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GROWTH RESPONSE OF DOUGLAS-FIR PROVENANCES TO CLIMATE CHANGE

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Abstract

The aim of the study is to establish the height growth response of Douglas-fir provenances in different climatic conditions in provenance test in Bulgaria. The provenance test is located on the lower part of the northern slopes of the Western Balkan Range (North-Western Bulgaria) and includes 54 provenances originating from North America. The provenances were separated into three groups – coastal, continental and Western Cascade Mountains. Regression models between the average height at the age of 24 and some climatic indicators were developed to reveal the correlation between climatic variables and height growth. The transfer distance was calculated as a difference between the respective climatic indicator of planting site (provenance test) and seed sources (provenances). For continental provenances, the transfer is to more humid and warmer climate, but its height growth is poorer. The coastal and West Cascade Mountains provenances were moved to more continental and drier climate but have a good height growth.

Key words: average height, climatic indicators, transfer.

Introduction

Climate change is expected to have an impact on the growth of tree species. There are opinions about reduced growth due to increased air temperature and rainfall reduction, but also for increased growth due to prolongation of the growing period and the higher rate of photosynthesis. According to O'Neill and Nigh (2011), climate change will lead to reduction in growth or slight increase for several decades, followed by decline in growth. The authors predict decline in the productivity of *Pinus contorta* in British Columbia, Canada, by at least 7–13 % by the end of this century. Reich and Oleksyn (2008) analyse the growth of 283 Scots pine (*Pinus sylvestris* L.) populations, originating from a broad geographic range in provenance tests in Europe.

They found that climate change, equivalent to warming by 1–4 ^{o}C, would lead to an increase in the growth of the most northern populations and to a reduction for the more southerly Scots pine population. Pedlar and McKenney (2017) reach to a similar conclusion for the growth of the northern and southern provenances of *Picea mariana* and *Pinus banksiana*. Messaoud and Chen (2011) study the impact of climate change on growth in height of natural stands of *Populus tremuloides* Michx and *Picea mariana* Mill. B.S. in British Columbia and found that the height growth of both species was positively related to temperature variables at the regional scale and with soil moisture and nutrient availability at the local scale.

Restaino et al. (2016) predicted a decrease in Douglas-fir growth across all latitudes in the western United States due to increased water vapour pressure deficit (VPD) as a result of increased air temperature. According to Spittlehouse (2003), the productivity of Douglas-fir will be reduced by about 30 % when the average daily temperature increases by 1–4 °C, due to the reduction of the moisture available during the summer period. He found a growth reduction of the habitats with shallower soils due to moisture stress at the beginning of the summer. Isaak-Renton et al. (2014) predict health worsening and reduced productivity of the Douglas-fir, not only for the more southern provenances and those ones of lower altitudes. This is because all locally adapted populations experience a discrepancy between the new climatic conditions and their individual climatic niches, to which they have been adapted. Nordic populations of Douglas-fir can be more vulnerable to climate change than those in the south. Chakraborty et al. (2015), based on studies in 50 Douglas-fir provenances test in Europe, predict decreasing growth performance at low and middle elevations of the case study area, but increasing growth performance on high elevation sites.

In a number of studies, models have been developed to assess the impact of climate change on the growth of the tree species. Andalo et al. (2005) develop models for the transfer of *Picea glauca* (Moench) Voss provenances, based on differences in temperatures and precipitation between seed sources and the location of the trial sites. The authors found that the provenances were optimally adapted to the thermal conditions of the experimental trials but not for moisture conditions, populations that originated from sites receiving more precipitation generally showed higher tree growth than the local sources.

Leites et al. (2012) establish that the most sensitive indicator of climate was the mean temperature of the coldest month for continental provenances of Douglas-fir. The maximum population height and height growth response to changes in climate were dependent on seed source climate. All populations had optimal height growth when transferred to climate with warmer winters. Those originating from sites with warmest winters were taller across sites and with highest growth at a transfer distance closest to zero; those from colder climates were shortest and had an optimal height when transferred utmost far away. Although this different response makes height growth differences among populations smaller, cold-climate populations still achieve their maximum growth at lower temperatures than warm-climate populations. The results highlight the relevance of understanding climate change impact on population level, particularly for species with big genetic variation among populations.

Schmidtling (1994) has suggested the use of a regression method to analyse the response of provenances to temperature differences between the provenance source and the provenance test planting sites. He found significant correlation between temperature and growth variables for loblolly pine (*Pinus taeda* L.) and Norway spruce (*Picea abies* (L.) Karst.), and predicted that an increase in average annual temperature of 4 °C would result in a relative height growth loss of about 5–10 % for these species. Carter (1996) applies Schmidtling's regression method for published provenance test data about the following 10 forest tree species native to eastern North America: *Acer rubrum* L., *Abies balsamea* (L.), *Betula alleghaniensis* Britton, *Picea glauca* (Moench) Voss, *Pinus strobus* L., *Pinus banksiana* Lamb., *Prunus serotina* Ehrh., *Fraxinus americana* L., *Fraxinus pennsylvanica* Marshall and *Larix laricina* (Du Roi) K. Koch. For all species except *Acer rubrum* and *Fraxinus pennsylvanica*, the northern provenances did not respond to warmer growing conditions with increased growth. Growth even decreased for some species on warmer sites.

