growth in the first year and retained its leading position in the next two years. Second was the provenance Berkovitza, and the German provenances Ebersdorf and Silberbach occupied third and fourth places for the entire three-year period (Fig. 29).

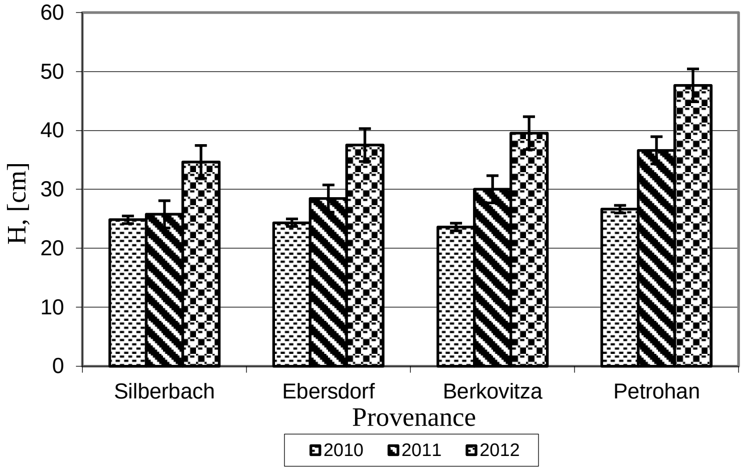


Fig. 29. Average height of the provenances after the first (2010), second (2011) and third year (2012) in the provenance test in Kipilovo

From the fourth to the eighth year after establishment in Varbitza and Kipilovo

For the first three years as well as after the fourth year, the provenances grew more vigorously in the provenance test in Varbitza than in Kipilovo. The tendency for better growth of the Bulgarian provenances over the first three years was maintained over the next five-year period. In Varbitza, after the fifth, sixth and seventh year the highest was the provenance Berkovitza and after the eighth – Petrohan - 179 cm (Fig. 30). It should be noted that the provenance Ebersdorf grew well, slightly less than the Bulgarian provenances. The provenance Silberbach more significantly lagged behind in height growth.

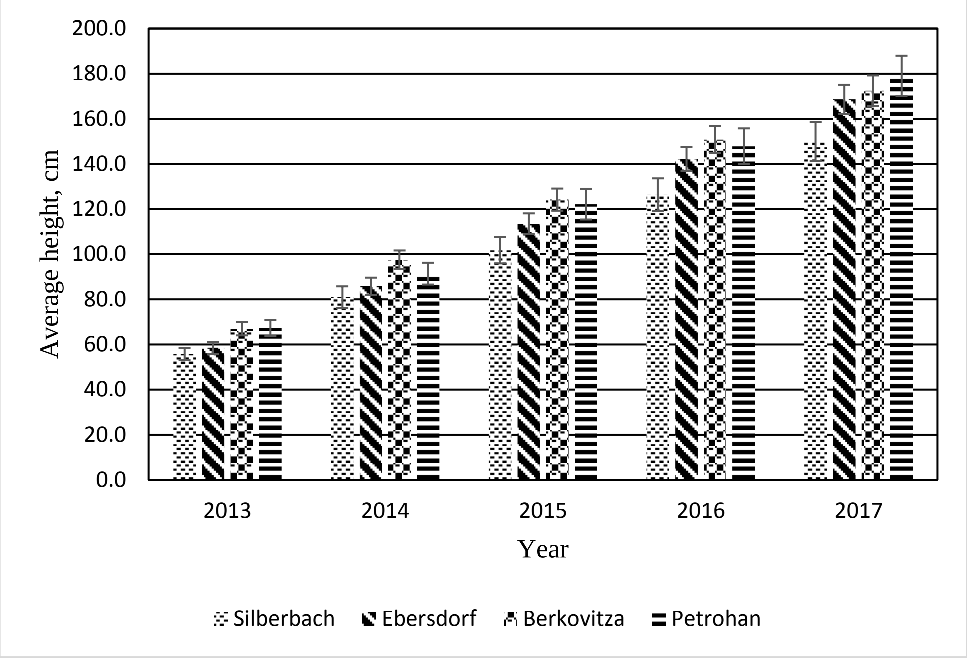


Fig. 30. Average height of the provenances from the fourth (2013) to the eighth (2017) year after establishment in Varbitza

