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Evaluation of lodgepole pine (*Pinus contorta* Dougl. ex Loudon) on a provenance plot situated in a formerly air-polluted area of the Krušné hory Mts. at the age of 34 years

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Abstract

Čáp J., Novotný P., Fulín M., Dostál J., Beran F. (2018): Evaluation of lodgepole pine (*Pinus contorta* Dougl. ex Loudon) on a provenance plot situated in a formerly air-polluted area of the Krušné hory Mts. at the age of 34 years. J. For. Sci., 64: 118–128.

The article evaluates 27 provenances of three subspecies of lodgepole pine on the Kovářská research plot (Krušné hory Mts.). The plot is part of a series of three established plots in various stand conditions. Two plots were already evaluated and the findings were published. At 34 years of age, we evaluated height, DBH, trunk shape, trunk forking, branch thickness, bark type, mortality, and defoliation. A total of 1,147 trees were measured. Above-average growth was achieved predominantly by the provenances of *Pinus contorta* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield from middle elevations. In the *Pinus contorta* subsp. *contorta* Douglas ex Loudon, only the 2099 Port Orford provenance from Oregon demonstrated favourable results, and in the *Pinus contorta* subsp. *murrayana* (Balfour) Engelmann it was 2098 Chemult. High mortality was demonstrated mainly in the *P. c.* subsp. *murrayana* provenance from high mountainous elevations in California and *P. c.* subsp. *contorta* from coastal regions of Oregon. Provenances from middle elevations had relatively lower mortality, especially *P. c.* subsp. *latifolia*. The pines usually were of good quality although this was not the case for defoliation and branch thickness. In comparing all plots of the series, growth was fastest at the Sofronka location in western Bohemia and slowest at the south Bohemian Mláka location. Only the best provenances of lodgepole pine can equal the domestic Scots pine (*Pinus sylvestris* Linnaeus).

Keywords: provenance research; geographic variability; introduction; biometric measurements; increment; climatic changes

Introduction of pines into the territory of the Czech Republic increased substantially at the turn of the 19th and 20th centuries. A disaster caused by *Lophodermium pinastri* (Schrader) Chevallier infections occurred at that time after a long period of drought, and newly established Scots pine stands were massively dying out (Kaňák 1988). Another period of increased interest occurred during the 1970s to 1990s in connection with deteriorating health of forests due to anthropogenic air pollution. Pilot plants and control areas with *Pinus contorta* Douglas ex Loudon, *Pinus banksiana* Lambert, *Pinus strobus* Linnaeus, *Pinus nigra* J.F. Arnold, and *Pinus strobiformis* Engelmann were established on clearings after salvage fellings and they were also used as substitute tree species (Kaňák 1999; Weger 1999). Certain pines were also tested on anthropogenic substrates (Kuznetsova et al. 2009). The resistance of lodgepole pine (*P. contorta*) to the effects of SO_2 was demonstrated by

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experiments established in the 1930s on the German side of the Krušné hory Mts., thereby drawing attention to possibilities of its use in places strongly affected by air pollution also on the Czech side of this mountain range (Kantor 1980). Other research on resistance to climate impacts was focused on selected provenances of lodgepole pine originating from three temperature different regions (cold, cool, and warm) in which temperature effects on radial growth were recorded (McLane et al. 2011). In North America, this pioneer tree species is valued for its rapid growth and undemanding soil requirements. It grows on poor sandy soils, on rocks, in peat bogs, in screes, in volcanic ash, and on lava fields. It extends to a considerable range also at sites of great fires, in particular in the northern part of Yellowstone National Park. In volcanic mountain ranges, it creates primary stages of forest ecosystems and its vitality is used to advantage there for eliminating the influence of climatic extremes and protecting the soil from erosion (Critchfield 1980).

Lodgepole pine occurs naturally along the Pacific coast from southern Alaska to northern Mexico. The eastern boundary of its range spans from Canada's Northwest Territories to New Mexico in the southern US (Farjon, Filer 2013). Considering the extent of this area, the species is usually divided into three allopatric subspecies (Businský 2008), sometimes considered mere varieties. *Pinus contorta* subsp. *contorta* Douglas ex Loudon is adapted to the oceanic climate, and in Central European conditions it forms low trees. *Pinus contorta* subsp. *murrayana* (Balfour) Engelmann is relatively resistant to freezing. In the Sierra Nevada, it reaches up to 3,700 m a.s.l. It is considerably deformed at that height and in that environment, however, and takes on stunted forms. *Pinus contorta* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield is characterized by a slim and straight trunk. It is of a rather continental character and it occupies the largest part of the species range (Businský, Velebil 2011).

The subject of this article is to evaluate selected quantitative and qualitative characteristics of lodgepole pine provenances on a research area in mountainous conditions of northwestern Bohemia in order to assess possibilities of its use in forestry.

MATERIAL AND METHODS

Based upon previous research activities with lodgepole pine elsewhere in the world, evaluation of the Křtiny provenance plot from the IUFRO 1969 series (Kantor 1980), and the aforementioned experiments on the German side of the Krušné hory Mts., it was decided to establish the Sofronka, Mláka, and Kovářská plots with previously unverified provenances from the range of the IUFRO 1969 experiment. These included several new provenances from British Columbia and Alberta.

Research plot No. 294 – Klášterec-Kovářská was established with 27 provenances in the spring of 1984 for the purpose of testing plantings in the conditions existing at that time of severe air pollution in the Krušné hory Mts. (Kaňák 1988). The plantation is situated at 870 m a.s.l. on a location with northeastern exposure. Mean annual temperature is 5.1°C and mean annual precipitation 814 mm. The wider surroundings of this plot are dominated by Proterozoic and Palaeozoic schists, paragneisses and orthogneisses of the Krušné hory Mts. crystalline complex. Soil type is Podzol to Cryptopodzol. The location is classified as farming type CHS 73 (farmlands of acidic stands at mountainous elevations) and forest site type 7K1 (acidic tussock grass spruce stands).

An area of 1.46 ha was divided into 27 plots in three blocks using a randomized complete block design. Plot size is 10 × 18 m, plant spacing 2 × 2 m. Originally, 45 seedlings were planted in each plot (i.e. 135 seedlings for each provenance; 3,645 seedlings in total).

