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Production potential and structural variability of pine stands in the Czech Republic: Scots pine (*Pinus sylvestris* L.) vs. introduced pines – case study and problem review

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Abstract: Scots pine (*Pinus sylvestris L.*) is one of the most important tree species in Eurasia. During the past centuries, it has been extensively introduced into artificial monocultures, but is currently experiencing a number of problems related to climate change and extreme droughts. There is a large-scale disintegration of its stands and, in addition to its replacement by other native trees, it is possible to use a wide range of introduced species of the same genus. The aim of the investigation was to compare production parameters, structure and diversity of pine stands at the age of 35 years in school Arboretum of Faculty of Forestry and Wood Science in Central Bohemia (320 m a.s.l., medium rich habitats, water deficit site). Seven species of pine were compared: ponderosa pine (*Pinus ponderosa* Douglas ex C. Hawson), Jeffrey pine (*Pinus jeffreyi* Balf.), black pine (*Pinus nigra* J.F.Arnold), eastern white pine (*Pinus strobus* L.), Lodgepole pine (*Pinus contorta* Douglas), Macedonian pine (*Pinus peuce* Griseb.) and the only native Scots pine. The results showed that significantly ($P < 0.001$) highest height, diameter at breast height and mean stem volume were achieved in *Pinus ponderosa* and *P. strobus* stands, while these parameters were lowest in *P. peuce* and *P. nigra*. In contrast, the lowest stand volume was calculated for *P. strobus* (112 $m^3 \cdot ha^{-1}$) due to the lower stand density, while the highest production was again in *P. ponderosa* (430 $m^3 \cdot ha^{-1}$). In terms of structural variability, the highest diversity was found in *P. jeffreyi* and *P. peuce*. The introduced pine species, especially *P. ponderosa*, could therefore play an important role in terms of production and economic potential and even replace native *P. sylvestris* on suitable sites.

Keywords: introduction; forest structure; biodiversity; timber production; Central Europe

The introduction of *Pinus* species in Bohemia and Moravia began more than 200 years ago (Businský, Velebil 2011). Initially, the main reason was the use of these species in chateau parks (Hieke 1984; Brusinský 2004), but later the economic aspect and the effort to increase forest yields by using highly productive introduced species prevailed (Poleno et al. 2009). A notable increase in introduction occurred especially at the turn of the 19th and 20th centuries, when a long dry period caused a calamity in forests (Nožička 1957; Stolina et al. 1985). The oldest stands or their fragments from this period are mainly American species of pine like eastern white pine (*Pinus strobus* L.), jack pine (*Pinus banksiana* Lamb.), sometimes also pitch pine (*Pinus rigida* Mill.); of European species mainly black pine (*Pinus nigra* J.F.Arnold) and Macedonian pine (*Pinus peuce* Griseb.) (Kaňák

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2004). Another period of increased interest in the introduction of forest tree species was associated mainly with the problems of air pollution in the 1970s to 1990s (Šika 1976; Šindelář 1979; Kaňák 1987, 1988, 1999; Podrázský 2006), and also with sites anthropogenically affected in other ways (Weger 1999). In relation to global climate change in the last decades, there is also a great interest in the introduction of promising pine species (Čáp et al. 2018), as in our case, for example, in the Arboretum of the Faculty of Forestry and Wood Sciences. This fact is enhanced by the higher susceptibility of trees to drought stress due to the southern exposure and the drying soil of the Arboretum. Many species of introduced pines grow in natural conditions on localities, which are characterized only by seasonal (winter) offer of moisture. Such pines are therefore generally adapted to overcome long periods of summer drought (Hereş et al. 2012).

