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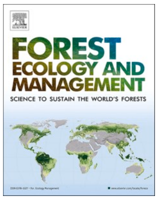

Scots pine (*Pinus sylvestris* L.), the suitable pioneer species for afforestation of reclamation sites?

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ABSTRACT

As a result of human population growth and human need for resources, the landscape has been increasingly transformed and devastated by mining activities. Subsequent reactivations are thus extremely important in the process of restoring the disturbed biosphere. The objective of this study was to determine differences between original forest sites and reclamation sites afforested with Scots pine (*Pinus sylvestris* L.) in terms of stand structure, diversity, biomass, productivity and climatic resistance. Three different types of reclamation were compared in the Czech Republic – (1) a post-mining coal site, (2) a former sand quarry and (3) a reclaimed sand dune that had been used for pasture. At the comparable stand age of 40–46 years, the stand volume and biomass were higher by 22% and 19%, respectively, on original forest sites (370–500 m^3 ha^{-1}, 332–422 t ha^{-1}) compared to reclamation sites (318–371 m^3 ha^{-1}, 287–325 t ha^{-1}). On the contrary, structure and diversity were more complex and richer in reclaimed areas. Climatic factors had a higher effect on radial growth on reclamation sites compared to original forest sites, but no significant differences were observed between the variants in terms of the occurrence of negative pointer years (extreme deflection in growth). A lack of precipitation and long-term droughts in vegetation periods were the main limiting factors of growth. Comparing all reclamation variants, the highest productivity was found on the reclaimed coal-mine, and the lowest differences between forest and reclamation sites were documented in the reclaimed sand quarry case. In relation to climate change, Scots pine proved a very adaptive and suitable tree species whose wood production on reclaimed post-mining sites is comparable to the original forest sites. Pine afforestation of reclamation sites brings invaluable environmental and production benefits.

1. Introduction

The landscape of the European continent has been strongly influenced by human activity in the recent millennia. People gradually transform the planet, and thus change the environment and, subsequently, also the living conditions for other organisms (Lanz et al., 2018; Stephens et al., 2019; Vitousek et al., 1997). The surface sand and coal mining activities are one of the essential landscape changes with significant impact on the environment (Fagiewicz and Łowicki, 2019; Pietrzykowski, 2008; Pietrzykowski and Krzaklewski, 2007; Pietrzykowski and Socha, 2011; Vacek et al., 2018). In the past 60 years, the scale of disturbances created by mining has been growing rapidly in relation to economic demands and technological capacity (Hancock et al., 2020). These primary ecosystems are therefore still being degraded by mining. The mining activities are then followed by restorations of ecosystems by different types of reclamations (Pavloudakis et al., 2020; Šebelíková et al., 2016; Tropek et al., 2012, 2010; Vondráčková et al., 2017).

After the end of surface mining activities, the transformed areas should undergo biological and ecological monitoring and evaluation, before the type of reclamation process is determined. The restoration and mitigation of the impact of surface mining follows the preparatory work in agreement with environmental legislation (Botta et al., 2009; Ignatyeva et al., 2020). First of all, the successful reclamation is based on the transformation of soil conditions (Bradshaw, 1997), during which the physical and chemical properties should be improved (Frouz et al.,

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2009, 2008, 2006; Pietrzykowski, 2008). Anthroposols, developed in post-mining areas, are derived from freshly deposited mining spoils and substrates from different geological epochs, characterized by unfavorable physicochemical properties such as low sorption capacity, lack of soil organic matter, and low biological activity (Józefowska et al., 2019). Therefore, the soil forming processes which improve soil conditions (like tree assimilation organs decomposition) are considered to be of the utmost importance (Bradshaw, 1997; Frouz et al., 2008; Prach et al., 2013; Walker et al., 2010).

One of the methods used to mitigate the negative impact of mining activities is forest reclamation (Schempf and Jacobs, 2020; Šebelíková et al., 2016; Vondráčková et al., 2017), which is aimed to reduce soil erosion and improve the soil conditions for future utilization of the reclaimed sites (Singh et al., 2002). To a considerable extent, reclamation can be accomplished by natural succession (Bradshaw, 1997). The process of spontaneous development of vegetation cover on reclaimed sites tends to be fairly rapid under the natural conditions of Central Europe (Frouz et al., 2008; Mudrák et al., 2010; Prach et al., 2013; Šebelíková et al., 2016). Therefore, spontaneous succession can be considered a suitable method of reclamation site restoration (Kompala-Bąba and Bąba, 2013; Mudrák et al., 2010; Pensa et al., 2004; Tischew and Kirmer, 2007). However, spontaneous succession is a long-term process compared to afforestation. The targeted afforestation of forest reclamation sites is a common alternative to spontaneous succession (Prach et al., 2013).

The forest reclamation optimization remains a widely discussed topic. Especially the selection of suitable tree species and their following adaptation in specific stands is evaluated (Kuznetsova et al., 2010; Pietrzykowski, 2008; Pietrzykowski and Socha, 2011; Vacek et al., 2018). However, the amount and quality of wood production in the reclaimed stands have not yet been evaluated and compared in the context of forest stands at comparable altitudes and climatic conditions. From the ecological point of view, the key question is whether – when restored – these ecosystems achieve a productivity comparable to natural ecosystems (Hüttl and Weber, 2001; Pietrzykowski and Krzaklewski, 2007; Pietrzykowski and Socha, 2011).

In the reforestation process of post-mining sites in Central Europe, Scots pine (*Pinus sylvestris* L.) is one of the most commonly used tree species (Kuznetsova et al., 2010; Pajak et al., 2016; Pietrzykowski and Socha, 2011; Woś and Pietrzykowski, 2019). However, the findings regarding the biomass amount, and the development of original forest sites where Scots pine is dominant, are mostly available only for the sites with standard forest soils (Ahtikoski et al., 2018; Bílek et al., 2018, 2016; Felton et al., 2020; Węgiel et al., 2018). Therefore, an evaluation of Scots pine production, structure and stability was performed in the forest stands established on reclaimed sites to compare them to stands on standard forest soils with similar conditions. The partial aims were (i) to evaluate the productivity, structure and growth resistance to climatic factors of Scots pine stands on anthropogenic soils, (ii) compare the observed production characteristics, structure and radial growth of Scots pine stands on anthropogenic soils with comparable stands on standard forest soils.