The provenances of *P. c.* subsp. *contorta* represented on the research plot originate from coastal regions with elevations of 30–75 m, the provenances of *P. c.* subsp. *latifolia* from higher inland elevations, and the provenances of *P. c.* subsp. *murrayana* from higher elevations of Oregon and California in the southern part of that area (Fig. 1). The basic characteristics of the original locations are presented in Table 1, which also shows their allocation to sites defined by Forrest (1980, 1981) on the basis of analysing monoterpenes. The provenance affiliation with individual subspecies is indicated in the following text using "*c*" for *P. c.* subsp. *contorta*, "*l*" for *P. c.* subsp. *latifolia*, and "*m*" for *P. c.* subsp. *murrayana*.

Measurements were taken in September 2015 (i.e. when pines were 34 years of age). We determined both quantitative (height, diameter at breast height) and qualitative (health, trunk shape and forking, relative branch thickness, bark character) characteristics. Overbark trunk volume was calculated according to the volumetric formula for Scots pine (Petráš, Pajtík 1991) and underbark trunk volume using a formula for lodgepole pine (Cole 1971). On the basis of the latter, per-hectare stand-

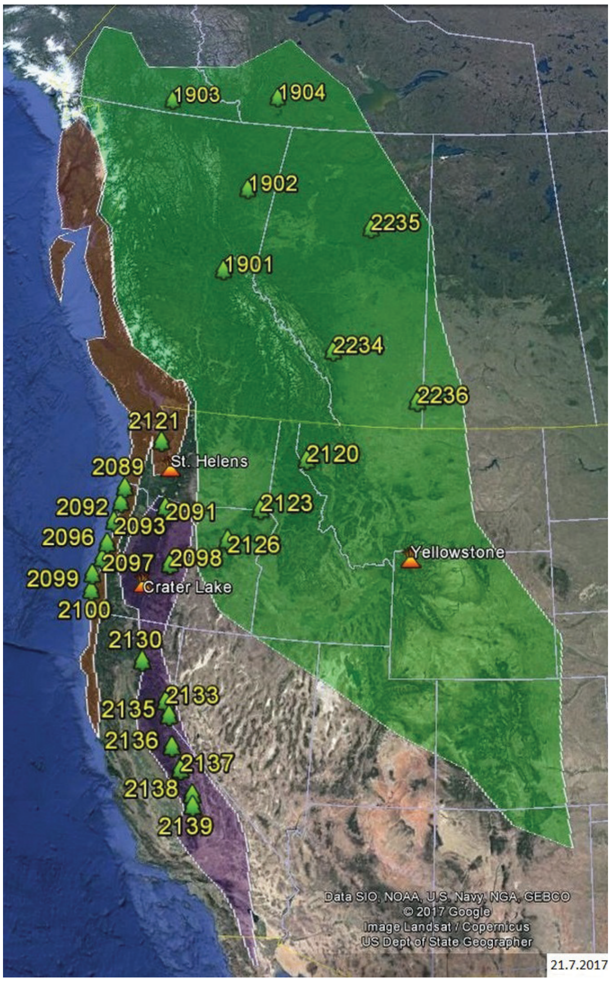


Fig. 1. Origin of provenances and their subspecies

red – *Pinus contorta* subsp. *contorta* Douglas ex Loudon, green – *Pinus contorta* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield, purple – *Pinus contorta* subsp. *murrayana* (Balfour) Engelmann, 1901 – Chetwynd, 1902 – Mile 86, 1903 – Upper Liard, 1904 – Wonowon, 2089 – Manzanita, 2091 – Mount Hood, 2092 – Pacific City, 2093 – New Port, 2096 – Carter Lake, 2097 – Hauser Dunes, 2098 – Chemult, 2099 – Port Orford, 2100 – Pistol River, 2120 – St. Regis, 2121 – Port Orchard, 2123 – Enterprise, 2126 – Prairie City, 2130 – Mineral, 2133 – Truckee, 2135 – South Lake Tahoe, 2136 – Yosemite, 2137 – Huntington Lake, 2138 – Mineral King, 2139 – Camp Nelson, 2234 – Kananaskis, 2235 – Calling Lake, 2236 – Cypress Hills

ing volume was determined. Height was measured using an ultrasound VERTEX III hypsometer (Haglöf, Sweden) to the nearest 0.1 m and DBH ($d_{1.3}$) using a millimetre calliper (Haglöf, Sweden) at two perpendicular directions (0.1 cm).

All tree qualitative characteristics were assessed according to the trunk shape (1: completely straight, 2: curved in one direction in the lower part, 3: curved in one direction along the entire trunk, 4: multiple curves, crooked), occurrence of trunk forking (1: non-forked, 2: forked in the upper third, 3: forked in the second third, 4: forked in the lower third), branch thickness (1: < 1/10 $d_{1.3}$, 2: 1/10–1/4 $d_{1.3}$, 3: > 1/4 $d_{1.3}$), and bark surface (1: smooth, 2: scaly, 3: ridged). Classification class 4 (i.e. deeply ridged bark), which was recorded in assessing the Sofronka plot from the same series (Novotný et al. 2017), did not occur on the Kovářská plot. Indices of these characteristics were calculated as averages of tree classification scores. Health was characterized as percentage of defoliation in 5% increments. Considering the absence of forestry interventions through the entire time of monitoring, mortality could also be assessed.

Survey analysis in QC.Expert (Version 3.1, 2008) did not confirm the normality of data sets for heights and DBH. Therefore Kruskal-Wallis one-way ANOVA (α = 0.05) was used and, upon rejecting the null hypothesis, a follow-up Kruskal-Wallis test of multiple comparisons in NCSS 10 (Version 10.0.6, 2015). In order to reveal the structure and links between the evaluated characteristics, we used multidimensional principal component analyses (PCA) and cluster analyses (CLU). To calculate these [STATISTICA (Version 12, 2013), PAST (Version 2.07, 2011)], the data was reduced so that the individual characteristics of the provenances were represented by their medians. Before calculating PCA and CLU (a dendrogram constructed using paired comparisons and Mahalanobis distances), the data was scaled using Z-score.