The aim of the study is to establish the height growth response of North American Douglas-fir provenances in different climatic conditions in a provenance test in North-Western Bulgaria.

Material and Methods

The Douglas-fir provenance test is located on the lower northern slopes of the Western Balkan Range (North-Western Bulgaria) in the Training-and-Experimental Forest Enterprise in Petrohan. The trial was established in a flat terrain facing the east, at an altitude of 600 m a.s.l., latitude 43°11'23.48" N and longitude 23°08'47.24" E. The soil is Orthic Luvisol (FAO), mixed sandy and clayey, slightly stony and very deep. The site is medium rich to rich. The climate in the region is temperate with an average annual temperature of 10.2 °C and annual precipitation of 1004 mm. The duration of the growing season is about 6 to 6.5 months. The 54 studied provenances originate from natural stands of Douglas-fir in North America and were classified into three groups: continental (CON), Western Cascade Mountain (CASC) and coastal (COAS) provenances. Along with the American provenances, the provenance Dimovets is included in the provenance test. This is the oldest Douglas-fir plantation in Bulgaria, established about 110 years ago and accepted for 'local' provenance in this study. In this plantation, the species is fully naturalized to local conditions. It is characterized by rapid growth, high productivity and successful regeneration (Popov 1991). Data about the provenances and weather stations, from which the climate data were included, are presented in Table 1. All climate data about the American provenances was normalized climate data (1982–2012) collected from weather stations closest to the population's origins (Anonymous 2018). The climate data about the 'local' provenance and about the trial site were as follows – for the temperatures for the period 1931–1970 (Kyuchukova et al. 1983) and for precipitations for the period 1931–1985 (Koleva and Peneva 1990).

The following climatic indicators were included in the analyses: mean annual temperature (MAT), average annual minimum temperature (AAMT), mean coldest month temperatures (MCMT), mean warmest month temperatures (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: sum of monthly precipitation). These climatic indicators and average height of each provenance at the age of 24 (according to Petkova et al. 2014) are listed in Table 2.

Analysis of variance (ANOVA) was used to determine if there were significant effects of populations on the height growth. The influence of the provenance groups on height growth was investigated by one way ANOVA and the differences between the means values in groups

Table 1. Data for Douglas-fir provenances and used climate stations.

Provenance group	Provenance number	Seedzone	Provenance name	Geographical latitude	Geographical longitude	Altitude,	Climate station	Geographical latitude	Geographical longitude	Altitude,
				° N	° W	m		° N	° W	m
CONTINENTAL										
Montana	3	Montana	Whitefish	48.5	114.5	1050	Whitefish	48.4	114.3	927
New Mexico	55	840	Alamogordo	33.0	105.8	750	Alamogordo	32.9	106.0	1317
Washington	1	612	Greenwood	49.0	119.0	1350	Omak	48.4	119.5	255
	2	600	Keremeos	49.0	120.0	750	Keremeos	49.2	119.8	414
	13	641	Naches	46.5	121.3	1050	Naches	46.7	120.7	443
East Cascade Mountains	14	661	Parkdale	45.5	121.5	1650	Dufur	45.5	121.1	410
Oregon	15	661	Parkdale	45.5	121.7	1500	Dufur	45.5	121.1	410
	16	661	Parkdale	45.5	121.5	1350	Dufur	45.5	121.1	410
	17	661	Parkdale	45.5	121.5	1200	Dufur	45.5	121.1	410
	18	661	Parkdale	45.5	121.5	1050	Dufur	45.5	121.1	410
	19	661	Parkdale	45.5	121.5	900	Dufur	45.5	121.1	410
	20	661	Parkdale	45.5	121.5	750	Dufur	45.5	121.1	410
	33	662	Warm Springs	45.0	121.5	667	Long Creek	44.7	119.1	1145
	32	662	Warm Springs	45.0	122.0	900	Long Creek	44.7	119.1	1145
	38	675	Santiam Pass	44.3	121.6	1125	Sisters	44.3	121.6	971
	47	681	Crescent	43.3	121.8	1650	Crescent	43.5	121.7	1358
	48	681	Crescent	43.3	122.0	1500	Crescent	43.5	121.7	1358
East Oregon	21	863	Bates	45.0	118.5	1667	Ukiah	45.1	118.9	1039
	22	863	Bates	45.0	118.5	1500	Ukiah	45.1	118.9	1039
	23	863	Bates	45.0	118.5	1333	Ukiah	45.1	118.9	1039
	35	892	Canyon City	44.5	119.0	1500	Prairie City	44.5	118.7	1079
	36	892	Canyon City	44.5	119.0	1350	Prairie City	44.5	118.7	1079
	37	892	Canyon City	44.5	119.0	1650	Prairie City	44.5	118.7	1079
Coastal Mountains	49	501	Crater Lake	42.7	122.5	1200	Chiloquin	42.6	121.9	1273