Furthermore, the phylogenetic relationships of many species or groups of pines have not been resolved (Parks et al. 2009), so there is little knowledge of the structure, growth and production of various pines in Europe (Kaňák 1999, 2004; Brusinský, Velebil 2011; Álvarez-Alvarez et al. 2018). In addition, these missing findings in the face of ongoing climate change (warming, climate extremes, long-term droughts, uneven precipitation) (Vacek et al. 2019a; Gallo et al. 2020a), with large-scale declines of coniferous stands (predominantly Norway spruce, also Scots pine) are gaining importance (Vacek et al. 2016; Hlásný et al. 2017; Netherer et al. 2019). Only in the Czech Republic in 2019, due to climate change and subsequent secondary bark beetle calamity, losses in the forestry sector reached EUR 1.12 billion (Toth et al. 2020). In addition, pine trees are relatively well adapted to stress drought compared to other tree species (Seidel et al. 2016; Vítámvás et al. 2019; Vacek et al. 2019b). Therefore, in these changing conditions, great attention is being paid to the cultivation of various pine species, especially in areas with limited rainfall (Balbinot et al. 2008; Rigueiro-Rodríguez et al. 2012; Lima et al. 2016; Alvarez-Alvarez et al. 2018; Bílek et al. 2018). The changing precipitation regime in Central Europe also plays a role, in particular the greater proportion and importance of winter rainfall, which corresponds to a number of natural habitats dominated by *Pinus* species. Given the origin and some of the positive features reported in the literature, not only the cultivated Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) or the black pine, could thus represent a prospective "substitute" tree for use in forestry (Bartoš, Kacálek 2011; Novotný et al. 2012; Podrázský et al. 2013; Mondek, Baláš 2019).

Despite limited number and extent of suitable stands of genus *Pine* in the Czech forests, the evaluation of existing plantations can give enough evidence for further research and practice aims. The aim of the presented paper is so to evaluate prosperity, vitality and production parameters of the plantations in the Arboretum of Faculty of Forestry and Wood Sciences and indicate the promising species. For these reasons, we tried to evaluate the production potential and structural variability of 7 species of Eurasian and American pine species in the conditions of Central Europe and a specific representative habitat (Central Bohemia - Arboretum in Kostelec nad Černými lesy). The hypothesis beyond is that there are species of the respective genus able to replace at defined conditions the decrease in pine wood production of *Pinus silvestris*, expected in the future.

MATERIAL AND METHODS

Study site. The arboretum is located 3 km north of Kostelec nad Černými lesy, at elevation of 300 to 345 m a.s.l. on a south-exposed slope. The geographical coordinates of the location are 14°51'easting and 50°01' northing. The soil base is Permian and Cretaceous sandstone with the occurrence of oligotrophic modal cambisol. From the typological point of view, it is the acidic beech oak (*Fageto-Quercetum acidophilum*) and the plant association *Luzulo albidae-Quercetum petraeae* Hilitzer 1932. Due to its southern exposure and drying-up soils, the arboretum site is quite dry with numerous droughts, especially in recent years. It is therefore a suitable model area for the research of various types of pines. According to the nearby weather station Kostelec - Truba (368 m a.s.l.), the average annual temperature was 8.14 °C (average temperature in January is –1.92 °C and in July 17.81 °C) and the average annual rainfall is 663 mm.

Data collection. The following 7 species of pines were evaluated in the stands at age 35 (measured in February 2020): ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), Jeffrey pine (*Pinus jeffreyi* Balf.), black pine (*Pinus nigra* J.F. Arnold), white pine (*Pinus strobus* L.), spotted Pine (*Pinus contorta* Douglas), Macedonian pine (*Pinus peuce*

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Griseb.) and the only one native Scots pine (*Pinus sylvestris* L.). Each variant/tree species was evaluated on an area of 500 m^2 in a 2 × 2 m tree spacing, i.e. in density of 2 500 trees·ha^{-1}. For individual tree species, tree height, green crown height, crown width and DBH were measured. The diameters were measured with a Blue Mantax metal caliper (Haglöf, Sweden) to an accuracy of 1 mm in two perpendicular directions and height using a Vertex laser hypsometer (Haglöf, Sweden) to an accuracy of 0.5 m.

Data analysis. From the measured dendrometric data, the following stand characteristics were calculated for each stand in the software SIBYLA Triquetra 10 (Fabrika, Ďurský 2005): mean DBH, mean stand height, stand volume per ha, number of trees per hectare, basal area, slenderness quotient, stand density index, total mean increment. The volume of trees was calculated according to the volume equations published in Petráš, Pajtík (1991). As a standard, the volume of the debarked timber to the top above 7 cm of diameter is used to assess the stand production.

In terms of evaluating stand structure and diversity, the DBH and height differentiation (Füldner 1995), Arten-profile index (Pretzsch 2006), vertical structure, crown differentiation and total stand diversity index (Jaehne, Dohrenbusch 1997) were calculated for each plot. The criteria of structural and complex indices are summarized in Table 1.