RESULTS

In the year of measurements, there were 1,147 trees growing on the plot (i.e. 31.5% of those originally planted). Mean mortality on the plot was therefore 68.5%. In the case of Oregon provenance 2100 Pistol River "*c*", mortality was 99.3%; in that of Californian 2136 Yosemite "*m*", it was 98.5%. These two provenances could not therefore be assessed due to their being represented by only one and two trees, respectively. In total, 1,144 trees were included in the calculations. High mortality was also recorded in the provenances 2138 Mineral King "*m*" (95.6%), 2099 Port Orfort "*c*" (94.8%), and 2137 Huntington Lake "*m*" (91.9%). The lowest losses were those of the provenances 2126 Prairie City "*l*" (31.9%), 1901 Chetwynd "*l*" (32.6%), and 2234 Manchester "*c*" (35.6%).

The median height for the plot as a whole was 12.9 m. The growth of the best provenances – 2091 Mount Hood "*l*", 2120 St. Regis "*l*", 2099 Port Orford

Table 1. Characteristics of verified provenances of *Pinus contorta* Douglas ex Loudon subspecies: *P. c.* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield, *P. c.* subsp. *contorta* Douglas ex Loudon, *P. c.* subsp. *murrayana* (Balfour) Engelmann

Provenance No.	Provenance name	Country	Subspecies	Monoterpenic regions*	Altitude (m a.s.l.)	North latitude	West longitude
1901	Chetwynd	British Columbia	*P. c.* subsp. *latifolia*	CI	700–1,000	55°37'	121°40'
1902	Mile 86		*P. c.* subsp. *latifolia*	CI	752–900	56°48'	121°35'
1903	Upper Liard	Yukon territory	*P. c.* subsp. *latifolia*	YU	701–761	60°05'	129°18'
1904	Wonowon	British Columbia	*P. c.* subsp. *latifolia*	CI	825–950	60°45'	121°29'
2089	Manzanita	Oregon	*P. c.* subsp. *contorta*	SC	30	45°43'	123°56'
2091	Mount Hood		*P. c.* subsp. *latifolia*	C	1,280	45°18'	121°45'
2092	Pacific City		*P. c.* subsp. *contorta*	NC	30	45°13'	123°57'
2093	New Port		*P. c.* subsp. *contorta*	SC	30	44°34'	124°04'
2096	Carter Lake		*P. c.* subsp. *contorta*	SC	30	43°50'	124°09'
2097	Hauser Dunes		*P. c.* subsp. *contorta*	SC	30	43°30'	124°14'
2098	Chemult		*P. c.* subsp. *murrayana*	C	1,675	43°19'	121°39'
2099	Port Orford		*P. c.* subsp. *contorta*	SC	30	42°46'	124°31'
2100	Pistol River		*P. c.* subsp. *contorta*	SC	30	42°15'	124°24'
2120	St. Regis	Montana	*P. c.* subsp. *latifolia*	SI	945	47°22'	115°24'
2121	Port Orchard	Washington	*P. c.* subsp. *contorta*	P	75	47°25'	122°40'
2123	Enterprise	Oregon	*P. c.* subsp. *latifolia*	RM	1,310	45°38'	117°16'
2126	Prairie City		*P. c.* subsp. *latifolia*	RM	1,490	44°32'	118°34'
2130	Mineral	California	*P. c.* subsp. *murrayana*	SN	1,490	40°21'	121°29'
2133	Truckee		*P. c.* subsp. *murrayana*	SN	1,830	39°13'	120°12'
2135	South Lake Tahoe		*P. c.* subsp. *murrayana*	SN	2,345	38°48'	119°58'
2136	Yosemite		*P. c.* subsp. *murrayana*	SN	2,405	37°51'	119°40'
2137	Huntington Lake		*P. c.* subsp. *murrayana*	SN	2,190	37°11'	119°12'
2138	Mineral King		*P. c.* subsp. *murrayana*	SN	2,410	36°27'	118°36'
2139	Camp Nelson		*P. c.* subsp. *murrayana*	SN	2,164	36°06'	118°32'
2234	Kananaskis	Alberta	*P. c.* subsp. *latifolia*	RM	1,524	51°05'	114°45'
2235	Calling Lake		*P. c.* subsp. *latifolia*	NA	1,005	55°38'	113°27'
2236	Cypress Hills		*P. c.* subsp. *latifolia*	RM	1,160	49°30'	110°15'

*Forrest (1980, 1981)

CI – Central Interior British Columbia, YU – Yukon and north British Columbia, SC – South Coastal, C – Cascades, NC – North Coastal, SI – Southern Interior British Columbia, P – Puget Sound, RM – Rocky Mountains, SN – Sierra Nevada, NA – North Alberta

"*c*", and 1901 Chetwynd "*l*" – was almost balanced (14.2, 14.0, 13.9, and 13.7 m). Notably small heights were determined in the Oregon provenances 2093 New Port "*c*" (5.2 m) and 2096 Carter Lake "*c*" (9.0 m) and in the Californian 2138 Mineral King "*m*" (9.6 m). Median heights of 9.8–12.4 m were determined also in other Oregon provenances, as well as in almost all "*m*" provenances originating from California (Table 2, Fig. 2).

Median DBH of all provenances was 17.2 cm. The lowest values were exhibited by the Oregon provenances 2097 Hauser Dunes "*c*" (10.8 cm), 2093 New Port "*c*" (10.8 cm), and 2096 Carter Lake "*c*" (11.5 cm), whereas the highest were recorded for 2091 Mount Hood "*l*" (21.1 cm), 2133 Truckee "*m*" (20.6 cm), and 2099 Port Orford "*c*" (19.6 cm).