Provenance group	Provenance number	Seedzone	Provenance name	Geographical latitude	Geographical longitude	Altitude,	Climate station	Geographical latitude	Geographical longitude	Altitude,
				° N	° W	m		° N	° W	m
South Oregon	50	501	Medford	42.5	122.5	1050	Medford	42.4	122.9	415
	51	502	Medford	42.6	122.8	900	Medford	42.4	122.9	415
WESTERN CASCADE MOUNTAINS										
Washington	4	402	Newhalem	48.5	121,5	667	Concrete	48.5	121.7	79
	5	402	Newhalem	48.5	121.5	500	Concrete	48.5	121.7	79
	6	403	Darrington	48.0	121.5	1167	Darrington	48.3	121.6	169
	7	403	Darrington	48.0	121.5	1000	Darrington	48.3	121.6	169
	8	403	Darrington	48.0	121.5	833	Darrington	48.3	121.6	169
	9	411	Monroe	47.8	121.3	525	Monroe	47.9	122.0	21
Oregon	24	452	Idanha	45.0	122.0	1050	Government Camp	45.3	121.8	1195
	25	452	Idanha	45.0	122.0	1200	Government Camp	45.3	121.8	1195
	26	452	Idanha	45.0	122.0	1050	Government Camp	45.3	121.8	1195
	27	452	Idanha	45.0	122.0	900	Government Camp	45.3	121.8	1195
	28	452	Idanha	45.0	122.0	1333	Government Camp	45.3	121.8	1195
	29	452	Idanha	45.0	122.0	750	Government Camp	45.3	121.8	1195
	30	452	Idanha	45.0	122.0	750	Government Camp	45.3	121.8	1195
	31	452	Idanha	45.0	122.0	750	Government Camp	45.3	121.8	1195
	39	473	Santiam Pass	44.3	121.8	1500	Sisters	44.3	121.6	971
	40	472	Oakridge	44.0	122.0	1667	Oakridge	43.7	122.5	369
	41	472	Oakridge	44.0	122.0	1500	Oakridge	43.7	122.5	369
	42	473	Oakridge	44.0	122.0	1333	Oakridge	43.7	122.5	369
	43	482	Oakridge	44.0	122.0	900	Oakridge	43.7	122.5	369

Provenance group	Provenance number	Seedzone	Provenance name	Geographical latitude	Geographical longitude	Altitude,	Climate station	Geographical latitude	Geographical longitude	Altitude,
				° N	° W	m		° N	° W	m
	44	482	Oakridge	43.8	122.5	1350	Oakridge	43.7	122.5	369
	45	482	Oakridge	43.8	122.5	1200	Oakridge	43.7	122.5	369
	46	472	Oakridge	43.8	122.5	1500	Oakridge	43.7	122.5	369
COASTAL										
Washington	12	12	Moclips	47.5	124.0	600	Moclips	47.2	124.2	40
	10	222	Bremerton	47.7	123.0	600	Brinnon	47.7	122.9	68
	11	222	Bremerton	47.7	123.5	450	Brinnon	47.7	122.9	68
Oregon	34	53	Toledo	44.6	123.8	150	Toledo	44.6	123.9	3
	52	82	Brookings	42.0	124.5	833	Gold Beach	42.4	124.4	17
	53	82	Brookings	42.0	124.5	667	Gold Beach	42.4	124.4	17
Local provenance			Dimovetz	42.6	25.4 E	750	Kazanlak			380

Note: Source for the climate data – https://en.climate-data.org/continent/north-america/; Sources – for the provenance data (Popov 1990, Popov 1991, Petkova et al. 2014), the climate data CLIMATE-DATA.ORG (Anonymous 2018).

by Tukey multiple comparisons of mean method.

For the development of a regression model, established by Schmidtling (1994) and confirmed by Carter (1996), the difference between the mean height of each provenance with the mean height of the 'local' provenance (height deviation, relative height, HD) was determined and accepted as a dependent variable and the difference between the average annual minimum temperature of each provenance and provenance test (TD) as an independent variable.

Table 2. Climatic indicators and average height at age 24 of the Douglas-fir provenances.