2. Material and methods

2.1. Study area

The research was conducted on reclamation sites (R) and original forest sites – historically managed commercial forest (F) in each of the three studied areas: the Sokolov region (1S), the Třeboň region (2T) and the Hradec Králové region (3H) (Fig. 1). The original forest sites were located close to reclamation sites, within 0.2–7.3 km, under the same

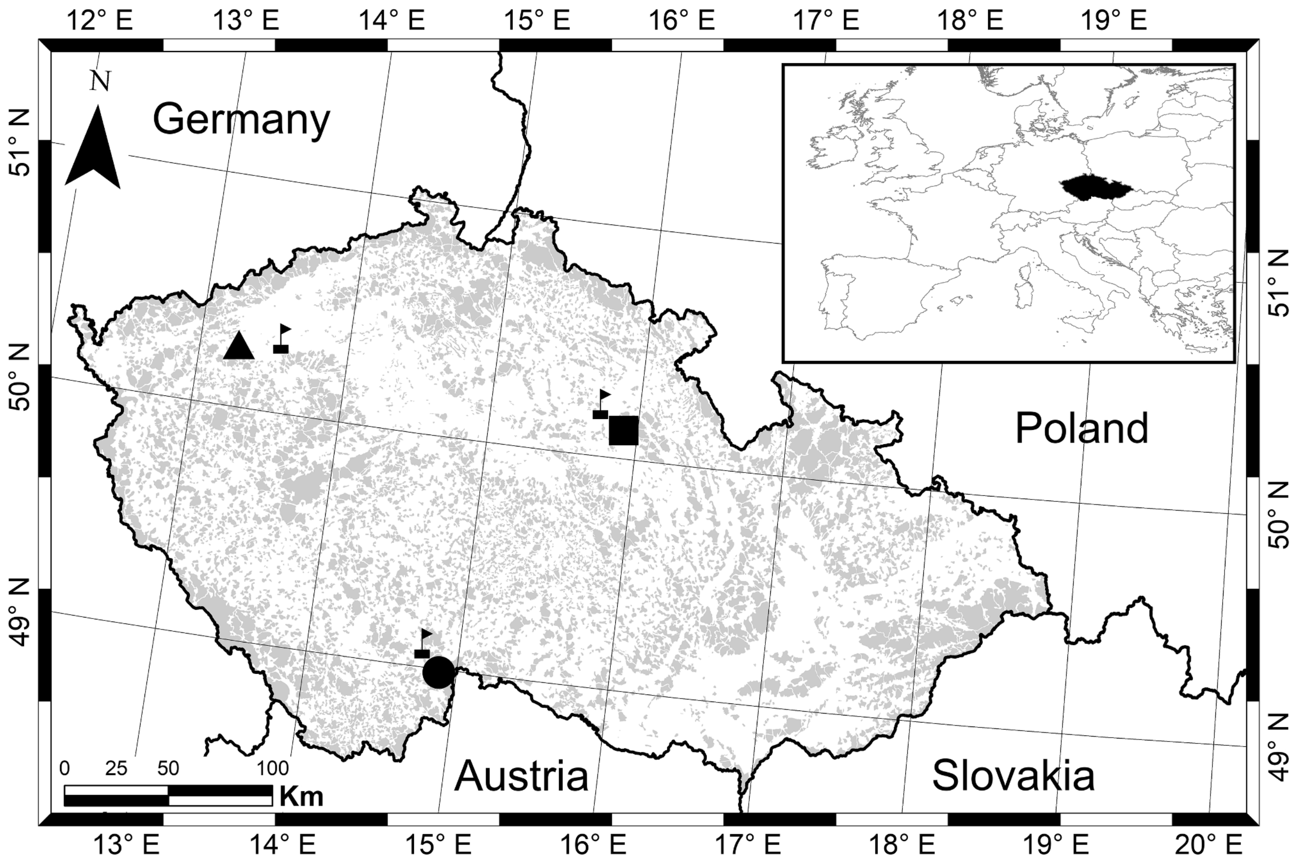

Fig. 1. Localization of Scots pine stands in the study area of the Sokolov region (▲), the Třeboň region (●) and the Hradec Králové region (■); meteorological stations are marked by symbol (⚑); the map was made in ArcGIS 10 software (Esri).

Table 1
Overview of basic site and stand characteristics of Scots pine stands in the study area of the Sokolov region (1S), the Třeboň region (2T) and the Hradec Králové region (3H) on reclamation sites (R) and original forest sites (F).

Plot	Study area	Historical land use	Stand age (year)	Altitude (m a.s.l.)	Slope (°)	Expo-sure	Annual temper. (°C)	Annual precip. (mm)	Forest site type	Soil type
1S_R	Sokolov	Reclamation	44	440	1–5	N, NE	7.7	925	*Fageto-Quercetum oligotrophicum*	Arenic Cambisol
1S_F		Forest	46	495	1–3	N, E				
2T_R	Třeboň	Reclamation	40	440	0–2	W, NE	8.3	595	*Pineto-Quercetum arenosum*	Arenic Regosol
2T_F		Forest	42	465	1–4	W, N				
3H_R	Hradec Králové	Reclamation	45	250	0–1	N, NE	8.1	620	*Pineto-Quercetum arenosum*	Arenic Regosol
3H_F		Forest	45	250	0–1	N, NE				

climatic conditions, to ensure soil type comparability. On both the forest and reclamation sites, there are 6 Scots pine stands of comparable age (40–46 years) in each area (Table 1). The stands were situated on predominately flat terrain with a 0–5° slope gradient and prevailing exposure to the north. Each studied area was characterized by a different type of reclamation.

The Sokolov region is a typical post-mining landscape in the western Czech Republic. The reclamation site is situated on the Antonín-Sokolov coal spoil heap (dump). Historically, the Antonín-Sokolov brown coal mine was in operation between 1881 and 1965, first as a deep mine, and later as a surface coal mine. Forest reclamation of the spoil heap started in 1972 after necessary technical operations (Vacek et al., 2018). This site was compared with original forest site. Annual temperature of this location is 7.7 °C, and annual precipitation varies approximately 925 mm. At an altitude of 440–495 m a.s.l., the study territory has typically warm, dry summers and cool, dry winters with a narrow annual temperature range (Cfb) according to Köppen climate classification (Köppen, 1936). Arenic cambisol is the predominant soil type. In terms of phytocoenology, the pine stands belong to *Fageto-Quercetum* (*pineosum*) *oligotrophicum,* vegetation association *Vaccinio vitis-idaeae-Quercetum* Oberdorfer 1957.

