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Which Douglas-Fir (*Pseudotsuga menziesii* (Mirb.) Franco) Provenances Provide the Best Productivity in the Hilly Area of Croatia?

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ABSTRACT

Background and Purpose: Recently raised questions on adaptability of native tree species to climate changes pointed to Douglas-fir as a species suitable for rapid reforestation and increase of stand resistance. The first results on provenance research need to be confirmed in later stages of stand development, so the paper answers the following two questions: (i) are there differences in growth of 14 Douglas-fir provenances still in the fifth decade of stand development, and (ii) which provenances should be used and which omitted from further use in the hilly area of Croatia?

Materials and Methods: Productivity of 14 provenances was evaluated on the basis of height, diameter at breast height and volume in the 46th year after planting. Growth dynamics was also statistically analysed using a repeated measure analysis of variance, for which purpose we partially used published data from the 2010.

Results: The analysis excluded Castle Rock and Shady Cove (Oregon) provenances due to their low values of all analysed growth indicators, as well as Castle Rock, Elma and Hvidilde provenances due to their high values. Average values of tree volume ranged from 0.53 m^3 (Shady Cove) to 2.05 m^3 (Castle Rock), while the tallest trees belonged to Elma provenance (29.6 m).

Conclusions: Different growth dynamics of provenances were confirmed for later development stage, so further monitoring is still required. Clear guidelines for the selection of provenances for practical forestry distinguish provenances from lower altitudes of the State of Washington, Denmark and Bulgaria as the most productive. Shady Cove and Salmon Arm provenances are not advised to be used in the future.

Keywords: Reforestation, diameter at breast height, tree height, tree volume

INTRODUCTION

The management of Croatian forests, as determined by the Forest Law and following a long-lasting forestry tradition, should rest on the principles of sustainable forest management and natural species composition. Climatic disturbances and pest damages raised three questions recently: (i) can native species adapt quickly enough, (ii) to what extent they can adapt to changed conditions, and (iii) what species and provenances can be used for the increase of forest resistance and resilience? Problems in management of autochthonous tree species refer to diverse site conditions and tree species present in all areas of the country. A good example is the decline of artificial Norway spruce forests, as well as close to nature European beech-Silver fir mixed forests in mountain areas. In this case, several strong negative and destructive events took place just in a few years, often affecting already reforested areas. The first significant damages ware caused by strong ice load in 2013, followed by strong bark beetle attacks and consecutive storms. This raised both the need for reforestation efforts in practical forestry and the need for new silvicultural solutions, especially in terms of quick and efficient reforestation techniques and tree species/provenance selection. In addition, studies from the region support the statements that native tree species can decrease their growth as a response to climate changes. For example, in a dendrochronological study Norway spruce decreased its radial growth in relation to the increase of mean annual temperature and mean temperature during growing season, which was significant in the period from 1980 to 2015 [1].

These newly developed problems in management of native tree species underline the use of non-native tree species for reforestation purposes. In that respect Douglas-fir (*Pseudotsuga menziessi* (Mirb.)) has distinguished itself among other non-native tree species. After its introduction from North America more than 150 years ago it has become one of the most economically important exotic tree species of European forests. It has been successfully introduced in almost all areas of the temperate zone (Europe, southern part of South America and Australia) [2]. Its durable, disease-resistant wood, rapid growth, adaptability to a spectrum of site conditions make it well suited for rapid reforestation and flexible forest management options [3-5]. Favourable Douglas-fir features justify the increase of Douglas-fir cultures in the future [6-9]. Countries with the highest coverage of Douglas-fir in Europe are France, Germany, Great Britain and the Netherlands [2], while in Croatia there are only a few localities of Douglas-fir stands. Compared to many tree species, Douglas-fir populations are generally regarded as being closely adapted to their environments with relatively steep clines associated with steep environmental gradients [10]. This is due to its extremely large natural distribution in both horizontal and vertical sense (from California up to British Columbia and from the Pacific coast up to 1500 m a.s.l.) [11]. Differentiation and development of a large number of provenances should be taken into account if the introduction and use of this tree species in areas outside of its natural distribution is aimed.