In the provenance test in Kipilovo, the Bulgarian provenances also had better growth: throughout the five-year period, the individuals of Petrohan provenance were the highest (Fig. 31). Again, Ebersdorf grew more vigorously than Silberbach. The latter was significantly inferior with regard to this indicator to the others. The provenance Silberbach was about 60 cm shorter by the eighth year than the Bulgarian provenance Petrohan, while Ebersdorf was close to the provenance Berkovitza.

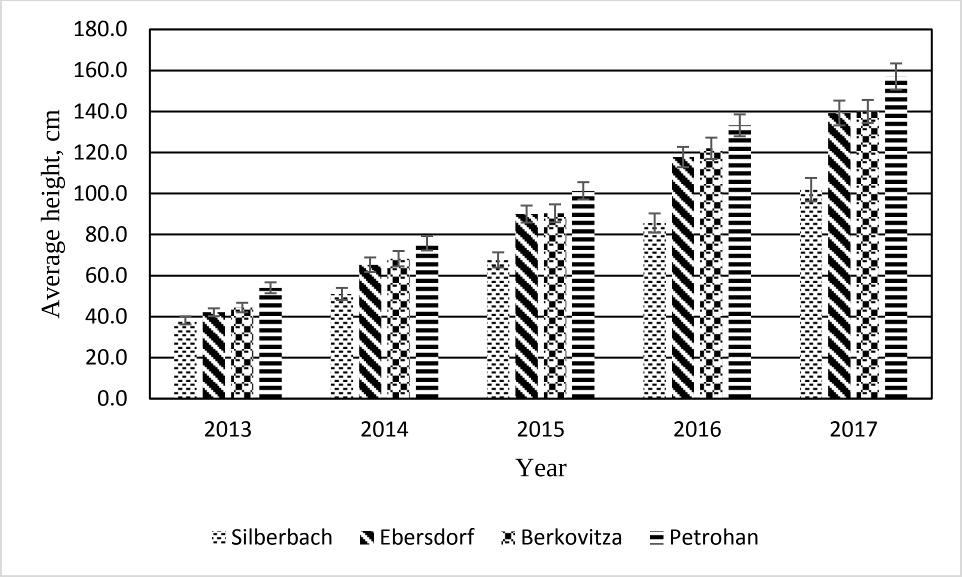


Fig. 31. Average height of the provenances from the fourth (2013) to the eighth (2017) year after establishment in Kipilovo

IV.2.4. *Dependence of height growth on the Ellenberg's quotient (EQ) and ecodistance (ΔE)*

The ecodistance (ΔE) of the German and Bulgarian provenances showed (Table 3) that their transfer to the provenance trials in Varbitza and Vidin was to drier and warmer conditions. In the provenance trial in Kipilovo, where only four of the eight provenances were included, only the value of Ebersdorf was positive. The negative values of the other three provenances (Silberbach from Germany and the Bulgarian provenances Berkovitza and Petrohan) indicated that the transfer was directed to slightly cooler and wetter conditions.