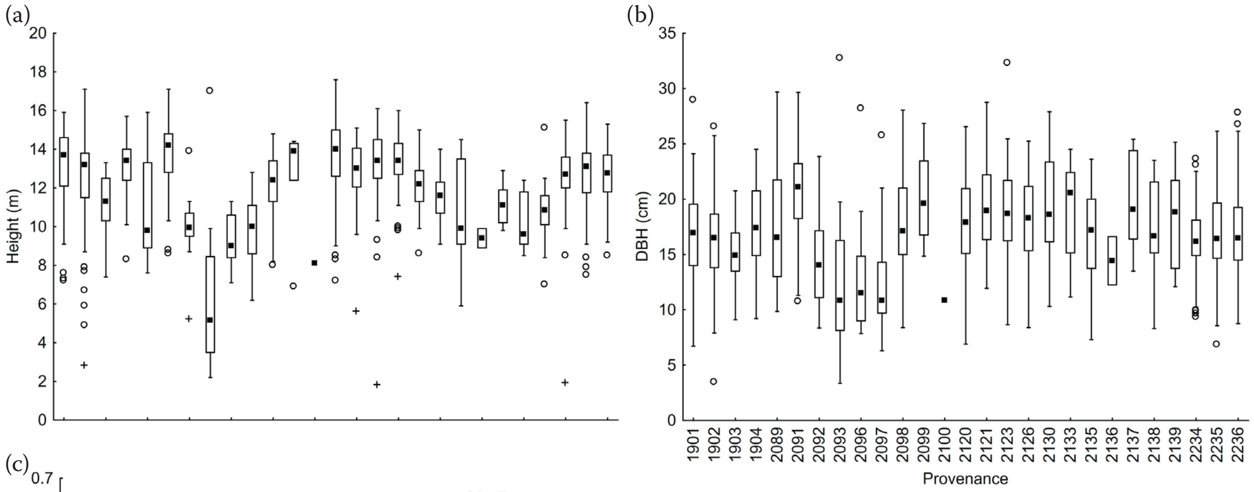
Trunk volumes calculated using formulas for Scots pine and lodgepole pine were practically identical. The highest values of underbark trunk volume established using the formula for lodgepole pine were found in the Oregon provenance 2091 Mount Hood "*l*" (0.203 m^3), California's 2133 Truckee "*m*" (0.175 m^3), and Oregon's 2123 Enterprise "*l*" (0.153 m^3). The lowest volumes were determined in Oregon provenances, including an extreme case (0.017 m^3) in 2093 New Port "*c*" (Table 2, Fig. 2).

The highest standing volumes were achieved by 2126 Prairie City "*l*" (262 $m^3 \cdot ha^{-1}$), 2123 Enterprise "*l*" (253 $m^3 \cdot ha^{-1}$), and 2091 Mount Hood "*l*" (241 $m^3 \cdot ha^{-1}$). The lowest standing volumes, apart from the almost extinct 2100 Pistol River "*c*" (1 $m^3 \cdot ha^{-1}$) and 2136 Yosemite "*m*" (3 $m^3 \cdot ha^{-1}$), were

Table 2. Results of investigated characteristics of individual provenances (age 34 years)

Provenance	No. of seedlings	No. of growing individuals	Mortality (%)	Median				Stand yield** ($m^3 \cdot ha^{-1}$)	Defoliation (%)	Index			
				height (m)	$d_{1.3}$ (cm)	stem volume* (m^3)	stem volume** (m^3)			trunk form	trunk forking	branch thickness	bark type
1901	135	91	32.6	13.7	16.0	0.127	0.123	229	32.4	1.473	1.077	2.098	1.824
1902	135	69	48.9	13.2	16.5	0.116	0.112	156	46.7	1.652	1.188	1.942	1.739
1903	135	30	77.8	11.3	14.9	0.089	0.085	51	49.2	1.467	1.133	1.933	1.800
1904	135	67	50.4	13.4	17.4	0.141	0.138	178	44.0	1.463	1.194	1.940	1.731
2089	135	26	80.7	9.8	16.5	0.092	0.090	70	59.8	1.269	1.192	2.769	2.077
2091	135	62	54.1	14.2	21.1	0.203	0.202	241	32.4	1.581	1.290	2.242	1.855
2092	135	14	89.6	10.0	14.0	0.067	0.064	21	41.4	1.857	1.214	2.643	2.143
2093	135	12	91.1	5.2	10.8	0.017	0.016	18	44.6	2.083	1.083	2.083	2.083
2096	135	23	83.0	9.0	11.5	0.051	0.047	27	47.2	1.652	1.130	2.000	1.609
2097	135	18	86.7	10.0	10.8	0.040	0.037	24	58.6	1.833	1.111	2.444	2.167
2098	135	86	36.3	12.4	17.1	0.120	0.117	226	52.4	1.442	1.302	2.326	1.756
2099	135	7	94.8	13.9	19.6	0.146	0.142	23	47.9	1.429	1.286	2.429	1.714
2100	135	1	99.3	8.1	10.9	0.035	0.033	1	80.0	1.000	1.000	3.000	2.000
2120	135	77	43.0	14.0	17.9	0.151	0.147	225	44.8	1.532	1.169	2.195	1.896
2121	135	36	73.3	13.0	19.0	0.152	0.15	113	26.0	2.250	1.278	2.250	2.722
2123	135	85	37.0	13.4	18.7	0.153	0.150	253	57.5	1.835	1.271	2.282	2.106
2126	135	92	31.9	13.4	18.3	0.152	0.149	262	45.8	1.326	1.207	2.174	1.620
2130	135	34	74.8	12.2	18.6	0.147	0.144	106	56.2	1.294	1.000	2.206	1.971
2133	135	13	90.4	11.6	20.6	0.175	0.174	37	76.5	1.615	1.231	2.231	2.000
2135	135	18	86.7	9.9	17.2	0.010	0.097	37	62.5	1.833	1.167	2.333	2.167
2136	135	2	98.5	9.4	14.4	0.072	0.069	3	90.0	1.500	1.000	2.000	2.000
2137	135	11	91.9	11.1	19.1	0.149	0.147	31	70.9	1.545	1.545	2.273	2.182
2138	135	6	95.6	9.6	16.7	0.091	0.089	13	87.5	1.500	1.500	2.333	1.667
2139	135	18	86.7	10.9	18.8	0.135	0.133	44	68.9	1.444	1.222	2.278	2.278
2234	135	87	35.6	12.7	16.2	0.115	0.112	190	42.1	1.333	1.172	2.092	1.862
2235	135	80	40.7	13.1	16.4	0.127	0.123	194	42.2	1.563	1.100	2.088	1.838
2236	135	82	39.3	12.8	16.5	0.119	0.116	197	49.4	1.890	1.110	2.268	1.988
Σ/mean	3,645	1,147	68.5	12.9	17.2	0.129	0.125	110	46.8	1.573	1.186	2.184	1.897

$d_{1.3}$ – DBH, *according to the volume equation for Scots pine (overbark) (Petráš, Pajtík 1991), **according to the volume equation for lodgepole pine (underbark) (Cole 1971), for details see Table 1