The Třeboň region consists of pine forest stands on original forest and reclamation sites in a former sand quarry. Characterized by numerous water-filled sand quarries, the locality is situated in the Protected Landscape Area Třeboňsko, close to the sand quarries of Cep I and Cep II. These quarries have been mined since 1948, 1949 and 1979 respectively. The Cep II is still in operation, with the sand containing gravel being surface-mined from water by suction dredger. The mean annual precipitation of the study area is 595 mm, and the mean annual temperature 8.3 °C. It also belongs to the Cfb regions according to Köppen climate classification (Köppen, 1936). The forest stands studied are situated at an altitude of 440–465 m a.s.l. In terms of phytocoenology, the pine stands belong to *Pineto-Quercetum arenosum* (*oligotrophicum*), vegetation association *Vaccinio myrtilli-Pinetum sylvestris* Juraszek 1928.

The last area (Hradec Králové region) was chosen in order to represent a different type of anthropogenic sand soil. The original forest site was compared with a site of a former sand dune. After the dune had been removed and the surface levelled, the site was used as a pasture and then afforested with Scots pine. The surrounding fields are still used as agricultural land. The annual temperature of this locality is 8.1 °C, and annual precipitation varies around 620 mm. The altitude is the lowest of all monitored areas – around 250 m a.s.l. The natural conditions of the region – i.e. climatic region (Cfb) according to Köppen classification (Köppen, 1936), soil type, forest site type and vegetation association – are the same as in the previous case of the Třeboň region (Table 1).

All Scots pine stands are owned by the Czech state (Czech state forests). The forest stands were established artificially with 10,000 pine seedlings per hectare (in accordance with Regulation No. 13/1978). The first thinning intervention was performed at the age of 15–22 years, with a stocking reduction by a maximum of 20%. Other reductions were aimed only at the removal of disturbed trees and through natural mortality. The plots establishment and following management were comparable because of the same intensity given by management methods used in the Czech state forests.

2.2. Data collection

FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.) was used to determine the tree layer structure and production parameters on permanent research plots (PRP) of 10 × 15 m (150 m^2) size in 2019–2020. Six PRPs were established on the forest soil and six PRPs on anthropogenic soil in three localities (the Sokolov, Třeboň and Hradec Králové regions; in total, 36 PRPs). Research plots were randomly distributed over the previously selected suitable area (in terms of soil type – reclamation and forest soil – and the stand age, which has to be comparable between all research plots and locations). The positions of all individuals of the tree layer with a diameter at breast height (DBH) ≥ 4 cm were recorded. The total tree heights and the heights of the live crown base were measured. Crown projections were measured from at least four directions perpendicular to each other. Diameters of the tree layer were measured by a Mantax Blue metal calliper (Haglöf, Sweden) with an accuracy to 1 mm, and tree heights were measured using a Vertex laser hypsometer (Haglöf, Sweden), with an accuracy to 0.1 m.

Thirty co-dominant and dominant pine trees according to the classification by Kraft (1884) were chosen as the significant growth response (compared to subdominant and suppressed trees; Remeš et al., 2015). These trees were randomly (RNG in Excel) selected for a dendrochronology analysis on each PRP. The appropriate sample depth was determined for sufficient level of expressed population signal (EPS) (Speer, 2010). The core samples were taken with Pressler auger (Haglöf, Sweden) at DBH perpendicular to the axis of the tree along/against the slope. The annual ring width was measured (accuracy 0.01 mm) using an Olympus binocular magnifying glass on a LINTAB measurement table, and registered using the TSAPWin software (Rinntech, USA). Individual dendrochronological samples were measured from the perpendicular direction from the bark to the stem core, so that every annual ring was measured in the perpendicular direction to the stem axis. Cross-dating was done in Cdendro software, so that index CC > 25 for each sample (Cybis Elektronik & Data AB).

A climate behavior evaluation with regard to the monthly air temperature and monthly sum of precipitation conditions was based on the data of the Karlovy Vary – Olšová Vrata meteorological station (602 m a.s.l.; GPS 50°12′5.71″N, 12°54′51.71″E) in the Sokolov region, of the Třeboň – Lužnice meteorological station (428 m a.s.l.; GPS 49°3′44.64″N, 14°45′32.03″E) in the Třeboň region, and the Hradec Králové meteorological station (240 m a.s.l.; GPS 50°13′21.32″N, 15°47′15.59″E) in the Hradec Králové region (Fig. 1). The climate data set was obtained by the Czech Hydrometeorological Institute (CHMI).

2.3. *Data processing*

The structure, diversity and production characteristics of the tree layer were evaluated by the SIBYLA Triquetra 10 forest growth simulator (Fabrika and Ďurský, 2005). The PointPro 2.1 (Zahradník and Puš, ČZU) program was used to calculate the characteristics of the horizontal layout of the individuals on the plots. As a basic diversity statistic, the tree diameter distribution was computed and presented in the form of the simple bar plot. For the evaluation of the spatial pattern, the aggregation index (Clark and Evans, 1954) was calculated. The structural diversity was evaluated by species profile index (Pretzsch, 2006), diameter and height differentiation (Füldner, 1995), crown differentiation, vertical diversity and total stand diversity (Jaehne and Dohrenbusch, 1997; Table 2).

The stand volume of pine was calculated using volume equations published by Petráš and Pajtík (1991). The growth of dominant trees is strongly correlated with the quality of the habitat (Crecente-Campo et al., 2009; Monserud, 1984), therefore, the site quality was derived from the dominant height (Sharma et al., 2016). A dominant height (h_{DOM}) was calculated as 95% quantile of heights of all trees forming the stand component (Vacek et al., 2016b). The tree biomass of pine in dry matter was derived from the model by Seifert et al. (2006). The crown closure (CC; Crookston and Stage, 1999) was calculated for each plot. The relative stand density index (SDI) was calculated as the ratio of the actual value of the stand density index to its maximum value. The stand density index representing the theoretical number of trees per hectare, if the mean quadratic diameter of the stand component were equal to 25 cm (Reineke, 1933). The maximum SDI value was derived from the model of yield tables (for pine 990 trees; Halaj, 1987). Standard deviations (SD) were calculated for the mean quadratic DBH and mean height.