Even though this species is well-investigated in the countries of its natural distribution [12-18], this kind of knowledge cannot be applied in Europe since it is a poor representation of Douglas-fir growth and development in significantly different growth conditions. To date, European research point to good growth and development of some provenances, while others show mediocre or extremely poor success, highlighting the appropriateness of provenances to specific site conditions [2, 19]. Similar conclusions were obtained through analysis of the first results of Douglas-fir research in Croatia, which was conducted in the frame of the international IUFRO programme for Douglas-fir provenance testing [20]. Early 20th century was the beginning of Douglas-fir introduction in Croatia in forest stands, but more intensive establishment of forest cultures started in the 1970s when experimental plots were established by Forest Research Institute, Jastrebarsko. The goal was to find an appropriate silvicultural solution in terms of suitable species and provenances for afforestation practices. From the results obtained so far Douglas-fir has proved to be one of the most successful coniferous non-native tree species in Croatia and as such should have a more significant role in afforestation and reforestation activities [21-25]. Nevertheless, the same research results also strongly underline the need for further continuous monitoring of the established trials of Douglas-fir provenances to support the first obtained results. The paper answers two basic research questions: (i) are there differences in growth of 14 Douglas-fir provenances still in the fifth decade of stand development, and (ii) which provenances should be used and which omitted from further use in the hilly area of Croatia? The added value of this study is to provide background for active use of Douglas-fir in practical forestry and to implement the obtained results into silvicultural recommendations. This is important from the aspect of climate changes and fast increase of reforestation needs in the future [26]. The paper provides data on productivity of 14 Douglas-fir provenances 46 years (2015) after planting, compared with their productivity in the 41st year (2010) with guidelines for the selection of appropriate provenances.

MATERIALS AND METHODS

Research Area

The experimental plot called Slatki potok is located in the hilly area of the Bjelovar Basin on 140–145 m a. s. l. (45°46’ N, 17°03’ E). The climate of the area is humid (Cfmbx’’ according to Köpen). Thornthwait’s index of rainfall effectivity (P/E) amounts to 72. Mean annual air temperature is 10.3°C, while in the warmest part of the year (June–September) it amounts to 16.6°C. Mean annual precipitation is 813 mm, 462 mm in the warmest part of the year (June–September). From the aspect of potential vegetation this is the area naturally dominated by mixed pedunculate oak and European hornbeam forests (*Carpino betuli-Quercetum roboris typicum* Rauš 71). According to Mayer, soil is defined as loess (on the plateau) up to mildly pseudogley (on the slopes) [27]. Mechanical soil properties point to the loam texture in the whole soil depth, while chemical analysis revealed that the soil is very acid. Prior to trial establishment the area was used for agricultural purposes several years in a row (corn production).

Experimental Design

The experiment on Douglas-fir (*Pseudotsuga menziessi* (Mirb.)) provenances was established in the spring of 1969 using a completely randomised block design with four replications. In this field test, eleven American (six from Washington, two from Oregon, three from British Columbia) and three European provenances (from Denmark, Bulgaria, and Croatia) were investigated. More detailed description of the experimental plots and site conditions are provided by Perić *et al*. [28] and Orlić and Perić [29]. For basic information on provenance origin see Table 1 [30].

The overall size of this trial is 3.6 ha and it includes 14 different Douglas-fir provenances, which were established with the aim of determination of best provenance selection for afforestation practices in the hilly area of the country. The experimental plot was established by planting three-year-old Douglas-fir seedlings grown in Jiffy-pots (2+1). In each repetition, 25 seedlings (5×5) were planted, i.e. a total of 100 seedlings per provenance. Planting spacing was 4×4 m, with Norway spruce and European larch planted between rows. These were cut during the first thinning to provide an optimal growth condition of targeted Douglas-fir trees. Diameter at breast height (DBH) and tree height (h) were measured in 2015. All trees on the experimental plots were measured and included in the analysis.

TABLE 1. Origin and codes of Douglas fir provenances tested on Slatki potok locality with some basic information on the origin of provenances.

Code	Provenance	Altitude (m a.s.l.)	Geographic coordinates	
			Width	Length
A	SHELTON, Washington	30 - 150	47°11' N	123°10' W
B	CORVALIS, Oregon	75	44°35' N	123°16' W
C	SHADY COVE, Oregon	1350	42°36' N	122°50' W
D	TENINO, Washington	100 - 200	46°45' N	122°40' W
E	ELMA, Washington	100 - 200	47°00' N	123°30' W
F	ELK RIVER FALLS, British Columbia	-	-	-
I	MERVILLE BLACK, British Columbia	15	-	-
J	HVIDILDE, Denmark	-	-	-
L	SALMON ARM, British Columbia	450 - 600	50°50' N	119°10' W
M	PE ALL, Washington	150 - 300	46°45' N	123°15' W
N	YELM, Washington	0 - 150	46°45' N	122°40' W
R	ŠIPKA, Bulgaria	650 - 780	42°43' N	25°20' W
S	ROVINJ, Croatia	-	-	-
T	CASTLE ROCK, Washington	-	-	-