Group	Provenance name/number	MAT	AAMT	MTCM	MTWM	Ic	MAP	H_{24}
		°C	°C	°C	°C	°C	mm	m
CON	Whitefish 3	5.6	-1.2	-6.5	17.4	23.9	532	10.6
CON	Alamogordo 55	15.8	7.4	5.5	26.2	20.7	282	6.2
CON	Greenwood 1	10.0	3.5	-3.2	22.3	25.5	296	9.9
CON	Keremeos 2	9.2	3.7	-3.7	21.3	25	278	9.7
CON	Naches 13	8.8	1.9	-2.2	19.9	22.1	280	15.3
CON	Parkdale 14	9.8	2.4	-0.2	19.8	20	345	15.8
CON	Parkdale 15	9.8	2.4	-0.2	19.8	20	345	16.6
CON	Parkdale 16	9.8	2.4	-0.2	19.8	20	345	15.3
CON	Parkdale 17	9.8	2.4	-0.2	19.8	20	345	16.1
CON	Parkdale 18	9.8	2.4	-0.2	19.8	20	345	16.2
CON	Parkdale 19	9.8	2.4	-0.2	19.8	20	345	13.6
CON	Parkdale 20	9.8	2.4	-0.2	19.8	20	345	13.2
CON	Warm Springs 33	7.4	-0.5	-1.7	17.4	19.1	394	12.9
CON	Warm Springs 32	7.4	-0.5	-1.7	17.4	19.1	394	14.9
CON	Santiam Pass 38	7.4	-0.7	-1.2	16.8	18	425	12.9
CON	Crescent 47	6.3	-1.8	-2.6	16.3	18.9	574	15.7
CON	Crescent 48	6.3	-1.8	-2.6	16.3	18.9	574	14.7
CON	Bates 21	6.7	0.5	-3.3	16.7	20	447	7.1
CON	Bates 22	6.7	0.5	-3.3	16.7	20	447	6.4
CON	Bates 23	6.7	0.5	-3.3	16.7	20	447	10.4
CON	Canyon City 35	7.8	-0.5	-2.6	18.9	21.5	360	10
CON	Canyon City 36	7.8	-0.5	-2.6	18.9	21.5	360	10.4
CON	Canyon City 37	7.8	-0.5	-2.6	18.9	21.5	360	6.4
CON	Crater Lake 49	7.4	-0.6	-1.7	17.8	19.5	511	15.3
CON	Medford 50	11.8	4.4	3.3	21.5	18.2	516	14.9
CON	Medford 51	11.8	4.4	3.3	21.5	18.2	516	15.2
CASC	Newhalem 4	9.9	5.1	2.3	17.8	15.5	1834	16.7
CASC	Newhalem 5	9.9	5.1	2.3	17.8	15.5	1834	18
CASC	Darrington 6	9.4	4.2	1.4	17.6	16.2	2064	20
CASC	Darrington 7	9.4	4.2	1.4	17.6	16.2	2064	17.9
CASC	Darrington 8	9.4	4.2	1.4	17.6	16.2	2064	16.1
CASC	Monroe 9	10.4	5.4	3.7	17.8	14.1	1244	17.9

Group	Provenance name/number	MAT	AAMT	MTCM	MTWM	Ic	MAP	H_{24}
		°C	°C	°C	°C	°C	mm	m
CASC	Idanha 24	5.5	0.8	-1.4	13.8	15.2	2137	12.3
CASC	Idanha 25	5.5	0.8	-1.4	13.8	15.2	2137	11.7
CASC	Idanha 26	5.5	0.8	-1.4	13.8	15.2	2137	14.2
CASC	Idanha 27	5.5	0.8	-1.4	13.8	15.2	2137	17.5
CASC	Idanha 28	5.5	0.8	-1.4	13.8	15.2	2137	16.9
CASC	Idanha 29	5.5	0.8	-1.4	13.8	15.2	2137	16.7
CASC	Idanha 30	5.5	0.8	-1.4	13.8	15.2	2137	16
CASC	Idanha 31	5.5	0.8	-1.4	13.8	15.2	2137	16.4
CASC	Santiam Pass 39	7.4	-0.7	-1.2	16.8	18	425	11.4
CASC	Oakridge 40	10.9	4.1	3.4	19.1	15.7	1184	13.9
CASC	Oakridge 41	10.9	4.1	3.4	19.1	15.7	1184	14.6
CASC	Oakridge 42	10.9	4.1	3.4	19.1	15.7	1184	14.8
CASC	Oakridge 43	10.9	4.1	3.4	19.1	15.7	1184	14.5
CASC	Oakridge 44	10.9	4.1	3.4	19.1	15.7	1184	14.7
CASC	Oakridge 45	10.9	4.1	3.4	19.1	15.7	1184	14.8
CASC	Oakridge 46	10.9	4.1	3.4	19.1	15.7	1184	12.7
COAS	Bremerton 10	10.2	5.1	3.3	17.7	14.4	1329	16.2
COAS	Bremerton 11	10.2	5.1	3.3	17.7	14.4	1329	17.9
COAS	Moclips 12	9.7	5.4	4.5	15.2	10.7	2699	16.5
COAS	Toledo 34	11.0	6.6	6.4	16	9.6	1958	11.5
COAS	Brookings 52	11.8	7.3	8.5	15.6	7.1	2012	14.6
COAS	Brookings 53	11.8	7.3	8.5	15.6	7.1	2012	15.9
LOCAL	Dimovetz	10.7	4.9	-0.7	21.4	22.1	588	14.2
Test site	Berkovitza	10.4	5.8	-2.2	21.2	23.4	825	

Note: MAT – mean annual temperature, AAMT – average annual minimum temperature, MCMT – mean coldest month temperature, MWMT – mean warmest month temperature, Ic – continentality index, MAP – mean annual precipitation, H_{24} – average height at age 24.