The DBH, tree height, and stem volume were compared between sites (forest and reclamation sites) regardless of the area (the Sokolov, Třeboň and Hradec Králové regions) using the Wilcoxon rank-sum test in all cases (because assumptions of *t*-test were not met in all cases). We also used the Kruskal-Wallis test for checking the differences between DBH, tree height and stem volume between all area–site type combinations (because assumptions of ANOVA were not met in all cases, again) with subsequent multiple comparisons (Siegel and Castellan Jr., 1988). Height curves were constructed using Näslund height–diameter function ($h = dbh^2 \times (a + b \times dbh)^{-2} + 1.3$; Näslund, 1936) for all area–site type combinations using all measured trees on particular location and soil type.

The differences between original forest sites and reclamation sites in all described parameters (production and diversity parameters, Tables 3 and 4) for each study area were tested by the *t*-test or the Wilcoxon rank-sum test (if the *t*-test assumptions were not met). The Welch *t*-test was used in the cases where the assumption of normality was met, but the tested samples had significantly different variances (tested by Fisher's F-test). We also specifically tested particular parameters between forest and reclamation sites across all study areas (the mean annual increment, total stand volume, biomass, and total diversity) and also on reclamation sites between all locations.

Dendrochronological analyses were performed with R software (R Core Team, 2020). DplR-package was used for detrending (Zang et al., 2018). Negative exponential detrending with inserted spline 1/3 of the age of the samples was used to remove the age trend of individual trees, and then we averaged these values with the "chron" function to obtain the average stand curve (Bunn and Mikko, 2018). The dendrochronological indicators were computed by using the tutorial methods Bunn (2018) and Bunn and Mikko (2018). The detrended ring-width data of Scots pine was used to calculate the EPS (expressed population signal). The EPS indicates the reliability of a chronology as a fraction of the joint variance of the theoretical infinite tree population. The criterion for using the dendrochronological data for correlation with climatic data was a significant limit of EPS > 0.85 (Bunn and Mikko, 2018). Signal to noise ratio (SNR) which describes the signal strength of chronology, and R-bar (inter-series correlations) was also calculated (Fritts, 1976).

The analysis of negative pointer years (NPY) was done according to

Table 2

Overview of indices describing the stand diversity and their common interpretation.

Criterion	Quantifiers	Label	Reference	Evaluation
Horizontal structure	Aggregation index	*R* (C&Ei)	Clark and Evans (1954)	mean value $R = 1$; aggregation $R < 1$; regularity $R > 1$
Vertical structure	Species 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 and Dohrenbusch (1997)	low $S < 0.3$, medium $S = 0.3$–0.5, high $S = 0.5$–0.7, very high diversity $S > 0.7$
Structural 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 and Dohrenbusch (1997)	low $K < 1.0$, medium $K = 1.0$–1.5, high $K = 1.5$–2.0, very high differentiation $K > 2.0$
Complex diversity	Stand diversity	*B* (J&Di)	Jaehne and Dohrenbusch (1997)	monotonous structure $B < 4$, uneven structure $B = 6$–8, very diverse structure $B > 9$

Table 3
The mean basic stand characteristics in the study areas of the Sokolov (1S), Třeboň (2T) and Hradec Králové regions (3H) on reclamation sites (R) and original forest sites (F); Testing for differences between original forest sites and reclamation sites in particular areas.

PRP	DBH ± SD (cm)	h ± SD (m)	h_{DOM} (m)	f	v (m^3)	N (trees ha^{-1})	BA (m^2 ha^{-1})	V (m^3 ha^{-1})	HDR	MAI (m^3 ha^{-1} y^{-1})	SDI	CC (%)	BIO (t ha^{-1})
1S_R	18.6 ± **2.3**	17.89 ± **2.2**	21.28	0.453	0.228	1689	45.0	371	96	8.43	0.94	86.4	325
1S_F	21.8 ± **2.9**	20.19 ± **1.1**	22.97	0.451	0.349	1511	54.7	500	93	10.87	1.10	92.5	422
2T_R	14.6 ± **0.8**	16.92 ± **0.5**	20.00	0.425	0.12	2822	46.5	335	117	8.38	1.09	88.8	315
2T_F	17.2 ± **0.8**	19.24 ± **1.1**	21.63	0.435	0.196	1911	44.3	370	112	8.81	0.96	87.5	332
3H_R	16.5 ± **4.2**	19.61 ± **4.8**	22.62	0.419	0.211	2111	38.3	318	119	7.07	0.95	85.7	287
3H_F	21.1 ± **2.9**	22.52 ± **2.1**	26.06	0.458	0.371	1355	45.1	466	107	10.36	1.00	85.7	392
						Testing for differences between site types							
1S	0.057	**0.046**	0.100	0.809	0.056	0.355	**0.037**	**0.03**	0.433	**0.03**	0.101	**<0.001**	**0.033**
2T	**<0.001**	**0.002**	**0.008**	0.122	**<0.001**	**0.001**	0.434	0.149	0.245	0.148	0.087	0.24	0.387
3H	**0.050**	0.201	0.131	**0.013**	0.073	0.139	0.128	**0.022**	**0.009**	**0.038**	0.637	0.988	**0.034**

Notes: DBH – mean quadratic diameter at breast height, SD – standard deviation, h – mean height, h_{DOM} – dominant height (95% quantile of heights of all trees), f – form factor, v – mean tree volume, N – number of trees per hectare, BA – basal area, V – stand volume, HDR – height to diameter ratio, MAI – mean annual increment, SDI – relative stand density index, CC – canopy closure, BIO – biomass in dry matter. P-values in bold depict statistically significant results.

Table 4
The computed *a* and *b* equation parameters of Näslund height-diameter curves for both site types in each of study area.