Field Measurements and Statistical Analysis

For this research we have measured manually DBH and h in the year 2015 (46 years after planting). On the basis of DBH and h, we have calculated wood volume (V) for 2015 for each provenance. Hamilton tables were used while calculating wood volume, so it could be compared to earlier research studies. We have also calculated descriptive statistics for all parameters by provenances for the 46th year after planting (2015). For the purpose of examining growth dynamics of provenances in relation to the five year interval we have partially used published data from 2010 (the 41st year after planting, 30). With a repeated measures analysis of variance (ANOVA) we have tested differences between provenances for all measured variables, which we could apply since the condition of variance homogeneity was proved. In the event where there was a significant statistical difference between provenances, we have determined which provenances differed between others by using the Tukey Post hoc test. Type I error (α) of 5% was considered statistically significant. We have made all analyses and graphs by using the statistical programme STATISTICA [31].

RESULTS

Variations in Diameter at Breast Height among Provenances

The average value of DBH on this experimental plot was 33.61 cm. The lowest DBH values at Slatki potok experimental plot belonged to the provenances from British Columbia, Oregon and Rovinj (Table 2). A 95% confidence interval for DBH for this site is shown in Figure 1. Salmon Arm (23.28±1.93 cm) provenance significantly differed by DBH from all other provenances, except for provenances from Oregon (Shady Cove – 24.27±1.13 cm; and Corvalis – 31.31±1.35 cm), British Columbia (Elk River Falls – 31.78 ±1.14 cm and Merville Black – 30.64 ±1.29 cm) and Croatian provenance Rovinj (31.81±1.46 cm). Castle Rock from Washington had the largest standard deviation (SD=7.28), pointing to the largest differences between DBH of individual trees for this provenance. The smallest differences between individual trees in terms of DBH showed ELMA from Washington (SD=0.91 cm), pointing to the good adaptability to local conditions.

Provenances with the highest average DBH values were Castle Rock (41.38±7.28 cm) and Elma (39.53±0.91 cm) from Washington. Castle Rock provenance from Washington statistically differed from Shady Cove (24.27±1.13 cm), Oregon and Salmon Arm (23.28±1.93 cm) and from British Columbia provenances. Even though it had the largest DBH it did not differ significantly from other provenances, showing that Shady Cove from Oregon and Salmon Arm from British Columbia were provenances with the lowest DBH on this locality. A 95% confidence interval for DBH is shown in Figure 1. The provenance with the largest DBH (Elma) also had the smallest standard deviation (SD=0.91cm), pointing to the lowest differences between individual trees. In terms of the highest DBH values this provenance was followed by Shelton (35.96±1.11 cm), Pe All (36.40±1.06 cm) and Yelm (35.30±1.30 cm) from Washington, Hvidilde (36.19±1.46 cm) from Denmark and Šipka (35.57±1.31 cm) from Bulgaria.

Furthermore, repeated measures ANOVA of DBH in the 46th year after planting in comparison with data from the year 2010 (41st year after planting) confirmed significant difference between DBH ($p<0.05$) both between the values of individual years, but also in relation to *provenance x year* (Table 3). This shows that provenances did not have the same DBH growth.