Table 3. Ellenberg's quotient (EQ) of investigated beech provenances as well as ecodistance (Δ*E*) of the provenances in the provenance tests in Vidin, Varbitza and Kipilovo

Country	**Provenance (code)**	**EQ**	**Δ*E***		
			Varbitza	**Kipilovo**	**Vidin**
Germany	Elchingen (E)	24.7	6.4		13.54
Germany	Silberbach (S)	24.0	7.1	-3.0	14.22
Germany	Ebersdorf (E)	17.0	14.1	4.0	21.22
Germany	Ebrach (Ebr)	25.3	5.8		12.93
Germany	Mindelzell (M)	19.6	11.5		18.63
Bulgaria	Peshtera (Psht)	17.2	13.9		21.02
Bulgaria	Berkovitza (B)	25.7	5.4	-4.7	12.52
Bulgaria	Petrohan (P)	21.1	10.0	-0.2	17.10

The measured mean heights of the provenances in the third year after establishment were adjusted for the site effect in order to allow comparison (the corrected heights are designated H'$_3$). The site effect of the provenance test was calculated as the difference between the average height of the four provenances (Silberbach, Ebersdorf, Berkovitza and Petrohan) of the respective provenance test and the average height total for the three provenance tests (Table 4).

Table 4. Mean tree height of the three provenance tests (PT) of four beech provenances (S, E, B, and P) after three years, site effect, dependence between corrected height (H'3) and ecodistance (ΔE) and results of a two-factorial ANOVA for differences between provenances.

PT	**Mean height, cm**	**Site effect, cm**	***f*(x) of H'$_3$ vs. Δ*E* of provenances**	**Differences between provenances**	
				F	***p***
Vidin	31.8 ± 4.5	-10.6	-0.019	11.31	***
Varbitza	55.3 ± 5.5	12.9	-0.35	4.58	**
Kipilovo	40.1 ± 5.6	-2.3	0.157	10.39	***
Total	42.4	n.a.	n.a.	n.a.	n.a.

Note: Significance level: ** – $p < 0.01$; *** – $p < 0.001$. n.a. – not significant

Corrected heights of the fourth provenances (Silberbach, Ebersdorf, Berkovitza and Petrohan) show diverse reactions to an increasing Ellenberg’s quotient (Fig. 32). For the provenance Petrohan, originating from a moister climate (EQ = 21.1), the height decreased with an increase in the EQ. This response can be expected, since harsher environmental conditions impair tree vigour and, hence, its ability to build up biomass. The response of the provenance Berkovitza (EQ = 25.7) was different: an increase in height was observed with an increase in the Ellenberg’s quotient. This can be due to the fact that these trees had already adapted to a more humid environment and, thus showed the best growth performance in drier and more xeric conditions than the provenances originating from the moister and colder site Petrohan. Conversely, the two German provenances Ebersdorf and Silverbach seemed to be unaffected by the changing environmental conditions. This can be due to a lower phenotypic plasticity, which is a crucial element of plants’ response to changing climatic conditions.