Area	Site type	Parameter *a*	Parameter *b*
Sokolov	forest	7.8636	0.1884
	reclamation	11.7775	0.1767
Třeboň	forest	8.4523	0.1842
	reclamation	6.9245	0.2008
Hradec Králové	forest	9.7541	0.1673
	reclamation	11.3238	0.1646

Schweingruber et al. (1990) and Desplanque et al. (1999). For each tree, the pointer year was tested as an extremely narrow tree ring that does not reach 40% of the increment average from the four preceding years. The occurrence of the negative year was proved if a strong reduction in increment occurred at least in 20% of trees on the plot. To express the relationship between climate characteristics (monthly average air temperatures and monthly sum of precipitation in particular years) and radial growth, the DendroClim software was used (Biondi and Waikul, 2004).

Unconstrained principal component analysis (PCA) in Canoco 5 (Šmilauer and Lepš, 2014) was used to analyze the relationships between the stand structure, wood production and diversity in relation to site variants. The data were log-transformed, centered and standardized before the analysis. The results of PCA were exported into the form of an ordination diagram. A situation map was made in ArcGIS 10 software (Esri, USA).

In all cases, the assumption of normality was tested by the Shapiro-Wilk normality test. All computations were performed in R software (R Core Team, 2020). All plots except for PCA diagram were made in R package "ggplot2" (Wickham, 2016). The alpha level was set to 0.05 for all statistic tests.

3. Results

3.1. Stand production

The comparison of basic stand characteristics (DBH, tree height and stem volume) showed significant differences in all cases when compared

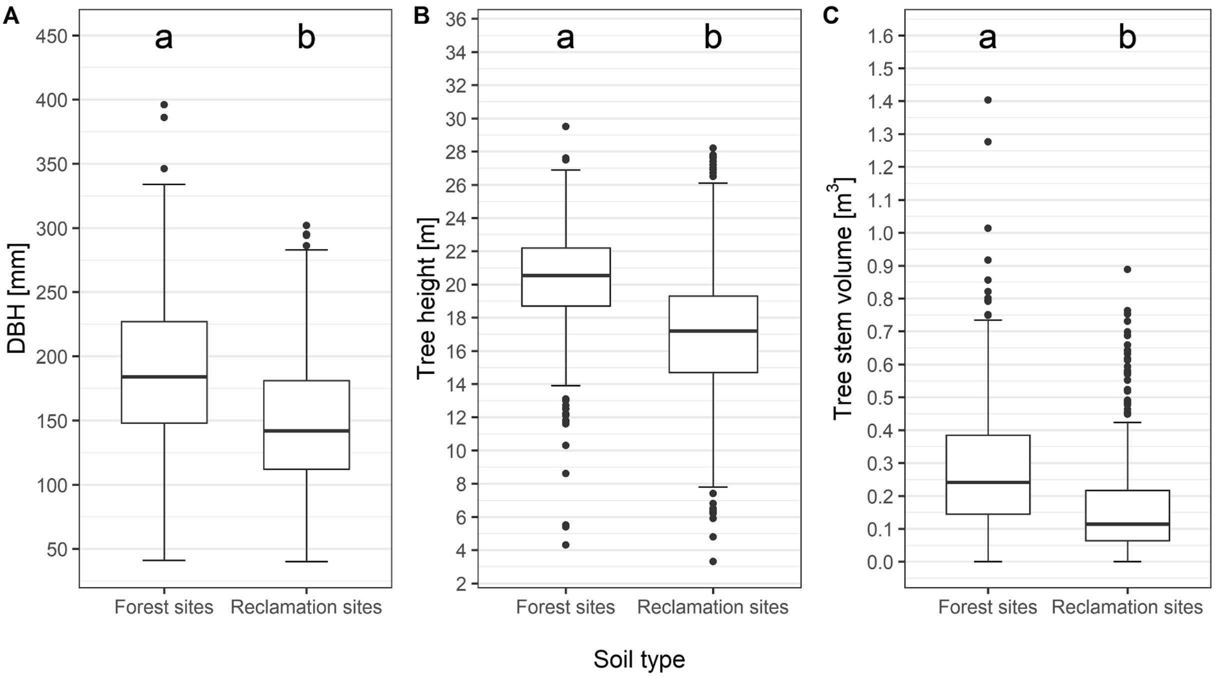

Fig. 2. The differences between selected site types in DBH (plot A), tree height (plot B) and tree stem volume (plot C) for all locations combined; Indices above the variants in boxplots depict statistically significant differences (significantly different variants are marked with a different letter).