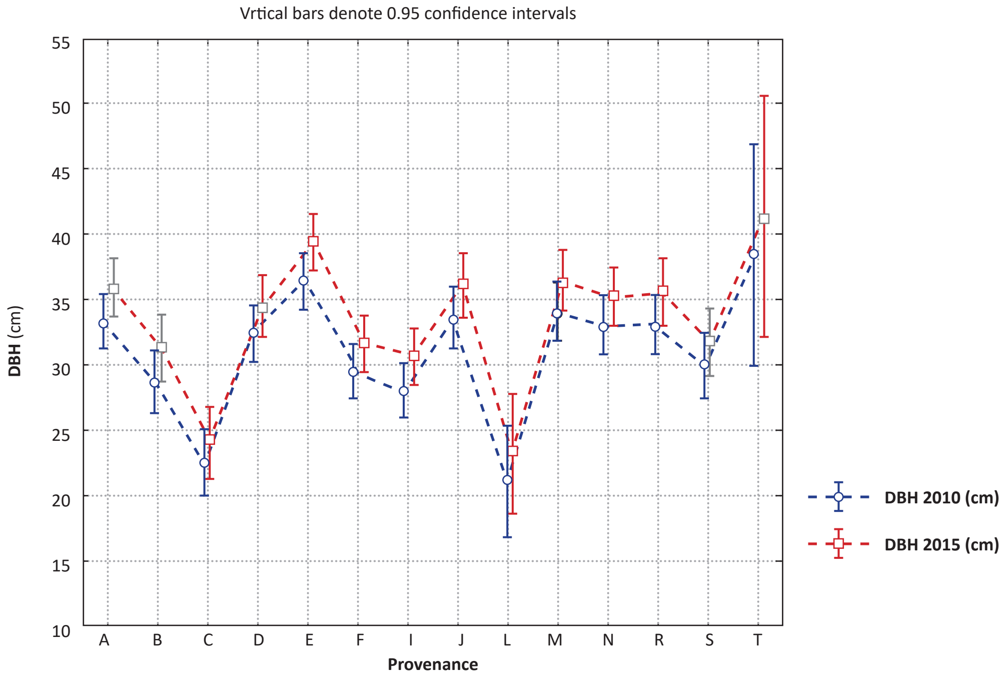

FIGURE 1. 95 % confidence intervals for DBH (in 46th year after planting) compared to data collected in the 41st year after planting [30] for 14 Douglas fir provenances grown on Slatki potok locality. For provenance codes see Table 1.

TABLE 2. Results of descriptive statistics and Tukey post hoc analysis for 14 Douglas-fir provenances (basic growth indicators) in the year 2015 (46th year after planting).

Code	Provenance	DBH (cm)	Height (m)	Volume (m^3)
A	SHELTON, Washington	35.96 ± 1.11 CILS	27.91 ± 0.50 BCILS	1.53 ± 0.10 CL
B	CORVALIS, Oregon	31.31 ± 1.35 CE	25.44 ± 0.64 ACEM	1.15 ± 0.11 CE
C	SHADY COVE, Oregon	24.27 ± 1.13 ABDEFIJMNRST	18.61 ± 0.63 ABDEFIJMNRST	0.53 ± 0.06 ABDEFIJMNRST
D	TENINO, Washington	34.52 ± 1.29 CL	27.04 ± 0.52 CL	1.43 ± 0.11 CL
E	ELMA, Washington	39.53 ± 0.91 BCFILS	29.61 ± 0.34 BCFILS	1.87 ± 0.09 BCFILS
F	ELK RIVER FALLS, Brit. Columbia	31.78 ± 1.14 CE	25.86 ± 0.53 CEL	1.17 ± 0.08 CE
I	MERVILLE BLACK, Brit. Columbia	30.64 ± 1.29 ACEJM	24.77 ± 0.60 ACEMN	1.11 ± 0.10 CE
J	HVIDILDE, Denmark	36.19 ± 1.46 CIL	26.62 ± 0.59 CEL	1.55 ± 0.13 CIL
L	SALMON ARM, Brit. Columbia	23.28 ± 1.93 ADEJMNRT	21.86 ± 1.03 ADEFJMNR	0.57 ± 0.11 ADEJMNRT
M	PE ALL, Washington	36.40 ± 1.06 CIL	28.25 ± 0.45 BCILS	1.56 ± 0.09 CIL
N	YELM, Washington	35.30 ± 1.30 CL	27.11 ± 0.50 CIL	1.49 ± 0.11 CL
R	ŠIPKA, Bulgaria	35.57 ± 1.31 CL	27.12 ±0.58 CL	1.50 ± 0.12 CL
S	ROVINJ, Croatia	31.81 ± 1.46 CE	24.63 ± 0.71 ACEM	1.16 ± 0.10 CE
T	CASTLE ROCK, Washington	41.38 ± 7.28 CL	27.55 ± 1.99 C	2.05 ± 0.69 CL

TABLE 3. Results of ANOVA – comparison of provenances by DBH on Slatki potok locality in the 41st and 46th year after planting (2015) for 14 Douglas-fir provenances.