The differences between individual tree species in terms of production and structure were tested in STATISTICA 12 (StatSoft) using analysis of variance (ANOVA) and Tukey HSD test. Statistically significant data were recorded as follows: $P > 0.05$, $P < 0.05$, $P < 0.01$ and $P < 0.001$. The analysis of the main components (PCA) was performed in CANOCO 5 program (Šmilauer, Lepš 2014) to evaluate the relationship between production, structure and diversity of individual tree species. Data were log-transformed and standardized before analysis. The results of multidimensional PCA analysis were visualized in the form of ordination diagram.

RESULTS

Production and structure

Significantly ($F_{(6, 212)} = 31.0$, $P < 0.001$) higher mean DBH was found in *Pinus ponderosa* (37.0 cm) and *P. strobus* (31.8 cm) compared to *P. peuce* (20.6 cm; Table 2). Similarly, significantly ($F_{(6, 212)} = 27.4$, $P < 0.001$) higher mean height was found in *P. ponderosa* (18.17 m) and *P. strobus* (16.77 cm) versus *P. peuce* (13.46 cm), *P. jeffrey* (14.28 m) and *P. nigra* (14.30 m). In terms of stability (slenderness coefficient), significantly ($F_{(6, 212)} = 10.5$, $P < 0.001$), *P. ponderosa* (49.1) and *P. strobus* (52.7) showed the best values, while the highest coefficients were found in *P. sylvestris* (69.6). Mean stem volume was significantly ($F_{(6, 212)} = 54.0$, $P < 0.001$) greatest in *P. ponderosa* (0.934) compared to nearly 5-fold lower volume in *P. peuce* (0.201).

In terms of stand characteristics, the highest number of trees occurred in *P. nigra* (880 trees·ha^{-1}), while in *P. strobus* the number was the lowest (180 trees·ha^{-1}). The largest basal area was measured in *P. ponderosa* (49.4 $m^2·ha^{-1}$), while in *P. strobus* it was again the lowest (14.2 $m^2·ha^{-1}$). The stand volume varied from 112 $m^3·ha^{-1}$ for *P. strobus* to 430 $m^3·ha^{-1}$ for *P. ponderosa*. Similarly, the average increase ranged from 3.20 to 12.29 $m^3·ha^{-1}·yr^{-1}$. The highest stand density index was also found in *P. ponderosa* (0.87) and the lowest in *P. strobus* (0.27).

Table 1. The indices describing stand structure and their common interpretation

Criterion	Quantifiers	Label	Reference	Evaluation
Vertical diversity	Arten-profile index	*A* (Pri)	Pretzsch 2006	range 0–1; balanced vertical structure *A* < 0.3; selection forest *A* > 0.9
	Vertical diversity	*S* (J&Di)	Jaehne, Dohrenbusch 1997	low *S* < 0,3, medium *S* = 0.3-0.5, high *S* = 0.5-0.7, very high *S* > 0.7
Structure differentiation	Diameter dif.	TM_d (Fi)	Füldner 1995	range 0–1; low *TM* < 0.3; very high differentiation *TM* > 0.7
	Height dif.	TM_h (Fi)		
	Crown dif.	*K* (J&Di)	Jaehne, Dohrenbusch 1997	low *K* < 1.0, medium *K* = 1.0–1.5, high *K* = 1.5-2.0, very high *K* > 2
Complex diversity	Stand diversity	*B* (J&Di)	Jaehne, Dohrenbusch 1997	monotonous structure *B* < 4; uneven structure *B* = 6–8; very diverse structure *B* > 9

https://doi.org/10.17221/42/2020-JFS

Table 2. Structural and production characteristics of pine stands on research plots in 2020 differentiated according to pine tree species; significant ($P < 0.05$) differences between values are denoted by different letters; statistically significant values for tree data and the highest values obtained for stand data are highlighted in bold