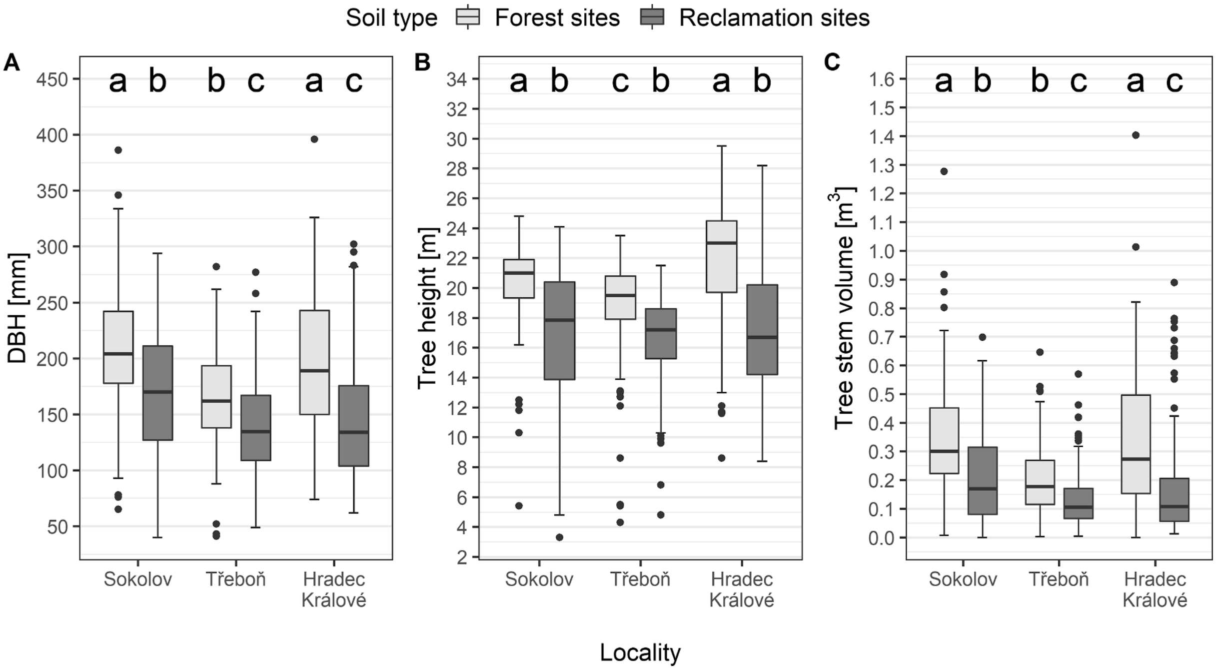

Fig. 3. The differences between selected area–site type combinations in DBH (plot A), tree height (plot B) and tree stem volume (plot C); Indices above the variants in boxplots depict statistically significant differences (significantly different variants are marked with different letter).

between site types across all study areas (Wilcoxon rank-sum test; $p < 0.001$ in all cases; Fig. 2). The observed DBH was lower by 21%, the tree height was lower by 16%, and the tree stem volume was lower by 43% on reclamation sites compared to original forest sites.

Significant differences were also obtained for comparison of these parameters between all area–site type combinations for all three parameters (Kruskal-Wallis test; $p < 0.001$ in all cases; Fig. 3). The results of multiple comparisons are depicted in a relevant plot. The overall analysis of DBH, tree height and tree stem volume between all area–site type combinations confirmed significant differences between site types in all three locations (higher values were observed on original forest sites in all 3 cases). The stands on original forest sites in the Sokolov and Hradec Králové regions were similar in all parameters, while all three parameters showed lower values in the case of the Třeboň region. The stands on reclamation sites in Sokolov showed significantly higher values of DBH and tree stem volume compared to stands on reclamation sites in other areas.

Basic stand characteristics (described in Table 2) were statistically compared between site types separately for each location. The results of testing, together with respective mean values, are presented in Table 3. In all cases (except the stand density index), differences between sites (forest vs. reclamation) in one location were observed. In terms of tree

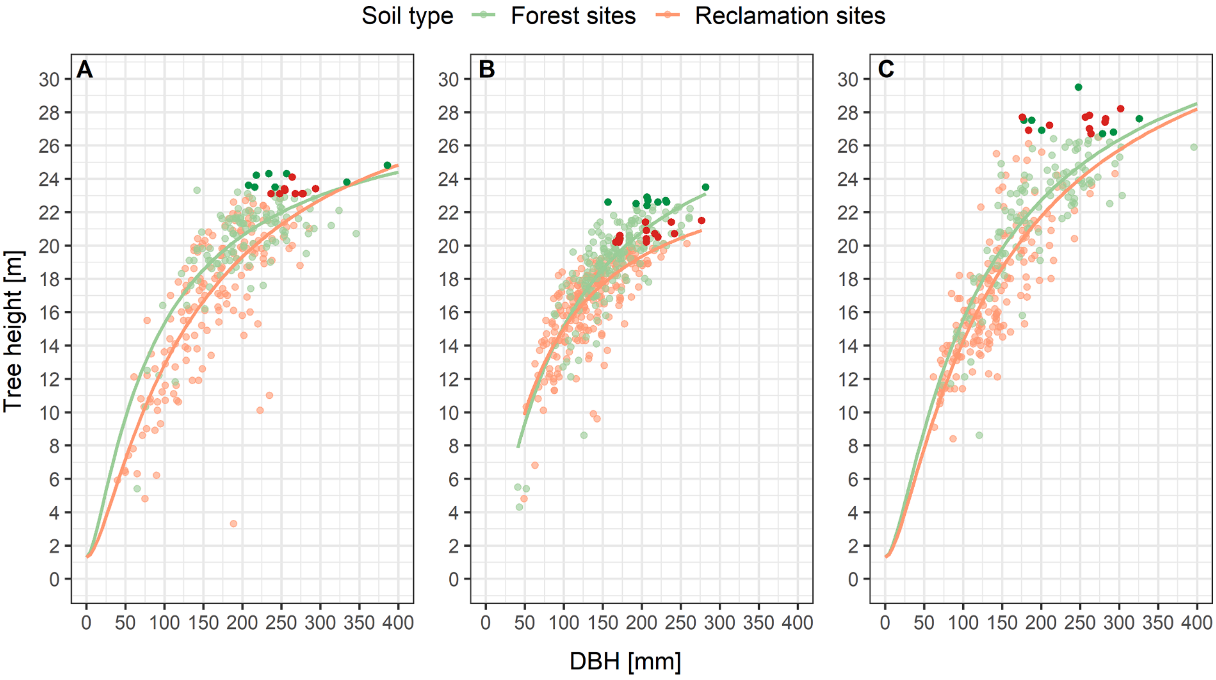

Fig. 4. Näslund height-diameter curves for dominant trees in both site types in each study area (plot A – Sokolov, plot B – Třeboň, plot C – Hradec Králové).

parameters, the highest differences between original forest sites and reclamation sites were observed in the poorest area, the Třeboň region, with no significant differences in the stand parameters. It was caused by a significantly higher tree density on the reclamation site ($p < 0.001$). Comparing all locations with each other, the number of trees ranged between 1355–1911 trees ha^{-1} on forest soils, and 1689–2822 trees ha^{-1} on reclamation sites. In terms of stand parameters, the highest differences between original forest sites and reclamation sites were in the nutrient-rich area of the Sokolov region, where the lowest differences between sites – in relation to tree parameters – were observed.