	Sum of squares	Degrees of Freedom	Mean Square Error	F	p
Provenance	20898.5	13	1607.6	9.825	0.000000
Error	115357.1	705	163.6		
Year	1007.8	1	1007.8	805.181	0.000000
Year*Provenance	43.5	13	3.3	2.675	0.001117
Error	882.4	705	1.3		

Variation in Tree Height among Provenances

The average value of height on this experimental plot was 26.17 m. Elma provenance from Washington was by far the tallest and it was statistically different from other provenances except those from Washington (Castle Rock - 27.55±1.99 m, Shelton - 27.91±0.50 m, Tenino - 27.04±0.52 m, Pe All 28.25± 0.45 m, and Yelm - 27.11±0.50 m) and Bulgaria (Šipka - 27.11±0.58 m). Washington and Bulgarian provenances were the most successful in terms of height (Figure 2). In general, the smallest height values were obtained in Salmon Arm (21.86±1.03 m) from British Columbia and Shady Cove from Oregon (18.61±0.63 m) provenances. Salmon Arm provenance (21.83 m) differed statistically from all other provenances except from Shady Cove (also the lowest height value of 18.61 m), Croatian provenance Rovinj (24.63 m), Elk Falls River (25.86 m) from British Columbia, Corvalis (25.44 m) from Oregon and Castle Rock (27.55 m) from Washington. Regarding DBH, Castle Rock from Washington had the largest standard deviation for height (SD=1.99 m), pointing to the largest differences between heights of individual trees. The smallest differences between individual trees in terms of height again showed ELMA provenance from Washington (SD=0.34 m).

Repeated measures ANOVA for height in the 46th year after planting in comparison with data from 2010 confirmed significant difference between heights (p<0.05) for all analysed provenances (Table 4). Differences observed in Figure 2 were confirmed by Tuckey post hoc test (p<0.05).

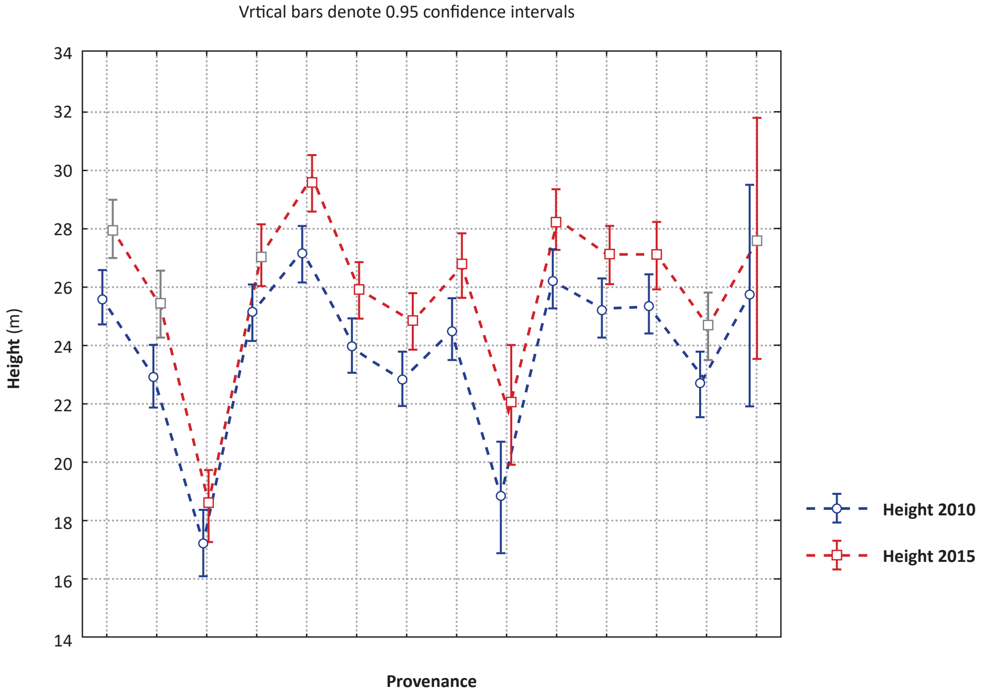

FIGURE 2. 95% confidence intervals for tree height compared to data collected in the 41st year after planting [30] for 14 Douglas-fir provenances on Slatki potok locality. For provenance codes see Table 1.

Variation of Tree Volume among Provenances

Descriptive statistics for V (Table 2) showed a large span from 0.53 m^3 to 2.05 m^3, while the average value for this locality is 1.34 m^3. Statistically significant difference between V in the years 2010 and 2015 points to different volume increment of analysed provenances (Table 5). Tuckey post hoc test ($p<0.05$) for V revealed which provenances differed significantly from others.