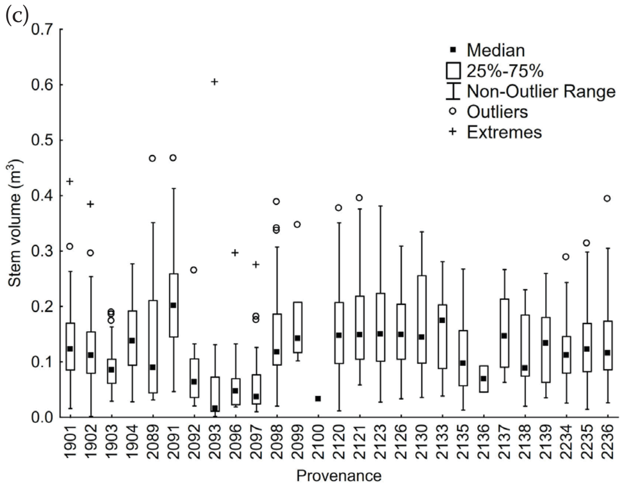


Fig. 2. Box plots for height (a), DBH (b), and stem volume (c) – STATISTICA (Version 12, 2013), stem volumes were calculated according to Cole (1971)

1901 – Chetwynd, 1902 – Mile 86, 1903 – Upper Liard, 1904 – Wonowon, 2089 – Manzanita, 2091 – Mount Hood, 2092 – Pacific City, 2093 – New Port, 2096 – Carter Lake, 2097 – Hauser Dunes, 2098 – Chemult, 2099 – Port Orford, 2100 – Pistol River, 2120 – St. Regis, 2121 – Port Orchard, 2123 – Enterprise, 2126 – Prairie City, 2130 – Mineral, 2133 – Truckee, 2135 – South Lake Tahoe, 2136 – Yosemite, 2137 – Huntington Lake, 2138 – Mineral King, 2139 – Camp Nelson, 2234 – Kananaskis, 2235 – Calling Lake, 2236 – Cypress Hills

reached by provenances 2138 Mineral King "*m*" (13 $m^3 \cdot ha^{-1}$) and 2093 New Port "*c*" (18 $m^3 \cdot ha^{-1}$).

Most trunks were straight or slightly curved; more deformed trunks were rather exceptional (e.g. 2121 Port Orchard "*c*" and 2093 New Port "*c*"). Mean value of the trunk shape index for the entire plot was 1.573 (Table 2). Mean value of the trunk forking index was 1.186, meaning that most trunks are not forked. Mean branch thickness index was 2.184. Bark type index had a mean value of 1.897, which is the closest value to scaly bark. Mean defoliation was 46.8%. The most vital provenances were 2121 Port Orchard "*c*" (26%) along with 1901 Chetwynd "*l*" and 2091 Mount Hood "*l*" (both 32.4%). On the other hand, the 2138 Mineral King "*m*" (87.5%) and 2100 Pistol River "*c*" (80.0%) provenances had the greatest foliage loss.

No provenances were identified as demonstrating simultaneously high production and quality. At the same time, however, no provenances simultaneously demonstrated decidedly slow growth and low quality.

Breaking out by subspecies, significant differences were determined in DBH, height, and trunk volume. In terms of height, the "*l*" subspecies ranked the best (median 13.2 m), followed by "*m*" (12.3 m) and "*c*" (10.5 m). A different order was recorded for diameter at breast height and trunk volume, when the highest-ranking subspecies "*m*" (18.6 cm, 0.143 m^3) was followed by "*l*" (17.1 cm, 0.126 m^3) and "*c*" (15.4 cm, 0.089 m^3). The ranking in mortality rate was "*l*" (44.6%), "*m*" (82.6%), and "*c*" (87.3%).

Significant differences were determined also between monoterpenic sites. The descending order of sites according to median values for height was Southern Interior British Columbia – SI, Central Interior British Columbia – CI, North Alberta – NA, Rocky Mountains – RM, Cascades – C, Puget Sound – P, Sierra Nevada – SN, Yukon and north British Columbia – YU, North Coastal – NC, and South Coastal – SC; for DBH it was P, C, SN, SI, RM, CI, NA, YU, NC, and SC; and for trunk volume C, P, SI, SN, RM, CI, NA, YU, NC, and SC.

To explain the variability in data using PCA (Fig. 3), height, DBH, and bark type are the most important characteristics, followed by trunk shape and branch thickness. Four groups took shape among the tested provenances based upon similarity of evaluated characteristics (Figs 3–4) (1: 2130, 2133, 2137, 2138, 2139; 2: 2123, 2135, 2236; 3: 2089, 2099; and 4: others). There were also five independent provenances (2091, 2092, 2093, 2097,

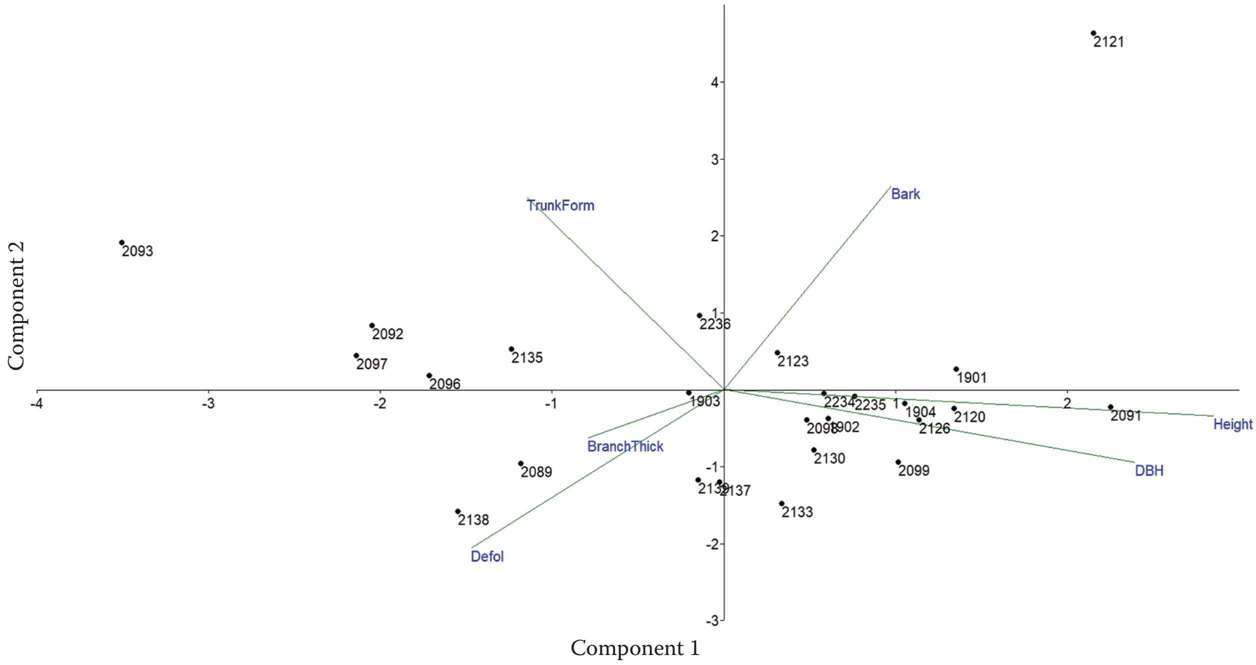


Fig. 3. Results of multidimensional principal component analysis. The biplot compares objects and traits in the dimension of main components 1 and 2 – PAST (Version 2.07, 2011)