Tree species	*DBH* (cm)	*h* (m)	*v* (m^3)	*h/d*	*N* (trees·ha^{-1})	*BA* (m^2·ha^{-1})	*V* (m^3·ha^{-1})	*PAI* (m^3·ha^{-1}·yr^{-1})	*SDI*
P. ponderosa	**37.0**^{c}	**18.17**^{c}	**0.934**^{d}	**49.1**^{a}	460	**49.4**	**430**	**12.29**	**0.87**
P. jeffreyi	24.9^{b}	14.28^{a}	0.318^{b}	57.3^{bc}	700	34.2	223	6.37	0.70
P. nigra	21.7^{ab}	14.30^{a}	0.237^{ab}	65.9^{d}	**880**	32.5	209	5.97	0.71
P. sylvestris	23.3^{ab}	16.21^{b}	0.311^{b}	69.6^{d}	700	29.9	218	6.23	0.63
P. strobus	**31.8**^{c}	**16.77**^{bc}	0.624^{c}	**52.7**^{ab}	180	14.2	112	3.20	0.27
P. contorta	23.8^{ab}	15.81^{b}	0.325^{b}	66.4^{d}	620	27.6	201	5.74	0.58
P. peuce	20.6^{a}	13.46^{a}	0.201^{a}	65.3^{cd}	840	28.1	169	4.83	0.62

DBH – mean quadratic diameter at breast height, *h* – mean height, *v* – mean stem volume, *h/d* – height to diameter ratio (slenderness ratio), *N* – number of trees, *BA* – basal area, *V* – stand volume, *PAI* – periodic annual increment, *SDI* – stand density index