Simple linear and parabolic regression models between the dependent variable HD and some climatic indicators were developed. The transfer distance was calculated as the difference of the respective climatic indicator of planting site (the provenance test) and seed sources (the provenance) – Leites et al. (2012), Lamy et al. (2013). For temperature related climatic indicators (MAT, MCMT, MWMT, Ic), the transfer distance is respectively denoted as MTD (the difference between the average annual temperature), CTD (the difference between the mean coldest month temperatures), WTD (difference between mean warmest month temperatures), DIc (the difference between the continentality index). The positive values denote transfers from climate cooler than the climate of the test site, while negative values represent transfers from climates warmer than that of the test site. Zero denotes the climate of the test site and the best match (Oke and Wang 2013). The transfer distance for mean annual precipitation (MAP) is denoted as DMAP (the difference between mean annual precipitations). Positive values mean that provenances were transferred to a place with more precipitation (more moist climate) and negative values indicate transfer to a drier climate.

Analysis of the data was carried out with the R package stats (R Core Team 2014) and the models were visualized with the graphical functions in the R package ggplot2 (Wickham 2009).

Results and Discussion

With a one-factor dispersion analysis, the statistical effect ($p < 0.01$) of the group of provenances (Coastal, Continental and Western Cascade) was found at the age of 24 (Table 3).

Table 3. ANOVA for the height of provenance groups.

Indicator	Df	Sum. Sq	Mean Sq	F value	Pr (>F)
Group	2	114.3	57.17	6.947	0.00215**
Residuals	51	419.7	8.23		

Note: Signif. codes: *** – 0; ** – 0.001; * – 0.01.

The mean values for the provenance groups in parentheses were compared by Tukey multiple comparisons of mean method and the differences were plotted (Fig. 1). No differences were found between coastal (COAS) and Western Cascades (CASC) provenances – the graph was symmetrically located on both sides of the zero. The provenances of these two groups were comparatively fast-growing and therefore there were no statistical differences between them (Table 4). Significantly slower-growing were continental provenances (CON). The differences between them and Western Cascade provenances (CASC) were entirely negative, i.e. they had a lower average height. The statistical significance of this assertion was high $p = 0.0027$ i.e. $p < 0.01$. The differences between the continental and coastal provenances groups were also negative for the most part. The continental provenances fall back to height on the coastal ones, with the probability of this assertion $p = 0.0745$ being relatively close to the threshold value $p = 0.05$.

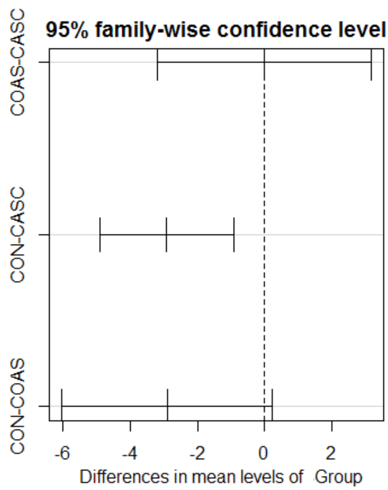

Fig. 1. Comparison of parent groups by Tukey test.

Table 5 presents the correlation between the different climatic variables. The established correlation between them does not exclude the specificities in the provenance responses, which were illustrated in the independent regression dependencies shown below. Parallel correlation of parameters allows their interpretation on different climatic indicators to be complementary, allowing for interpretation of the impact on the height of more than one climatic variable.

Table 4. Statistical differences between the provenance groups.

Indicator	Diff	Lwr	Upr	Padj
COAS-CASC	-0.007575758	-3.197051	3.1818990	0.9999819
CON-CASC	-2.913986014	-4.920073	-0.9078992	0.0027076
CON-COAS	-2.906410256	-6.042871	0.2300501	0.0745497

Note: Diff – difference between the mean values of the two groups concerned; Lwr/Upr – lower and upper confidence interval of this difference (the 95 % confidence interval of that difference is between); Padj – the p-value adjusted for multiple comparisons.

Table 5. Correlation between the climatic variables.

Variables	Variables	Cor. coef.	P-value
MAT	MTD	-1	0
MAT	CTD	-0.779	0
MTD	CTD	0.781	0
MAT	WTD	-0.731	0
MTD	WTD	0.728	0
CTD	DIc	-0.75	0
WTD	DIc	0.54	0
CTD	DMAP	0.402	0.003
WTD	DMAP	-0.678	0
DIc	DMAP	-0.797	0

Note: MAT – mean annual temperature, MTD – difference between average annual temperature, CTD – difference between the mean coldest month temperatures, WTD – difference between mean warmest month temperatures, DIc – difference between the continentality index, DMAP – difference between mean annual precipitations.