1901 – Chetwynd, 1902 – Mile 86, 1903 – Upper Liard, 1904 – Wonowon, 2089 – Manzanita, 2091 – Mount Hood, 2092 – Pacific City, 2093 – New Port, 2096 – Carter Lake, 2097 – Hauser Dunes, 2098 – Chemult, 2099 – Port Orford, 2100 – Pistol River, 2120 – St. Regis, 2121 – Port Orchard, 2123 – Enterprise, 2126 – Prairie City, 2130 – Mineral, 2133 – Truckee, 2135 – South Lake Tahoe, 2136 – Yosemite, 2137 – Huntington Lake, 2138 – Mineral King, 2139 – Camp Nelson, 2234 – Kananaskis, 2235 – Calling Lake, 2236 – Cypress Hills

and 2121). The cophenetic correlation coefficient in calculating CLU was 0.917. In the dendrogram (Fig. 4), the individual subspecies were relatively well separated, with "*c*" creating a common cluster that included all but the 2096 and 2121 provenances. Only three provenances (2091, 2123, and 2236) were not included in the common cluster of the "*l*" subspecies. The cluster of the "*m*" subspecies included all but two provenances (2098 and 2135), whose indicators were therefore closer to those of the "*l*" group.

DISCUSSION

The Kovářská research plot was previously evaluated eight times, and therefore the provenances at 34 years of age can be compared with data from past measurements (Kaňák 1996, 2001). Height growth can be observed from the age of 3 years (Fig. 5), at which time seedling height in a tree nursery had been measured before the planting of the experimental series. After the planting was established, rapidly and slowly growing provenances could be differentiated after mere 6 years. Larger changes in the rank occurred between 15 and 19 years of age, and this was repeated at 34 years. At this age, the pines are beyond the culmination of their growth increment. Above-average heights are currently demonstrated predominantly by "*l*" provenances from middle elevations. In the "*c*" subspecies, the only favourable data was from the Oregon provenance 2099 Port Orford. As for "*m*" subspecies none reached average. Above-average growth of the 2099 provenance can be explained by its having rather large growing space due to high mortality.

According to the growth tables (Černý et al. 1996), the two best provenances, 2126 Prairie City "*l*" and 2123 Enterprise "*l*", with the standing volume of 262 and 253 $m^3 \cdot ha^{-1}$, respectively, corresponded to the fourth relative yield class of Scots pine. Although Kantor (1980) mentioned experience in Norway with achieving mature stands of lodgepole pine even without management, in the case of conventional forestry, interventions would undoubtedly have occurred in a stand of such age and the values of growth indicators would be relatively higher. Only the best provenances of lodgepole pine equal the local Scots pine in growth characteristics, both in acidic spruce stands and on poor sands (Fulín et al. 2017) or in conditions

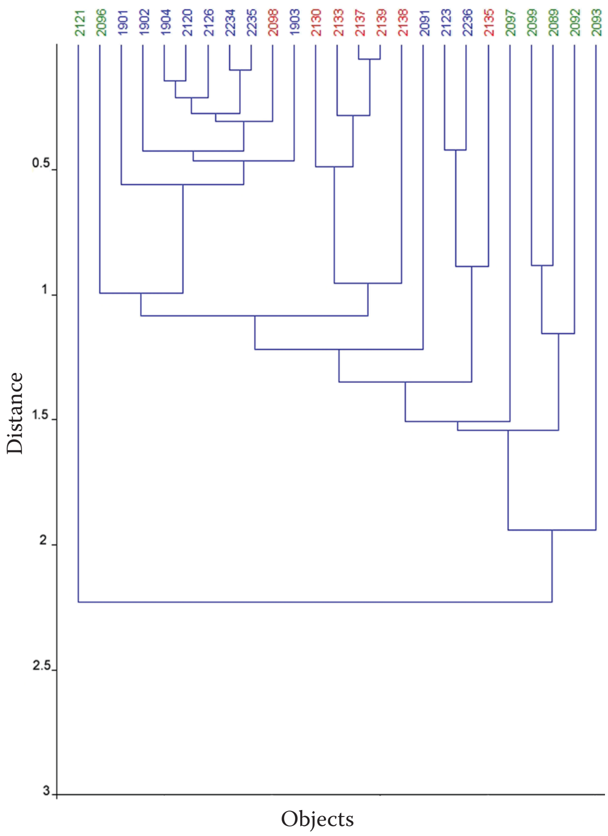


Fig. 4. Output of cluster analysis – PAST (Version 2.07, 2011) green – *Pinus contorta* subsp. *contorta* Douglas ex Loudon, red – *Pinus contorta* subsp. *murrayana* (Balfour) Engelmann, blue – *Pinus contorta* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield, 1901 – Chetwynd, 1902 – Mile 86, 1903 – Upper Liard, 1904 – Wonowon, 2089 – Manzanita, 2091 – Mount Hood, 2092 – Pacific City, 2093 – New Port, 2096 – Carter Lake, 2097 – Hauser Dunes, 2098 – Chemult, 2099 – Port Orford, 2100 – Pistol River, 2120 – St. Regis, 2121 – Port Orchard, 2123 – Enterprise, 2126 – Prairie City, 2130 – Mineral, 2133 – Truckee, 2135 – South Lake Tahoe, 2136 – Yosemite, 2137 – Huntington Lake, 2138 – Mineral King, 2139 – Camp Nelson, 2234 – Kananaskis, 2235 – Calling Lake, 2236 – Cypress Hills

of beech-oak stand (Kantor 1980). Quite different results, however, emerged from comparative research with Scots pine and Norway spruce on a series of research plots in Germany (Rohmeder, Meyer 1952). In that case, at 23 years of age, lodgepole pine unequivocally outgrew both domestic species. The reported conclusions suggest the rapid early growth of this species, which was presumed by Kaňák (1996) to continue until 25 years of age and to be followed by slowing down thereafter. According to annual height increments calculated through the entire time of monitoring, it seems that on the Kovářská plot height increment culminated in *P. c.* subsp. *contorta* and *P. c.* subsp. *latifolia* already between the ages of 15 and 19 years, whereas in *P. c.* subsp. *murrayana* it has not probably occurred yet.