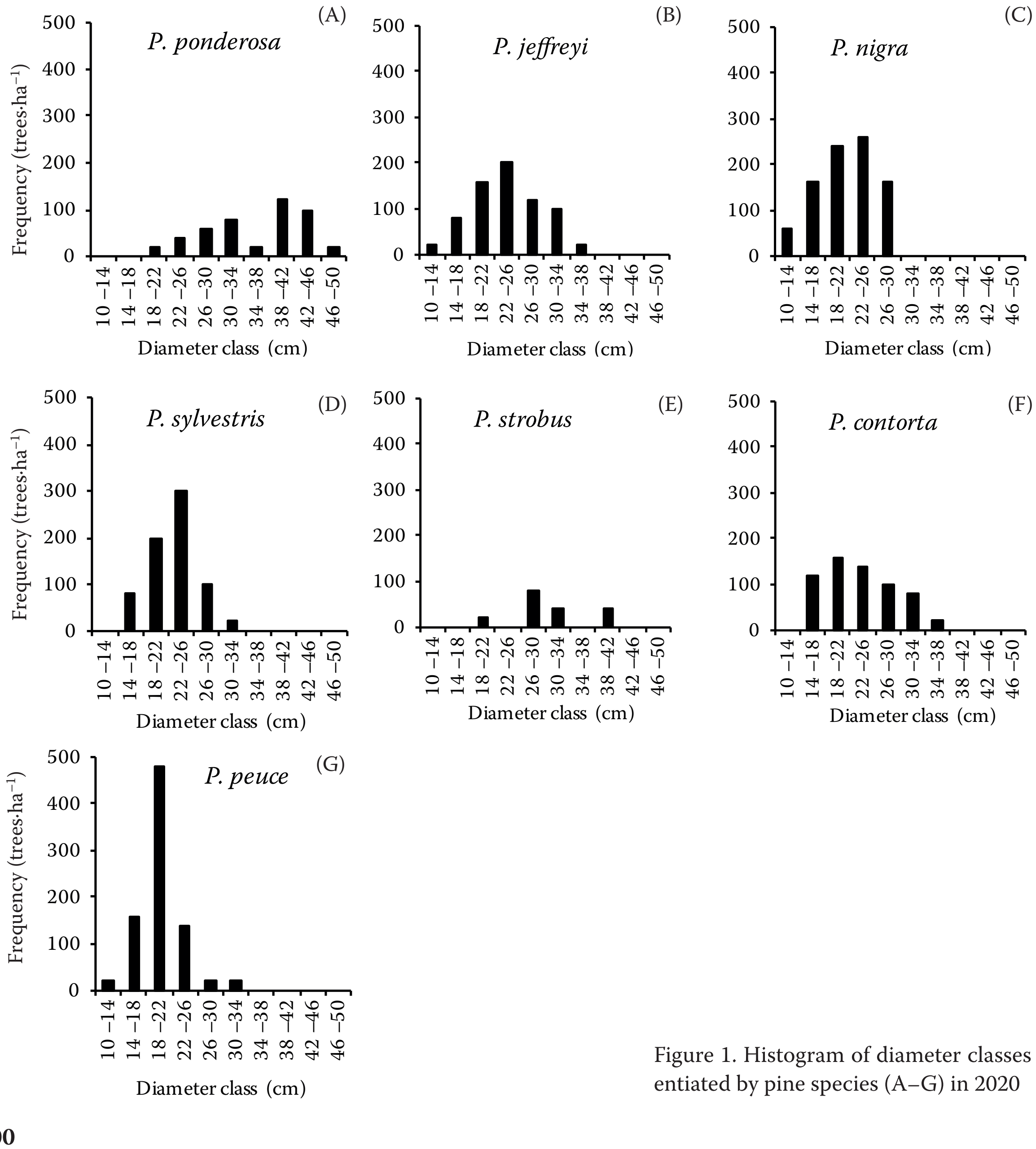

Figure 1. Histogram of diameter classes differentiated by pine species (A–G) in 2020

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Table 3. Stand diversity on research plots in 2020 differentiated according to pine trees species; the highest values are highlighted in bold

Species	Indices											
	A (Pi)		*S* (J&Di)		TM_d (Fi)		TM_h (Fi)		*K* (J&Di)		*B* (J&Di)	
P. ponderosa	0.386	↓	0.393	↓	0.199	↓↓	0.094	↓↓	1.153	↓	3.171	↓
P. jeffreyi	0.098	↓↓	**0.569**	↑	**0.248**	↓↓	**0.163**	↓↓	0.974	↓↓	3.554	↓
P. nigra	0.507	↑	0.299	↓↓	0.209	↓↓	0.065	↓↓	1.008	↓	2.715	↓↓
P. sylvestris	0.333	↓	0.476	↓	0.192	↓↓	0.111	↓↓	0.742	↓↓	3.011	↓
P. strobus	0.595	↑	0.261	↓↓	0.212	↓↓	0.129	↓↓	1.353	↓	2.899	↓↓
P. contorta	**0.608**	↑	0.400	↓	0.212	↓↓	0.093	↓↓	1.172	↓	3.198	↓
P. peuce	0.453	↑	0.342	↓	0.128	↓↓	0.075	↓↓	**1.785**	↑	**3.677**	↓

A – Arten-profile index, *S* – vertical structure, TM_d – diameter differentiation, TM_h – height differentiation, *K* – crown differentiation, *B* – total stand diversity, diversity scale: ↓↓ low, ↓ medium, ↑ high, ↑↑ very high

Figure 1 shows the diameter distribution of individual pine species. In most cases, the diameter distribution approaches the shape of the Gaussian curve typical for even-aged forests. In other cases, uneven diameter structure was found in *P. strobus* and left-sided structure was observed in *P. peuce* with a significant proportion of the 18–22 cm (480 trees·ha^{-1}) diameter class. The highest frequency in the same class was achieved in *P. contorta*. In case of *P. nigra*, *P. jeffreyi* and *P. sylvestris*, the most represented class was 22–26 cm. In *P. strobus*, most trees were in the following 26–30 class and in *P. ponderosa* even in the class 38–42 cm. The distribution of diameter curve was most convex in *P. peuce* and *P. sylvestris*, while it was relatively flattened in case of *P. strobus* and *P. ponderosa*. In relation to diameter variability, the largest number of represented diameter classes was documented in *P. ponderosa* (8 classes), on the contrary, the least range representation of classes was in *P. strobus* (4 classes).

Stand diversity

In terms of vertical structure, the highest diversity according to the *A* index was achieved in *P. contorta* (0.608) and according to the *S* index in *P. jeffreyi* (0.569), indicating a high vertical diversity in these cases. Diameter (0.248) and height differentiation (0.163) were found to be highest in *P. jeffreyi*. All tree species showed low diversity in terms of structural differentiation. In crown differentiation, the highest value was found in *P. peuce* (1.785), indicating moderate diversity. The overall diversity was highest in *P. peuce* (3.677), pointing to a uniform stand structure, which was also the case for most of the other pines. *P. nigra* (2.715) and *P. strobus* (2.899) showed very low diversity and monotonous structure of stand according to index *B* (Table 3).