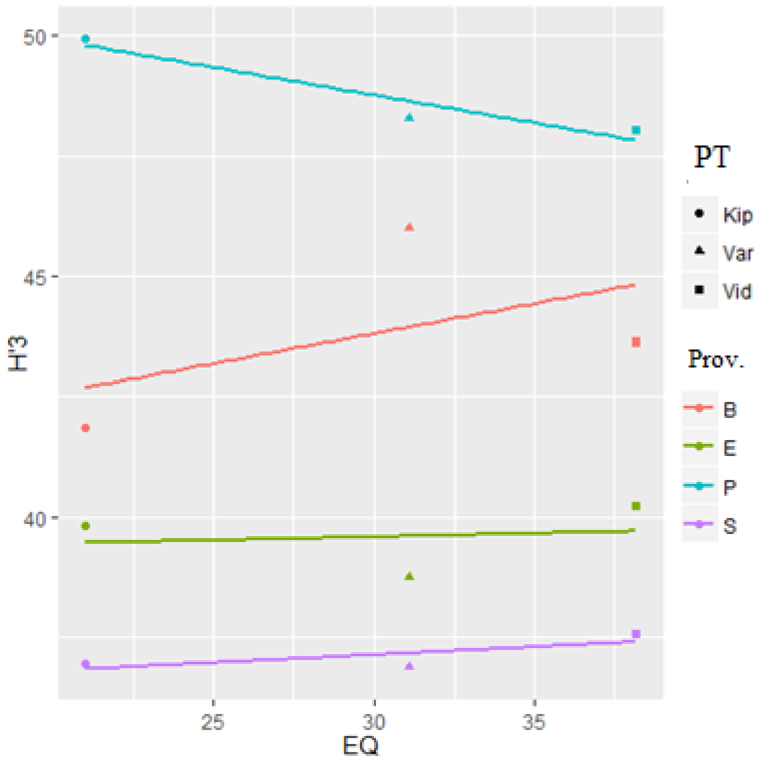


Fig. 32 Reaction norm of the corrected heights (H'$_3$) of beech provenances (Prov.) displaying individual differences in response to EQ values of provenance tests.

Note: B – Berkovitza, *EQ* = 25.7; E – Ebersdorf, *EQ* = 17.0; P – Petrohan, *EQ* = 21.1; S – Silberbach, *EQ* = 24.0; PT – provenance test, Kip – Kipilovo, Var – Varbitza and Vid – Vidin.

Height growth of all 8 provenances decreased with increasing ecological distance (ΔE) at both the more humid trial site in Varbitza and the more arid trial site in Vidin (Fig. 33). A statistically significant correlation between corrected heights of beech provenances and the average ecological distance was not established at both provenance tests. However, the distribution of provenances was similar in both provenance trials. The highest height belonged to the provenance Ebrach and the shortest one - to Peshtera. Both provenance tests had an Ellenberg's quotient of over 30, i.e. in both sites beech was at the limits for its successful development; in the provenance test in Vidin the conditions were even critical. Moreover, the survival of beech provenances sharply decreased in the first years, and after the third year, only some individuals remained. Under these extreme conditions, by the third year after establishment the best growth indicators belonged to the Bulgarian provenances Petrohan and Berkovitza from an altitude up to 900 m, while the provenance Peshtera from an altitude of 1300 m was shorter than that the German provenances. The lack of statistical significance of the correlation between the corrected height and ecodistance can be explained by the absence of genetic differentiation between the German and Bulgarian provenances (Fig. 33). This indicates that, in warmer climates, the German provenances have a similar height growth rate as the local ones, which is a sign of good adaptability to such conditions.