Assessing the suitability of growing an introduced species cannot be based solely on evaluating its growth characteristics. It is necessary also to consider the responses to the biotic and abiotic ecological conditions at the planting site. Similarly to other pines (Podrázský 2006), the influence of *P. contorta* on soil characteristics is poorer in comparison with Norway spruce. Another shortcoming is strong damage by hoofed game, snow, ice, frost, and wind (Balcar et al. 2008). In the Krušné hory Mts., the use of coastal and high-elevation mountainous provenances is limited primarily by drought and freezing damage in the first years after planting (Stephan 1980). High mortality on the Kovářská plot affected predominantly the "*m*" provenances from mountainous elevations in California and "*c*" provenances from coastal Oregon. Provenances of middle elevations (825–1,490 m a.s.l.) with the greatest proportion of subspecies "*l*" had relatively low mortality ranging from 31.9% (Oregon 2126 "*c*") to 50.4% (1904 "*l*" from British Columbia). The rate of mortality, however, does not result solely from the influence of provenance, as damage by animals also contributes to it.

Further comparison is possible using the results available from evaluations of the Mláka and Sofronka research plots of the same series at the identical age of 34 years (Fulín et al. 2017; Novotný et al. 2017). Provenances at the Sofronka location excelled in height growth, and 12 of them in total exceed the tallest provenance 2091 Mount Hood "*l*" at the Kovářská plot. The lowest heights were found at the Mláka location. Trunk volume was the greatest at Sofronka again and the least at Mláka. Provenances at the Kovářská plot are ranked best in most qualitative features (trunk shape, trunk forking, and bark type), and especially those of the "*l*" subspecies. On the other hand, values at the Krušné hory Mts. plot are the poorest for vitality as expressed by defoliation and branch thickness. There, similarly to the Sofronka plot, the greatest defoliation was detected in high-elevation mountainous provenances of the "*m*" subspecies and in the Oregon provenance 2100 Pistol River "*c*". The CLU result (Fig. 4) expressing clustering of provenances based on combinations of values of the determined quantitative and qualitative characteristics documents that the individual subspecies can be relatively well distinguished by phenotypic expression. This is true especially of the "*c*" subspecies, which was well distinguished also at the Sofronka and Mláka plots, whereas the analyses