Interaction between production, structure, diversity and pine tree species

PCA results expressing the relationship between production, structure and diversity of individual pine species are presented in the form of ordination diagram in Figure 2. The first ordination axis represents 35.4%, the first two axes 64.6% and the four axes together account for 95.3% of data variability. The x-axis represents height, diameter, diameter differentiation and slenderness coefficient. The y-axis represents the stand density index and Arten-profile index. The mean stem volume was positively correlated with height, diameter, height and diameter structure, while these parameters were negatively correlated with slenderness coefficient (HDR). The stand volume was positively correlated with basal area and stand density index – stocking, while these parameters were negatively correlated with Arten-profile index and crown differentiation. The differences between tree species were significant, especially for *P. strobus* and *P. ponderosa*, characterized by a high volume of the mean stem. In contrast, similarity was found in *P. nigra* and native *P. sylvestris*. The upper part of the graph (*P. strobus*, *P. peuce* and *P. contorta*) is characterized by high vertical diversity and crown differentiation, compared to *P. ponderosa*, *P. jeffreyi* and *P. sylvestris* (at the bottom of the diagram) they reach a high stand volume.

DISCUSSION

The *Pinus* genus is of enormous ecological and economic importance worldwide (Price et al. 1998;

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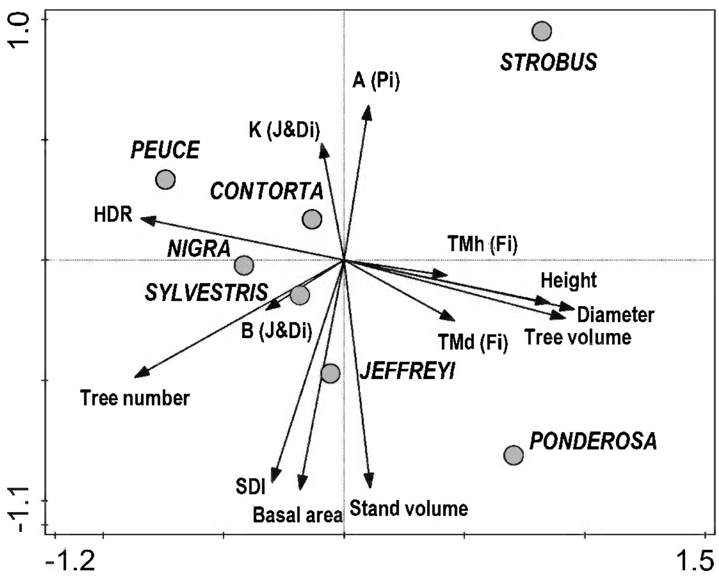

Figure 2. Ordination diagram showing results of principal components analysis of relationship between stand parameters (Height, Diameter, Tree number, Stand volume, Stem volume, HDR – height to diameter ratio, *SDI* – stand density index), structural and diversity indices (*A* – Artenprofile index, TM_d – diameter differentiation, TM_h – height differentiation, *K* – crown differentiation, *B* – total stand diversity) and pine tree species (*P. ponderosa*, *jeffreyi*, *nigra*, *sylvestris*, *strobus*, *contorta*, *peuce*) in 2020

Farjon 2001; Musil, Hamerník 2007; Businský, Velebil 2011; Álvarez-Álvarez et al. 2018). With more than a hundred recognized species, *Pinus* is the largest conifer species and is the major, often dominant component of many natural forest ecosystems in the tropical, temperate, boreal and subalpine belt (Richardson 1998). The economic importance of pines comes with their use as a source for wood, pulp, resins and coal (Olson et al. 2018). So, the pines are often subject of introduction because of their flexibility and adaptability to particular regions and environmental conditions. In addition, pines are currently the subject of biomass research as a promising species for energy production forest plantations (Álvarez-Álvarez et al. 2018). The genus *Pinus* is divided into subgenus *Strobus* and subgenus *Pinus*, the other consisting of parts of *Pinus* (subsection *Pinus* and *Pinaster*) and section *Trifoliae* (subsection *Contortae*, *Ponderosae* and *Australes*) – (Gernandt et al. 2005). The phylogenetic relationships of pine are still completely unresolved, especially between terminal taxa in the *Strobus* and *Australes* subsections (Eckert, Hall 2006; Parks et al. 2009; Gernarndt et al. 2018). In addition, group species have been specifically discussed and their exact composition and relationships have been questioned, such as the *Pinus banksiana* and *P. concorta* (Yang et al. 2007), the Asian Khasi pine (*Pinus kesiya* Royle ex Gordon) (Businský et al. 2014) as well as the European bog pine (*Pinus mugo* Turra) (Christensen 1987) and Mediterranean pines (Syring et al. 2005; Grivet et al. 2013). This limitation of species delineation poses problems when attempting to identify forest materials at species level based on solid wood products from species that are not well identified by wood characteristics, as is the case for closely related species such as *Pinus sylvestris* and *Pinus nigra* (Schoch et al. 2004). These problems should not block further research and use of appropriate sources for forest functions restoration of declining forests.