Comparing research plots in all areas, the stand volume was significantly (*t*-test, $p < 0.001$) higher (by 22%) on original forest sites (370–500 m^3 ha^{-1}) compared to reclamation sites (318–371 m^3 ha^{-1}). Similarly, the dominant height was significantly (*t*-test, $p = 0.014$) higher on original forest sites. When comparing the reclamation stands between study areas, the lowest stand volume was on the former sand dune – the Hradec Králové region (318 m^3 ha^{-1}), while the highest was observed on the coal spoil heap – the Sokolov region (371 m^3 ha^{-1}), with the differences being insignificant (ANOVA, $p = 0.59$). On the other hand, there were significant (Kruskal-Wallis test, $p = 0.08$) differences in the dominant height between areas in the case of reclamation sites. The highest h_{DOM} was observed for the Hradec Králové region (22.62 m), compared to the lowest value (20.00 m) in the Třeboň region. The mean annual increment was in the range of 8.81–10.87 m^3 ha^{-1} y^{-1} on original forest sites and 7.07–8.43 m^3 ha^{-1} y^{-1} on reclamation sites. There were also significant differences observed between original forest sites and reclamation sites (*t*-test, $p = 0.001$), such as in the case of biomass (*t*-test, $p = 0.002$). The amount of biomass was higher by 19% on original forest sites (332–422 t ha^{-1}) compared to reclamation sites (287–325 t ha^{-1}) across all areas.

Näslund height-diameter curves were constructed for both soil types in each of the study locations. The height-diameter curves have different courses, but in all localities, the curves for the original forest sites are higher above the curves for the reclamation sites (Fig. 4). The computed *a* and *b* equation parameters are described in Table 4.

3.2. Stand structure and diversity

The differences in selected diversity indicators between site types were statistically tested separately for each area (similarly as in the case of production parameters, Table 3). The results of testing the site types together with their respective mean values are presented in Table 5. Comparing all structural indices, the highest differences in diversity between original forest sites and reclamation sites were in Třeboň (sand quarry). The Třeboň region was also specified by a regular horizontal structure of trees on reclamation sites, while in all of the other cases, the spatial pattern of the tree layer was random. The vertical structure according to *A* index was significantly higher in reclamation sites compared to original forest sites (t – *t*-test, $p = 0.001–0.046$), except the Hradec Králové region, where the vertical structure was higher on original forest sites according to *S* index. Generally, only in two cases (from all monitored indices), the diversity was significantly higher on the original forest sites (*A* and *B* index in Hradec Králové) compared to 6 cases on the reclamation sites.

Table 5
Mean diversity indicators of the stand structure in the study area of the Sokolov (1S), Třeboň (2T) and Hradec Králové regions (3H) on reclamation sites (R) and original forest sites (F).

PRP	**R**[*]	**A**	**S**	**TM_d**	**TM_h**	**K**	**B**
	(C&Ei)	(Pi)	(J&Di)	(Fi)	(Fi)	(J&Di)	(J&Di)
1S_R	1.065	0.485	0.649	0.268	0.194	1.154	3.823
1S_F	1.171	0.281	0.375	0.231	0.105	0.770	2.554
2T_R	1.205^R	0.487	0.467	0.259	0.124	0.819	2.932
2T_F	1.178	0.244	0.378	0.226	0.099	0.567	2.372
3H_R	1.079	0.378	0.393	0.254	0.128	0.541	2.492
3H_F	1.026	0.376	0.477	0.262	0.138	0.594	2.868
Testing for differences between site types							
1S	0.057	**0.046**	0.593	0.056	0.355	0.065	**0.030**
2T	**<0.001**	**0.001**	0.122	**<0.001**	**0.001**	0.434	0.149
3H	0.050	0.201	**0.045**	0.073	0.139	0.128	**0.026**

Notes: R – aggregation index, A – species profile index, S – vertical diversity, TM_d – index of diameter differentiation, TM_h – index of height differentiation, K – index of crown differentiation, B – stand diversity index

[*] Statistically significant ($\alpha = 0.05$) for horizontal structure (^{A} – aggregation, ^{R} – regularity). P-values in bold depict statistically significant results.

In terms of structural differentiation, the crown differentiation showed no differences between sites. Both the height and diameter differentiation were significantly higher on the reclamation sites in the Třeboň region (sand quarry), compared to the original forest sites (t – *t*-test, $p = 0.001$). For the following description of the tree diameter structure, a simple bar plot of diameter classes (histogram) was constructed (Fig. 5). In all cases, the diameter distribution had the shape of a Gaussian curve characteristic for even-aged stands. The diameter class of 16–20 cm was the most frequently represented on the original forest sites, while the class of 12–16 cm was higher on the reclamation sites. For stands on the original forest sites, a shift to higher diameter classes was observed compared to reclamation sites. The largest convex shape of the diameter curve is shown in the case of the former sand quarry in Třeboň.

In terms of total diversity, the *B* index showed insignificant differences between original forest sites and reclamation sites (Wilcoxon rank-sum test, $p = 0.08$), while the mean higher value was observed for reclamation sites ($B = 3.082$), compared to original forest sites ($B = 2.598$) across all study areas. However, comparing stands on reclamation sites between study areas, *B* index showed significant differences (Kruskal-Wallis test, $p = 0.02$). The highest value was observed in the case of Sokolov (coal spoil heap), followed by Třeboň (former sand quarry) and Hradec Králové (transformed sand dune). Multiple comparisons showed significant differences between the Sokolov and Hradec Králové regions ($B = 3.823$ in Sokolov and 2.492 in Hradec Králové).

3.3. Dynamics of radial growth in relation to climate

The largest mean value of tree-ring width was found for pine stands in the Sokolov location, and the lowest mean was found for Hradec Králové (Supplementary material). Comparing reclamations with each other, the highest radial growth was observed on the coal spoil heap (3.449 mm ± SD 1.356), and the lowest on the transformed sand dune (1.995 mm ± SD 0.566). The tree-ring width was nearly balanced between both site types, higher by 2.2% on original forest sites compared to reclamation sites. Original forest sites also showed a lower variability in radial growth (by 7.0%) compared to reclamation sites. The SNR shows the best dendrochronological pattern (without any noise) for the former sand dune (the Hradec Králové region) and the poorest for the original forest site in the Třeboň region. This indicates that these variants with a higher SNR are more homogeneous than variants with a low SNR. A generally higher SNR, such as R-bar, was observed for reclamation sites. The necessary condition of $EPS > 0.85$ was fulfilled in all cases (Supplementary material).