The highest average V was recorded in Castle Rock provenance (2.05±0.69 m^3) from Washington (Figure 3). Statistically, it significantly differed from the lowest value for V, which was measured in Shady Cove provenance (0.53±0.06 m^3) from Oregon and Salmon Arm provenance (0.57±0.11 m^3) from British Columbia. These two provenances differed from all other provenances, which isolates them in terms of low growth and proves them to be inadequate for this habitat. There were no statistically significant differences between other provenances. Based on this data it can be concluded that Elma provenance from Washington, and generally the Washington region along with European provenances from Bulgaria, Denmark and Croatia, proved to have the highest V in the hilly area. Castle Rock from Washington had the largest standard deviation for V (SD=0.69 m^3), as in the case of DBH and height. The smallest differences between individuals in terms of V were again obtained in Shady Cove from Oregon (SD=0.06 m^3), and Elma and Pe All from Washington (SD=0.09 m^3, respectively).

TABLE 4. Results of ANOVA – comparison of provenances by tree height on Slatki potok locality in the 41st and 46th year after planting (2015).

	Sum of squares	Degrees of Freedom	Mean Square Error	F	p
Provenance	8678.2	13	667.6	21.23	0.000000
Error	22164.1	705	31.4		
Year	770.8	1	770.8	927.57	0.000000
Year*Provenance	34.9	13	2.7	3.23	0.000092
Error	585.9	705	0.8		

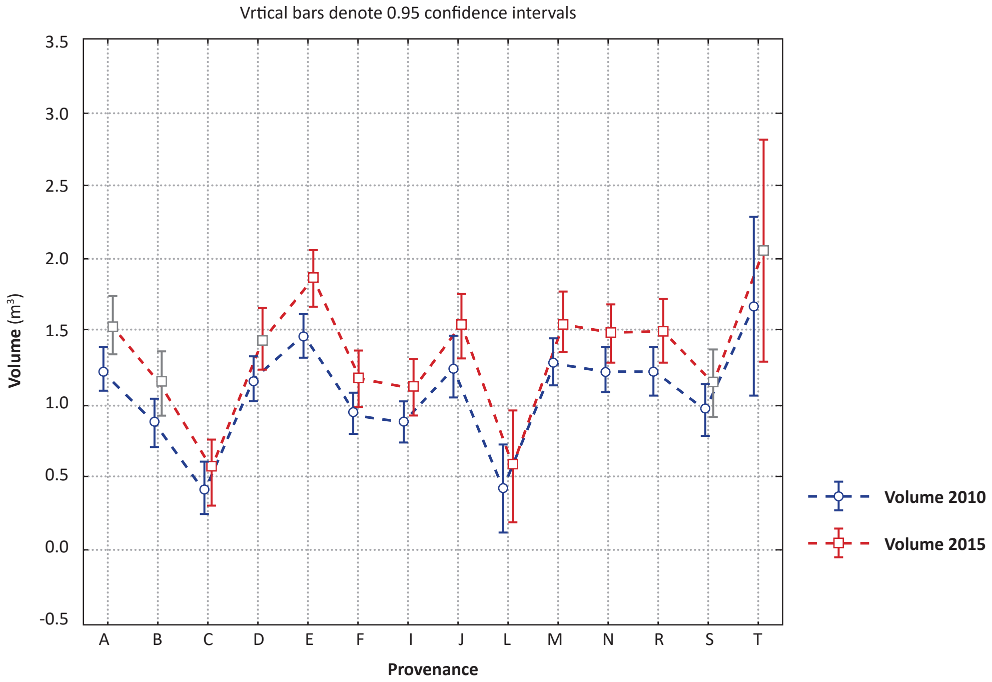

FIGURE 3. 95% confidence intervals for tree volume compared to data collected in the 41st year after planting [30] for 14 Douglas-fir provenances on Slatki potok locality. For provenance codes see Table 1.

TABLE 5. Results of ANOVA – comparison of provenances by volume on Slatki potok locality in the 41st and 46th year after planting for 14 Douglas-fir provenances.