In our case, in terms of production parameters, the largest mean stem volume was documented in *P. ponderosa* (0.93 m^3), *P. strobus* (0.62 m^3) and *P. contorta* (0.33 m^3), while the lowest volume was found in *P. peuce* (0.20 m^3) and *P. nigra* (0.24 m^3). In addition to tree species, provenance also plays an important role (Kapeller et al. 2012; Ulbrichová et al. 2015). Novotný et al. (2017) reported for *P. contorta* at the same age (34 years) a lower mean volume in the range 0.05–0.28 m^3, depending on provenance. In terms of stand characteristics, the highest basal area was found in *P. ponderosa* (49.4 $m^2 \cdot ha^{-1}$) and *P. jeffreyi* (34.2 $m^2 \cdot ha^{-1}$), whereas in *P. strobus* it was lowest (14.2 $m^2 \cdot ha^{-1}$) due to high mortality and low stand density, followed by *P. contorta* (27.6 $m^2 \cdot ha^{-1}$). Similarly, the stand volume of pines varied from 112 $m^3 \cdot ha^{-1}$ for *P. strobus* to 430 $m^3 \cdot ha^{-1}$ for *P. ponderosa*. The low density of *P. strobus* is caused by high susceptibility to climatic changes and susceptibility to fungal pathogens (Mácová 2008; Liška, Lorenc 2016), which resulted in high mortality in our case. Similarly, *P. strobus* reached the lowest stand volumes (103 $m^3 \cdot ha^{-1}$) at the Antonín (Sokolovsko) reclama-

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tion site at the age of 45 (Vacek et al. 2018b), while the highest stand volumes were reached by *Pseudotsuga menziesii* (685 $m^3 \cdot ha^{-1}$) and *Pinus sylvestris* (425 $m^3 \cdot ha^{-1}$). Podrázský et al. (2019) reported from the same locality the highest production potential also in *Pseudotsuga menziesii* (453 $m^3 \cdot ha^{-1}$), *Pinus sylvestris* (396 $m^3 \cdot ha^{-1}$) and *P. nigra* (298 $m^3 \cdot ha^{-1}$), while the lowest stand volumes were in *P. strobus* (103 $m^3 \cdot ha^{-1}$), *P. rotundata* (117 $m^3 \cdot ha^{-1}$) and blue spruce (*Picea pungens* Engelm.) (131 $m^3 \cdot ha^{-1}$). Our native pine (*P. sylvestris*) in the area of interest reached 218 $m^3 \cdot ha^{-1}$ which is slightly below average in timber production compared to introduced pines (224 $m^3 \cdot ha^{-1}$). For comparison, a similar stand volume of *P. sylvestris* (190 $m^3 \cdot ha^{-1}$) was found at the age of 30 in Estonia (Pensa et al. 2004). Dragoun et al. (2015) reported a higher volume of 336 $m^3 \cdot ha^{-1}$ at the age of 40 in *P. sylvestris* monocultures. Overall, coniferous stands surveyed compared to deciduous stands (28–97 $m^3 \cdot ha^{-1}$) reached significantly higher values in a locality with similar elevation (Vacek et al. 2018a).