Fig. 2 presents a regression model for the relationship between the relative height of the provenances at the age of 24 (HD) and the difference between the mean annual minimum temperature of the seed source and the planting site (TD). According to Carter (1996), when the peak of the regression curve is at the point where 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. At a peak at the point where TD is a negative number, the provenances grow best in warmer locations with a corresponding deviation of 0 °C, and at a peak at the point where TD is a positive number, the provenances grow best at sites cooler than their original locations. The model obtained in the present study is identical to that used by Carter (1996). Here the peak of the regression curve (parabola) for the Douglas-fir provenance test is at TD = -1.66 °C, which shows that the optimal growth of Douglas-fir in the studied provenance test is observed for provenances transferred

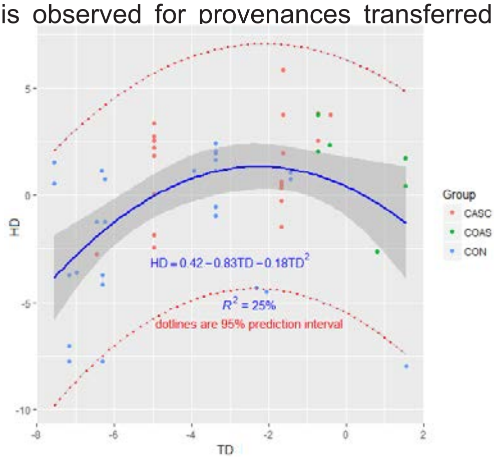

Fig. 2. Correlation between the relative height at the age of 24 and the difference in the mean annual minimum temperature between the seed source and the provenance test (TD).

from cooler places with 1.66 °C compared to provenance test (Fig. 2). All provenances, the relative heights of which are greater than the ordinate's value 0, are higher than the 'local' provenance.

For the continental group (CON), the moving in the provenance test 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 is with about 10 ° to the north and in a cooler climate (Tables 1 and 2). For 14 of the continental provenances their height growth in provenance test conditions is slower than that of 'local' provenances. The other 12 provenances had a better growth than them. For all Western Cascade provenances (CASC), the moving was to a warmer climate. Under these conditions, most were taller than the 'local' provenance. For half of the coastal provenances (COAS), the transfer is to warmer climate and for the other – to a cooler climate than the seed source. There were taller than the 'local' provenance, with the exception of the provenance 34 Toledo, which retreats on this indicator to the 'local' provenance (Table 2).

A regression relationship, represented by a parabolic model (Fig. 3), was established regarding the difference between the temperature of the coldest month of the provenance test and the seed source (CTD). The model is statistically significant with a value of R^2 = 0.28 and p-value = 0.0002196 i.e. $p < 0.001$. The peak of the regression curve of the parabolic model is at CTD = -5.5 °C, i.e. the optimal height growth is observed for provenances for which the winters in the provenance test are colder than 5.5 °C from the point of origin. This condition corresponds to coastal provenances 10 and 11 Bremerton and the continental provenances from Southern Oregon 50 and 51 Medford. Similar is the transfer distance (-5.6 °C) for the provenances of Western Cascades 40–46 Oakridge (Table 2). For all Western Cascades provenances (CASC) and for the coastal (COAS) provenances, relocation is to colder winters. For most of the continental provenances, the transfer to North-Western Bulgaria is to a colder winter, and only for a part of it to a warmer winter. The shifted provenances to a colder winter have better growth on height than the 'local' provenance compared to those for which the relocation is to a warmer winter (Fig. 3, Table 2). Such a conclusion is made by Leites et al. (2012), who investigate the height growth response of Douglas-fir continental provenances to climate change using the mean temperature of the coldest month and identifying it as the most sensitive climatic indicator.

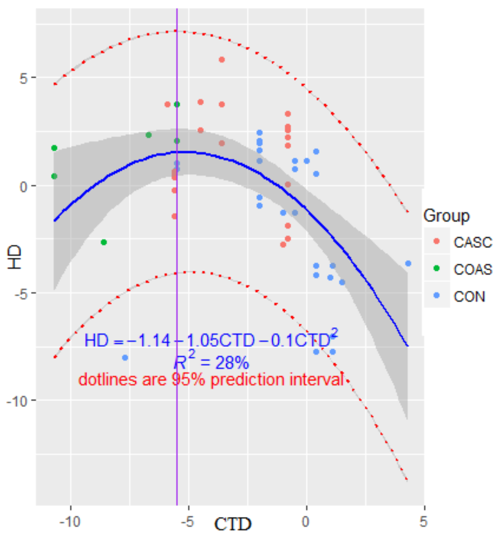

Fig. 3. Correlation between the provenances relative height at the age of 24 (HD) and the difference in the coldest month temperatures between provenance test and seed source (CTD, °C)

The correlation between the relative height and the difference in the continentality index is presented in Fig. 4 with two regression models – linear (Fig. 4a) and parabolic (Fig. 4b), the statistical significance of the linear is respectively $R^2 = 0.22$ and p-value = 0.0003765 and for parabolic $R^2 = 0.31$ and p-value = 0.00006. The continentality index (Ic) of the provenances varies from 7.1 (extreme hyperoceanic climate, typical for coastal provenances 52 and 53 Brookings – Table 2) to 25.5 (moderate continental for provenance Greenwood) – Rivas-Martinez et al. (2017). Moderate continental (Ic = 23.4) is the provenance test climate, as well. With increasing the difference in the continentality index (DIc) and the relative height (HD) when the transfer is to more continental climate, the provenances are taller than the 'local' one. Particularly great were the differences in the moving of the coastal provenances (COAS) but this does not negatively affect their growth. The optimum in height growth was observed when the continentality index increases by 12.7 towards the seed sources. Chakraborty et al. (2015) point out the continentality as one of the most important climatic indicators that influence the Douglas-fir provenances growth in provenance tests in Austria and Germany.