	Sum of squares	Degrees of Freedom	Mean Square Error	F	p
Provenance	130.702	13	10.054	10.336	0.000000
Error	684.822	704	0.973		
Year	12.758	1	12.758	578.622	0.000000
Year*Provenance	1.552	13	0.119	5.415	0.000000
Error	15.523	704	0.022		

DISCUSSION AND CONCLUSIONS

Climate changes, together with the increase of society demands from forests and forestry sector, are predicted to grow constantly and fiercely in the future. The use of NNTS such as Douglas-fir has been in focus of European countries because of their higher adaptive capacities compared to limited ability of some native tree species to cope with climate changes [32]. Recently, this tree species has gained a lot of interest not only due to its high wood production, but also due to its potential use as a new silvicultural option in reforestation and afforestation activities [26]. Even though comparison with native, but highly susceptible Norway spruce was not compared in this research, initial comparative studies had proved Douglas-fir to be good choice both in the lowlands, hilly and coastal parts of the country [27, 33-37]. For Slatki potok locality, Douglas-fir trees were 148% higher, 166% thicker (based on DBH measurements) and had 477% more volume compared to Norway spruce fifteen years after planting [38]. This claim is further supported by international research. For example, in an Austrian research coastal provenances Tenino from Washington and Cascadia from Oregon showed better growth than Norway spruce [39]. Furthermore, the comparison of these two species showed better resistance of Douglas-fir seedlings to drought several years after reforestation [40]. Thus, we conclude that a wisely chosen provenance could present good solution for reforestation after Norway spruce decline, which is a pronounced problem in Croatia at the present.

First of all, the use of Douglas-fir in Croatia has already been advised for four decades, but the amount of Douglas-fir cultures is still small. Former research studies initiated hypotheses that there is a difference among provenances even in the later stages of development [41, 42]. This claim was proven by this research. The research also proved that the selection of appropriate provenances has crucial influence on growth and development of an established forest culture. This research aimed to pinpoint the most productive provenances, so different growth indicators have been used to provide a comprehensive analysis. On the basis of the obtained results, we strongly support coastal provenances, especially those from the State of Washington, for the use in practical forestry in the hilly area of Croatia. This includes Castle Rock, Elma, Pe Ell, Yelm, Tenino, and Shelton provenances from Washington. Nevertheless, provenances from Europe (Hvidilde from Denmark and Šipka from Bulgaria) also showed good productivity and are advised to be used in reforestation and afforestation activities. Castle Rock and Elma clearly distinguish themselves among all other provenances by their superior growth, which has been observed for all measured parameters. The results are supported by international research as well [43, 44]. On the other hand, we do not support provenances from Oregon and British Columbia to be used in the hilly area since they have shown poor growth results for all analysed parameters. Low values of growth parameters, especially tree volume in the case of Castle Rock and Shady Cove provenances are derived from the low number of survived trees in the trial, which is evident in all four repetitions. Already from the first years after planting strong abiotic influences caused the decline of trees of Castle Rock provenance [22]. Thus, the survival during the first years after planting is an important parameter to be taken into account.

Secondly, the survival of provenances should be considered as well. Even though the survival of tested provenances is a basic trait to assess when adaptation to climate change is considered, especially for provenances moved over long distances, it cannot provide sound conclusions in this late stage of development. The survival of individual trees is strongly influenced by silvicultural measures, which were needed in this late in tree development since the growing space was far below the needed (due to high tree dimensions). On the studied trial, thinning from below was conducted, leaving only the most suited trees from each provenance. Nevertheless, this way the survival of provenances as a basic indicator was not taken into account, leaving the published data from earlier developmental stages as the more reliable ones. Thus, the survival data were not included into the analysis. The satisfactory survival of the selected provenances based on productivity data is supported by earlier research [20, 30, 38], further highlighting the use of Washington provenances for forest culture establishment. It should also be noted that, if regarded from the aspect of survival of young generation after plating, Douglas-fir provenances growing quickly are also the ones with better quality and less prone to frost and low temperatures; conversely, the ones growing slowly are of lower quality and are more sensitive to low temperatures [22].

Finally, if research results should be applied in practical forestry, nursery production has to be harmonised with silvicultural needs in practice and should anticipate the forthcoming needs for reforestation purposes [45]. Nevertheless, the data on nursery production of Douglas-fir [45-47] show insufficient amount of produced Douglas-fir seedlings. Thus, we strongly propose to include that research results into nursery production plans locally, but on the national level as well. Regarding the significance of Norway spruce in Croatia and the scale of its decline [48, 49], it can be concluded that the use of Douglas-fir research should be continued in the hilly area, but also broadened to other areas of Croatia, especially mountain areas.

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