In addition to the production function, the stability, structure and diversity of the stand also play an important role (Bílek et al. 2016; Vacek et al. 2017; Sharma et al. 2019; Gallo et al. 2020b). The lowest values of slenderness quotient were found in *P. ponderosa* and *P. strobus*, indicating high stability of the stand (Sharma et al. 2017). In terms of structural diversity, the highest index values describing the vertical structure, diameter and height differentiation were achieved by *P. jeffreyi*. In crown total stand diversity, *P. peuce* came first. In contrast, the lowest overall diversity was found in *P. nigra* and *P. strobus*. Similarly, at the Antonín dump, the lowest overall diversity was found in *P. strobus* and *P. nigra*, while the black spruce (*Picea mariana* Mill.) and European larch (*Larix decidua* Mill.) was characterized by a relatively diverse structure (Vacek et al. 2018b). Generally, higher total biodiversity (B) was observed in native coniferous tree species (B = 5.6) compared to introduced tree species (B = 4.7). In our case, native *P. sylvestris* showed lower total diversity (B = 3.0) than average value (B = 3.2) of other introduced pines. Podrázský, Prknová (2019) showed also higher total diversity (B = 3.7) in study of six introduced pines compared to *P. sylvestris* in our case.

An important shortcoming of such studies is that it is difficult to ensure continuity of monitoring and representativeness for a limited area. The stands were established in similar conditions according to the period parameters of experimental plantings, but those are difficult in the current levels of conditions for the statistical evaluation. Nevertheless, these plantings can serve as a source of valuable knowledge and inspiration for further research (Beran 2018).

The genus *Pinus* is very promising in terms of the use of species that tolerate climatic extreme conditions in the current climate of Central Europe. Due to their low competitiveness, they are naturally confined to conditions that other woody species find difficult to survive in and show resistance primarily to extreme precipitation conditions (Hamerník, Musil 2007). On the other hand, they are characterized by a wide valence of climatic conditions with extreme humidity or temperature conditions, tolerance of air pollution, and therefore they were often verified in air pollution areas, where many experiences with them originate (Kaňák 1999; Dimitrovský 2001). In the current situation, many of them would be suitable for planting on calamity clearings resulting from the disintegration of mainly Norway spruce stands, from lower to lower mountain sites (Businský, Velebil 2013; Vaněk, Bednář 2013; Čáp et al. 2018; Sullivan et al. 2020). High mortality rates of this species were also observed in the monitored area and in this case the results are not representative. On the contrary, the shortage of coniferous timber can be expected in the coming decades due to the decline of "traditional" tree species (Palátová et al. 2017; Riedl et al. 2019).

Of the pine species tested in the Kostelec arboretum, the *P. ponderosa* appears to be promising in comparison with the domestic *P. sylvestris*, of which there is little knowledge of our conditions, then the *P. concorta*, where the provenance will be very important (Čáp et al. 2018) and *P. nigra*, with which they have many years of experience in many European countries and in Czech conditions (Kaňák 1999; Farjon 2001; Trasobares, Pikkala 2004; Stankova, Zlatanov 2010; Businský, Velebil 2013). Considering the proximity of its natural area to the Czech territory, it is also possible to speak of assisted transfer (Podrázský, Prknová 2019).

However, a number of conditions must be observed during the introduction in order to avoid negative effects on domestic species and damage to ecosystems (Beran, Šindelář 1996; Hadincová et al. 1997; Šindelář, Frýdl 2004; Vaněk, Bednář 2013). Another important aspect of research to be is the level of ability of these

https://doi.org/10.17221/42/2020-JFS

species to form mixtures with domestic species. Invasiveness can be supposed at specific sites for some species too (*P. strobus*), but low competitiveness of pines prevents this phenomenon in many cases – the prevention is of high importance.

CONCLUSION

Out of the studied introduced species of pine, *P. ponderosa* clearly achieved the best production parameters and stand stability. In terms of stand volume, these values were lowest in *P. strobus* because of the very low stand density. In terms of overall stand diversity, all species of pines are of even stand structure and low diversity stand in *P. nigra* and *P. strobus*. In contrast, the highest diversity was found in *P. jeffreyi* and *P. peuce*. The use of introduced pine species can only be recommended on sites where due to global climatic change and decay of forest stands *P. sylvestris* fails to fulfill its production and ecological functions, i.e. when it is severely damaged and dies. From the point of view of production and economic potential, *P. ponderosa* appears to be particularly important in areas of lower altitude. It is very important to select suitable provenances of introduced species of pines that have already been verified in given or similar environmental conditions in the Czech Republic or in Central Europe.

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