A regression correlation between the relative height and the difference in the mean annual precipitation (DMAP) between the planting site and seed source was presented by a linear model (Fig. 5). The model is statistically significant with values of $R^2 = 0.24$ and p-value = 0.0002. Positive DMAP values indicate that the provenances are transferred to more humid conditions, i.e. the annual precipitations of the provenance test is bigger than that of the corresponded provenance. It is clearly seen from Fig. 5, that the all continental provenances (CON) were transferred to more humid climate, while coastal (COAS) and Western Cascade provenances (CASC) were moved to significantly more dry conditions. The figure shows clear clustering of provenances with most continental provenances having a lower height than 'local' provenance. It seems illogical when increasing the precipitations in the new location, the provenances do not take advantage of better humidity conditions, which should have a positive effect

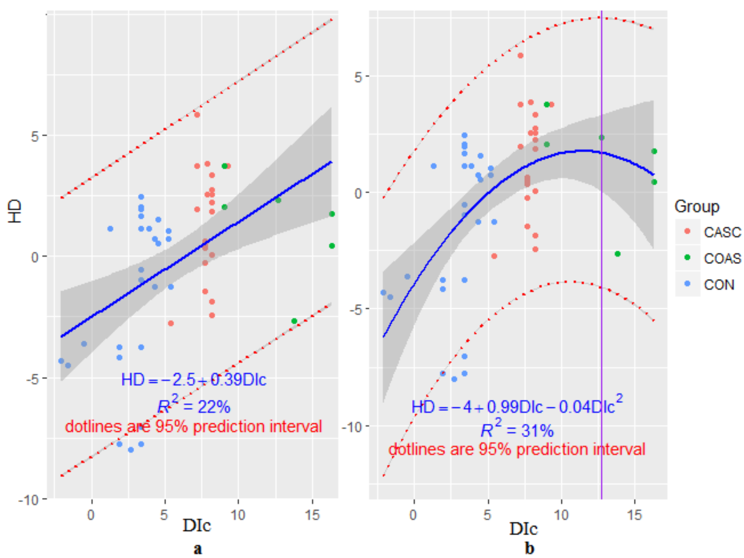

Fig. 4. Correlations (a – linear and b – parabolic) between the relative height at the age of 24 (HD) and the difference in the continentality index of the provenance test and the seed source (DIc).

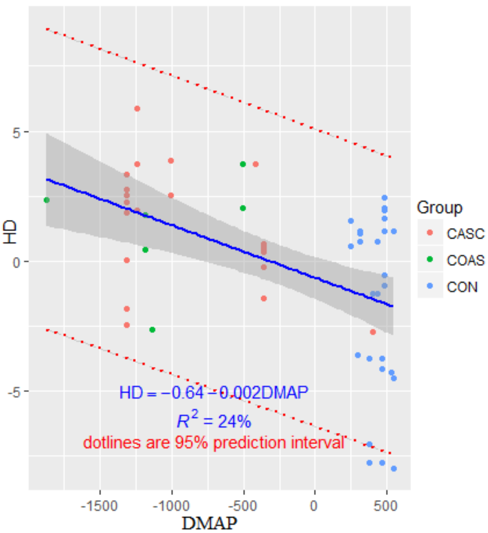

Fig. 5. Correlation of the relative height at the age of 24 (HD) and the difference in the average annual precipitations (DMAP, mm).

on their height growth. Here, on the one hand, 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 to *Rhabdocline pseudotsugae* Syd., which are also found in the studied provenance test, a prerequisite for the development of which are the more humid conditions of this location. The continental provenances Greenwood and Keremeos from Washington, Whitefish from Montana, Bates and Canyon City from Eastern Oregon and Alamogordo from New Mexico have the poorest growth and highest sensitivity to the above mentioned fungal pathogens (Petkova et al. 2014). Kimberley et al. (2011) in New Zealand also determined decline of Douglas-fir growth due to fungal pathogen *Phaeocryptopus gaeumannii* (Rohde) Petrak.

Regression correlation was also found in the mean annual temperature (MAT) and the difference in the mean warmest month temperature (WTD), but the established correlations are poor (with $R^2 < 0.15$). However, the obtained models are presented because the results correspond to those obtained by other authors.