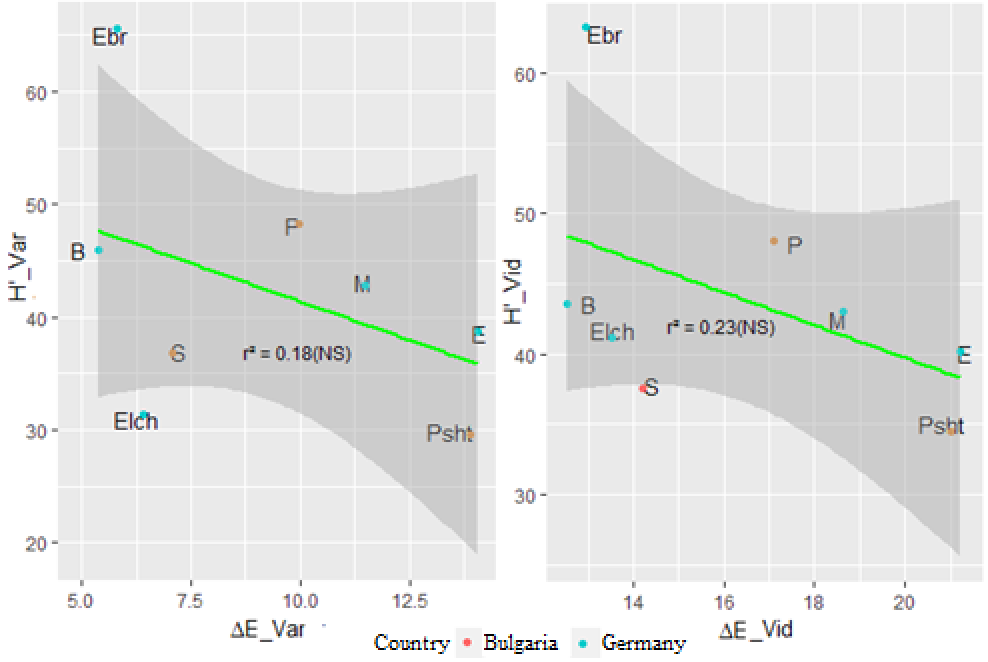


Fig. 33. Regression of the corrected height (H'_3) of the eight beech provenances with ecodistance (ΔE), in the two provenance tests with different EQ values

Note: Elch – Elchingen, S – Silberbach, E – Ebersdorf, M – Mindelzell, Ebr – Ebrach, Psht –Peshtera, B – Berkovitza and P – Petrohan; left – Varbitza (Var) – *EQ* 31.1; right – Vidin (Vid) – *EQ* 38.2.

V. CONCLUSIONS AND RECOMMENDATIONS

1. The phenophases of the investigated Douglas-fir and common beech provenances are more genetically predetermined and are less influenced by changing environmental conditions.

2. The survival of the studied provenances of both tree species can be considered as an initial indicator of their adaptation to the new conditions.

3. It has been statistically proven that for the Douglas-fir provenances:

- the fastest growing in the provenance test in Berkovitza are Münden from Lower Saxony and Kaiserslautern W from Rheinland Palatinate, and in Petrohan - Darrington and Newhalem from the Western Cascade Range.
- the slowest growth was exhibited by Schneifel from Rhineland Palatinate and Schnaittenbach from Bavaria in Berkovitza and Alamogordo from New Mexico in Petrohan.
- with age, many fast-growing provenances changed their height ranking while the slowest-growing ones retained their ranking.

4. The Oakridge provenances from the Western Cascade Range in Oregon did not change their growth rate in cultivation in Northwestern Bulgaria, which is a sign of their adaptability to these conditions.

5. For Douglas-fir, there is a statistically significant positive correlation between the coefficient of mechanical stability and the degree of wind damage.

6. The most productive are the Douglas-fir provenances Newhalem, Darrington, Idanha and Parkdale, and above average level is the productivity of the 'local' provenance Kazanlak.

7. The stem volume of Douglas-fir provenances is in statistically significant negative correlation with the altitude.

8. The average annual volume increment of the most productive Douglas-fir provenances is similar to that in their native range, which is evidence of their good adaptation to the climate of Northwestern Bulgaria.

9. The precipitation has a particularly strong influence on the survival of common beech provenances: a value of the Ellenberg's quotient of less than 30 should be assumed.

10. The Bulgarian common beech provenances have better height growth in the warmer and drier climate in Bulgaria, which is a sign of their good adaptation to the local conditions, while the German ones grow successfully, but more slowly.

11. There is a statistically proven regression relationship between the height of common beech provenances on the one hand, and, on other hand, the Ellenberg's quotient (EQ) and ecological distance (ΔE). Provenances respond differently to the increase in the Ellenberg's quotient but show the same tendency for a decreasing height with an increase in ecodistance.

12. Bulgarian common beech provenances, which are part of the beech southeastern range, have a longer growing period and better height growth than the German provenances. However, their early development makes them more sensitive to low spring temperatures. Therefore the assisted migration of beech seeds from Southern to Central Europe should be critically considered at this stage.

The results and conclusions allow to make the following more important **recommendations** for the future work with Douglas-fir and common beech provenances:

1. The phases of vegetation termination and hardening of the terminal shoot of Douglas-fir provenances should be recorded when the mean diurnal temperature remains below 10°C for a long period of time.

2. When necessary to establish Douglas-fir plantations with imported seeds, the provenances Newhalem and Darrington from the Western Cascade Range in Washington State should be preferred as the most productive and most resistant to fungal pathogens. The second-generation provenances Münden from Lower Saxony and Kaiserslautern W from Rhineland-Palatinate may be used as an alternative.