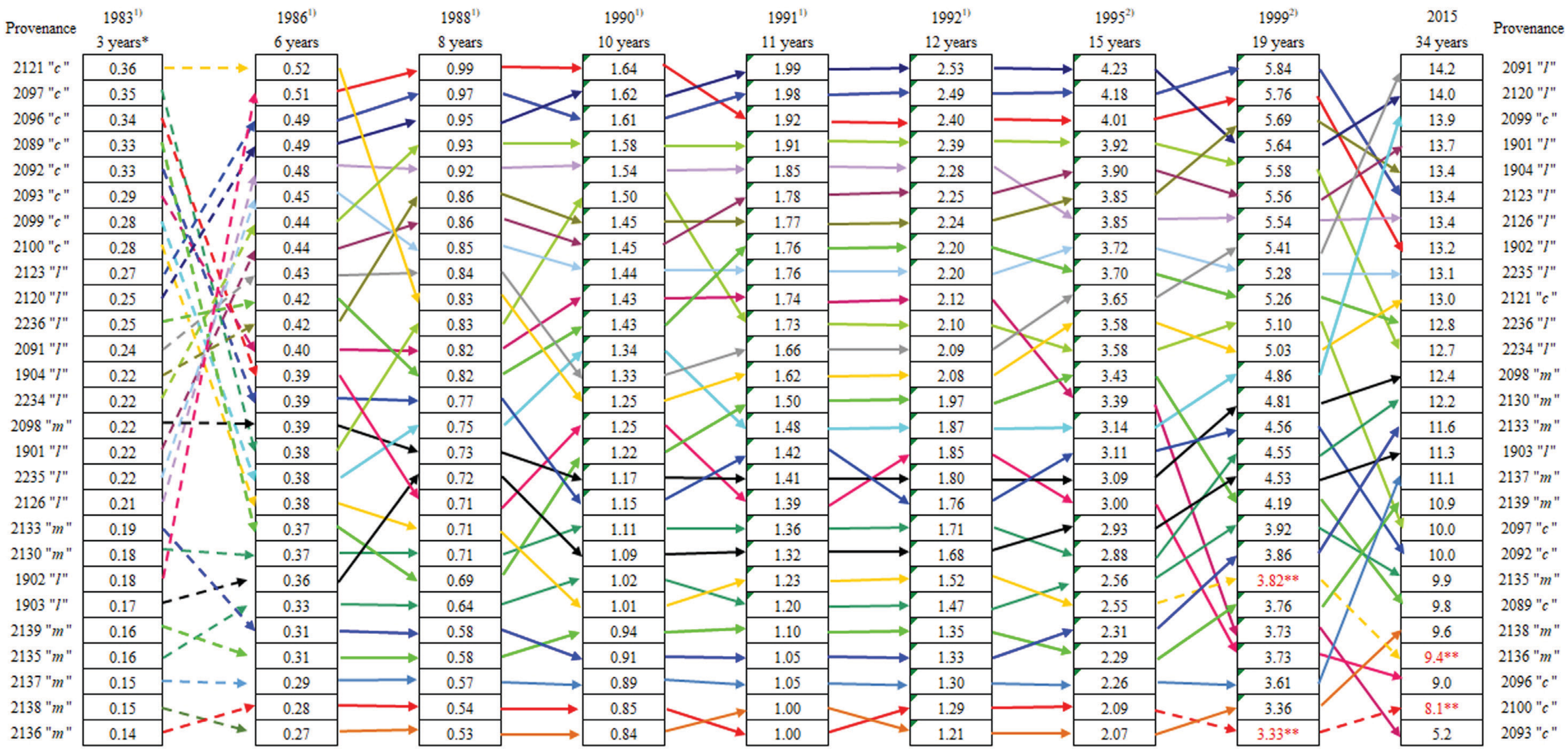


Fig. 5. Development of height growth of provenances

1901 – Chetwynd, 1902 – Mile 86, 1903 – Upper Liard, 1904 – Wonowon, 2089 – Manzanita, 2091 – Mount Hood, 2092 – Pacific City, 2093 – New Port, 2096 – Carter Lake, 2097 – Hauser Dunes, 2098 – Chemult, 2099 – Port Orford, 2100 – Pistol River, 2120 – St. Regis, 2121 – Port Orchard, 2123 – Enterprise, 2126 – Prairie City, 2130 – Mineral, 2133 – Truckee, 2135 – South Lake Tahoe, 2136 – Yosemite, 2137 – Huntington Lake, 2138 – Mineral King, 2139 – Camp Nelson, 2234 – Kananaskis, 2235 – Calling Lake, 2236 – Cypress Hills, "*c*" – *Pinus contorta* subsp. *contorta* Douglas ex Loudon, "*l*" – *Pinus contorta* subsp. *latifolia* (Engelmann ex S. Watson) Critchfield, "*m*" – *Pinus contorta* subsp. *murrayana* (Balfour) Engelmann, [1)]Kaňák (1996), *height of seedlings in a nursery before planting onto research plots, [2)]Kaňák (2001), **very high mortality, data not evaluated show the "*l*" and "*m*" subspecies to be phenotypically closer.

In comparing production from the aspect of monoterpenic sites (Forrest 1980, 1981) at the Mláka (C, CI, and NA), Sofronka (P, SC, NC, and SI), and Kovářská (C, P, and SI) research plots, the best verified site at the Kovářská plot corresponds to the Mláka location, followed by sites identical to the Sofronka plot (Fulín et al. 2017; Novotný et al. 2017). The best provenances on the Sofronka plot therefore originated from coastal regions, with the exception of one provenance from an inland monoterpenic site (SI). On the other hand, the best provenances at the Mláka location originate from the Cascade Range (C) and continue through the central inland region of British Columbia (CI) to northern Alberta (NA). At the Kovářská plot, provenances from the compact zone of the Cascades, Puget Sound (P), and southern inlands of British Columbia (SI) fared the best.

On the German side of the Krušné hory Mts., mean lodgepole pine heights of 10.0, 11.3, and 13.0 m were determined at 32 years of age at the Adorf, Hundhübel, and Steinbach research plots, respectively (Meyer 1963). These values are comparable with those of the Kovářská plot at 34 years of age (12.9 m).

After 15 years under evaluation at a series of 6 experimental plots in Germany involving 11 provenances of *P. contorta* (Stephan 1976), the coastal provenances "*c*" and several inland "*l*" provenances proved to be the best. Provenances of the "*l*" subspecies from further inland had about average growth and inland "*m*" provenances were unsatisfactory. In another German series of 8 plots by IUFRO with 140 provenances of lodgepole pine (Stephan 1980), after 8 years the "*c*" provenances from the coasts of Oregon, Washington, and southern British Columbia again grew the best along with certain inland "*l*" provenances from the south and centre of British Columbia. Provenances from the north of British Columbia, Alberta, Yukon, and Alaska grew unsatisfactorily, as did the mountain provenances of the "*m*" subspecies. Even though ecological conditions on German plots are different, the above-average growth of inland "*l*" provenances matches the results at the Kovářská location.

Results from Finland and Norway at ages of 8 and 11 years, respectively, are also available (Hahl 1978; Skrøppa, Dietrichson 1978). In those conditions, height growth was the greatest especially in "*l*" provenances from 54–56°N in inland British Columbia and Alberta. Positively evaluated regions, therefore, also nearly match the results from the mountain conditions at the Kovářská plot, where "*l*" provenances from Oregon, Montana, and British Columbia and "*c*" provenances from coastal Oregon grew the best.

Differences were observed also in evaluating a series of provenance plots in the Czech Republic. Acidic oak stands at the Sofronka location (Novotný et al. 2017) are the most suitable for provenances of the "*c*" subspecies from the coasts of Washington, Oregon, and California, whereas the conditions of a poor pine stand at the Mláka location (Fulín et al. 2017) suited the Oregon provenances of the "*c*" and "*l*" subspecies. The distinct acidic spruce stand at the Kovářská location was again, however, the best suited to the "*l*" provenances from Oregon. Successful cultivation of lodgepole pine, therefore, requires an analysis of the natural conditions at the planting site and subsequent selection of the most suitable provenance.

CONCLUSIONS

Above-average height was achieved predominantly by provenances of *P. c.* subsp. *latifolia* from middle elevations. From the *P. c.* subsp. *contorta* subspecies, only the Oregon provenance 2099 Port Orford was shown to be favourable; and from the *P. c.* subsp. *murrayana* subspecies, none reached average. High mortality was confirmed mainly in the provenances of *P. c.* subsp. *murrayana* from high-elevation mountainous conditions in California and *P. c.* subsp. *contorta* from coastal areas of Oregon. Provenances from middle elevations had relatively lower mortality, especially *P. c.* subsp. *latifolia*. The provenances, and especially *P. c.* subsp. *latifolia*, usually were of good quality (trunk shape, trunk forking, bark type), although this was not the case for defoliation and branch thickness.

As opposed to poor and dry stands, the best provenances at 34 years of age in the Krušné hory Mts. appeared to be those of the subspecies *P. c.* subsp. *latifolia* from inland Oregon. In comparing all three plots of the experimental series, the highest values of growth indicators were shown by selected provenances on sites of an acidophilic oak stand at the Sofronka location in western Bohemia and the lowest in the conditions of a poor pine stand at the south Bohemian location Mláka. Better quality (trunk shape, trunk forking, bark type) was achieved in the mountains. This, however, did not apply to defoliation (vitality) and branch thickness. We identified no provenances that would excel both in exceptional production and in quality. Heights of lodgepole pine achieved in the Krušné hory Mts. are comparable with those from geographically similar areas abroad. Only the best provenances of lodgepole pine can match the production of the domestic Scots pine. Its use can therefore be considered only on specific sites where domestic species fail. Very important is to select a suitable provenance that can fulfil all the required functions in the given conditions.

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