For example, a strong correlation was established between MAT and MTD (Table 5), which means that the studied model correlations for MAT are also expected for MTD. However, the search for regression correlations between HD and MTD did not lead to adequate models, and testing of the correlation between HD and MAT was done using the $y = a + bx + cx^4$ model due to the presence of a strongly divergent value of MAT (provenance Alamogordo 55 – Table 2). The regression correlation between HD and MAT is presented in Fig. 6. The resulting parabolic model shows that the optimal height growth is characterized by the provenances of sites with an average annual temperature of 9.4 °C. This condition corresponds to the provenances of Darrington by Western Cascade Mountains in Washington State. This result is consistent with the conclusion of Chakraborty et al. 2016, according to data for 290 origins of Douglas-fir in 50 provenance tests in Austria and Germany, that the best growth is the provenances of Western Cascades and the coastal areas of Washington, Oregon and British Columbia, for which the average annual temperature is from 6 to 9.5 °C. The provenance 7 Darrington is one of the tallest provenance and in another Douglas-fir prove-

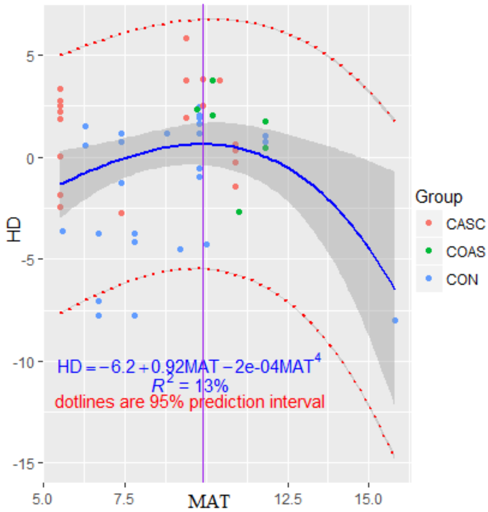

Fig. 6. Correlation between the relative height of the provenances at the age of 24 (HD) and the mean annual temperature (MAT) of the seed sources.

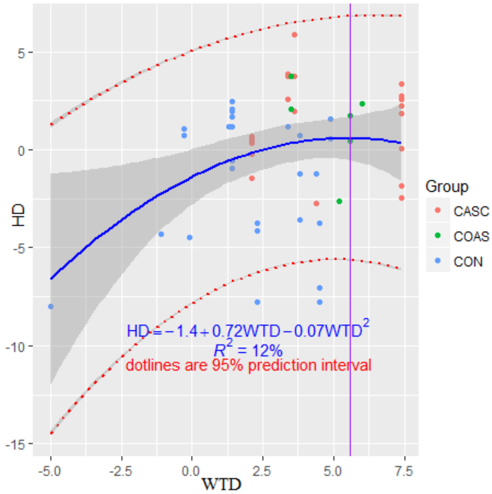

Fig. 7. Correlation between the relative height at the age of 24 (HD) and the difference in mean warmest month temperatures of provenance test and seed source (WTD, ℃).

nance test, established in South-Western Bulgaria (Popov 2011).

The correlation between height and mean warmest month temperatures was also presented with parabolic model (Fig. 7). The transfer for most provenances (except continental Alamogordo, Greenwood, Keremeos and Medford) was for a warmer summer compared to the seed source. The peak of the parabolic model is at WTD = 5.6 °C, i.e. the growth optimum is for provenances that have been moved from a cooler summer to 5.6 °C compared to this of the provenance test (Fig. 7). Under these conditions, almost half of the provenances have better growth than the 'local' provenance. Correlation of the growth rate of 8 Douglas-fir provenances on mean warmest month temperature is also found by Montwé et al. (2015) in provenance test in British Columbia (Canada).

Conclusions

The climatic conditions in the studies provenance test (North-Western Bulgaria) differ from those in the natural range of the Douglas-fir, from where the seeds were imported.

For continental provenances, the transfer is to more humid and warmer climate, but they do not response with better growth, on the contrary, their height growth is poor. An explanation for this is their genetic features and their infection with the fungal pathogens *Phaeocryptopus gaeumannii* (Rohde) Petrak and *Rhabdocline pseudotsugae* Syd., to which they are susceptible.

Coastal and West Cascade Mountains provenances are found on more prominent continental and drier climate, but they grow well. Thus Oakridge's provenances from the Western Cascades in the provenance test in North-Western Bulgaria at the age of 24 have an average height of 12.7 to 14.8 m or 0.52 – 0.62 m average annual height increment, and in provenance tests in their natural range – British Columbia (Canada) and Oregon (USA) at the age of 48 have an average height of 25.17 m or 0.52 m mean annual height increment (Ye and Jayawickrama 2014), i.e. the values of the increment are similar. These provenances were transferred to North-Western Bulgaria in a more continental climate with lower annual precipitations, cooler winter and warmer but more humid summer. So far, their height growth is not negatively affected by the changed climate conditions. It can be assumed that such an assertion will be valid for the other provenances from these two groups, but requires confirmation by facts about their growth in their maternal climate.

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