3. As a seed source from Bulgaria, older Douglas-fir plantations with a good overall condition can be used, especially those which have been proven to be genetically related to the coastal (Pacific) Douglas-fir variety.

4. The continental provenances Greenwood and Keremeos from Washington State, Whitefish from Montana, Bates and Canyon City from eastern Oregon and Alamogordo from New Mexico should be excluded from future plantation establishment due to their slow growth, low productivity and high susceptibility to fungal pathogens such as *Phaeocryptopus gaeumannii* and *Rhabdocline pseudotsugae*.

5. The previously accepted limit value of the mechanical stability coefficient of Douglas-fir should be corrected to a lower value.

6. For further beech provenance tests and other experimental plantations, sites with an Ellenberg’s quotient (EQ) of not more than 30 should be selected.

7. At this stage, it is too early to give reliable recommendations for the use of beech provenances for assisted migration.

This research demonstrates the importance of long-term experiments in assessing the response of Douglas-fir and common beech to climate change. It can be used as a theoretical prerequisite for recommending appropriate provenances and transfer of forest reproductive material of these tree species in the context of climate change.

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CONTRIBUTIONS IN THE DISSERTATION

Scientific and scientific-methodological contributions

1. This dissertation introduces a classification procedure that uses ABC analysis in Douglas-fir research as a research method for the first time, thus allowing analysis of results when significant part of the data variation cannot be interpreted for a particular indicator.

2. A non-linear logistic model (Nls Logistic Model) has been applied to determine the average date of phenophases in Douglas-fir and common beech provenances.

3. Regression models for the relationship between height growth of Douglas-fir provenances in Northwestern Bulgaria and main climatic indicators have been developed for the first time.

4. The earlier onset of vegetation in continental Douglas-fir provenances and later in Pacific coastal provenances has been confirmed.

5. Evidence has been obtained that the slowest growing Douglas-fir provenances retain their rank with age.

6. The earlier leaf flush of common beech provenances from the southeastern part of the native range (Bulgaria) compared to that of Central Europe (Germany) has been confirmed.

7. The specificity in the phenological phases’ progress of Bulgarian common beech provenances gives grounds to assume that they represent ecologically-determined phenotypes.

8. A linear relationship between phenophases (average date of leaf flush and leaf coloring) of common beech provenances on the one hand, and latitude and longitude, on the other, has been established.

9. The higher survival rate of the continental Douglas-fir provenances compared to the Pacific coastal ones has been confirmed.

10. For Douglas-fir provenances, a significant negative correlation has been found between stem volume and altitude.

Scientific-applied contributions

1. The most productive and adaptive to the climatic conditions in Northwestern Bulgaria are the Douglas-fir provenances Darrington and Newhalem from the Western Cascade Range, which are promising provenances for future plantation establishment in this region.

2. The phenological traits, survival and height growth of the investigated Douglas-fir and common beech provenances can be used as criteria for the selection of appropriate provenances in the conditions of climate change.

3. The studied local common beech provenances allow to select these provenances which, if faster climatic changes occur, can successfully support beech adaptation.

4. The Ellenberg’s quotient is a reliable criterion for the growth and vigour of common beech, and can be successfully applied in assessing the condition of beech forests in Bulgaria.

List of publications related to the dissertation

1. Huber, G., K. Petkova, M. Konnert, D. Thiel. 2014: Transferversuche mit Buche (*Fagus sylvatica*) zur Prüfung der Angepasstheit im Klimawandel. Teil I: Anzucht unter stark unterschiedlichen Klimabedingungen, Allgemeine Forst- und Jagdzeitung, 185 Jahrgang, Heft 3/4, s.82 – 96. **ISSN 0002-5852, SJR 2014 – 0445 Q2, IF 2014 – 0.681.**
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