The dynamics of radial growth in 1985–2019 with the occurrence of NPY is mentioned in Supplementary material. Growth dynamics did not vary significantly between both site types (forest vs. reclamation sites). Only at reclamation sites in Sokolov (coal spoil heap), one more NPY (1992) was observed. Significantly extreme low radial growth in the mentioned year was caused by an above-average warm beginning of the year, combined with the lowest amount of precipitation in May (17 mm, average 61 mm), and the longest-lasting sunshine (299 h, average 200 h) in the study period of 1985–2019. Negative year 2003 was characterized by the historically shortest sunshine in May (91 h, 200 h), and an extremely dry July (precipitation lower by 57%). No NPY was observed in the Třeboň region, but significantly lower radial growth of pine in

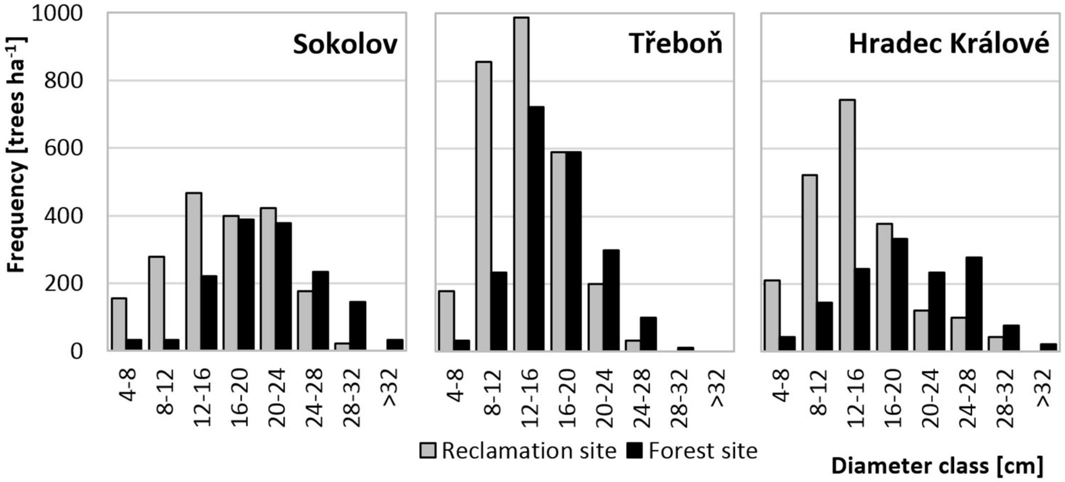

Fig. 5. Diameter structure of pine stands on permanent research plots in the study area of the Sokolov, Třeboň and Hradec Králové regions, differentiated according to the site (reclamation vs. forest).

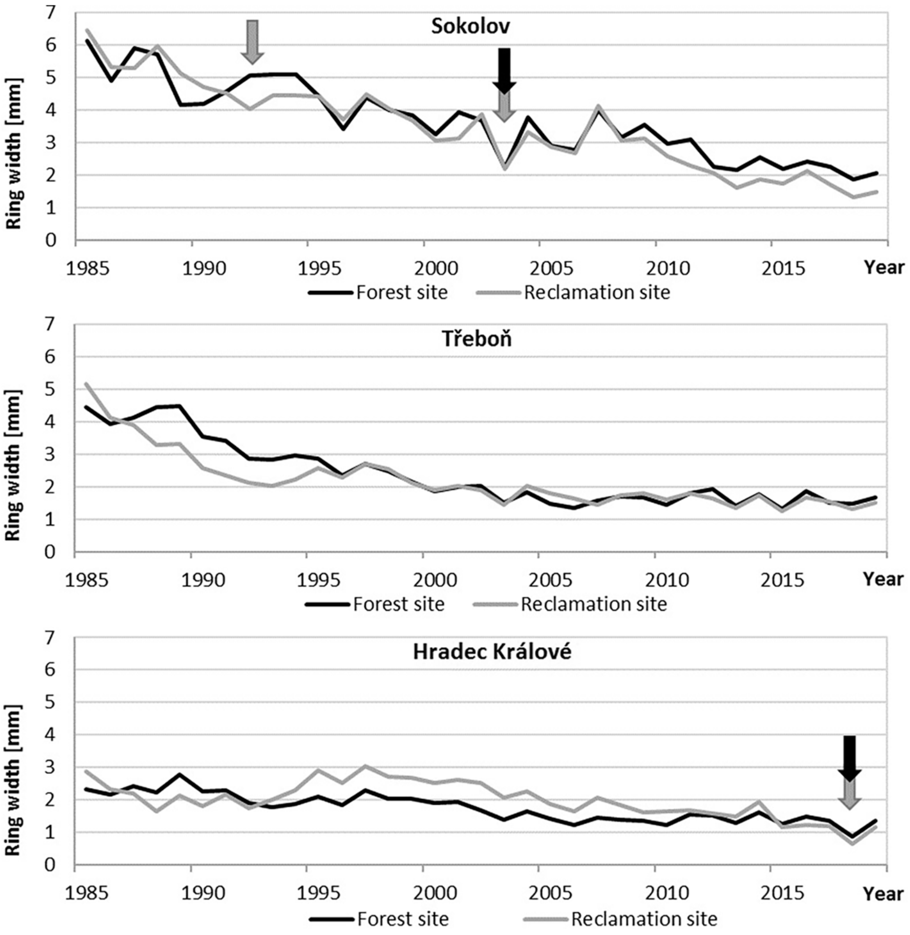

Fig. 6. Ring width (in mm) of Scots pine on original forest sites (black line) and reclamation sites (gray line) in study areas (the Sokolov, Třeboň, Hradec Králové regions) in 1985–2019; arrows indicate negative pointer years with significantly extreme low radial growth.

1987–1996 was observed in the former sand quarry, compared to the original forest site. In the Hradec Králové region, extremely low radial growth in 2018 was caused by synergism of the driest (508 mm, average 743 mm) and warmest year (9.7 °C, average 7.7 °C) in history. Moreover, an extremely warm beginning of the vegetation period was observed that year – 14.4 °C in April (average 9.2 °C) and 17.9 °C in May (average 14.1 °C) – together with insufficient precipitation (see Fig. 6).

Significantly higher differences between reclamation sites and original forest sites were observed in terms of the monthly air temperature effect, and the sum of precipitation on the radial growth of pine (Fig. 7). Generally, climatic factors had a higher effect on pine growth on reclamation sites (16 significant months), compared to original forest sites (10 months), especially in relation to precipitation (9 vs. 4 months). In terms of monthly air temperature, the highest positive effect on radial

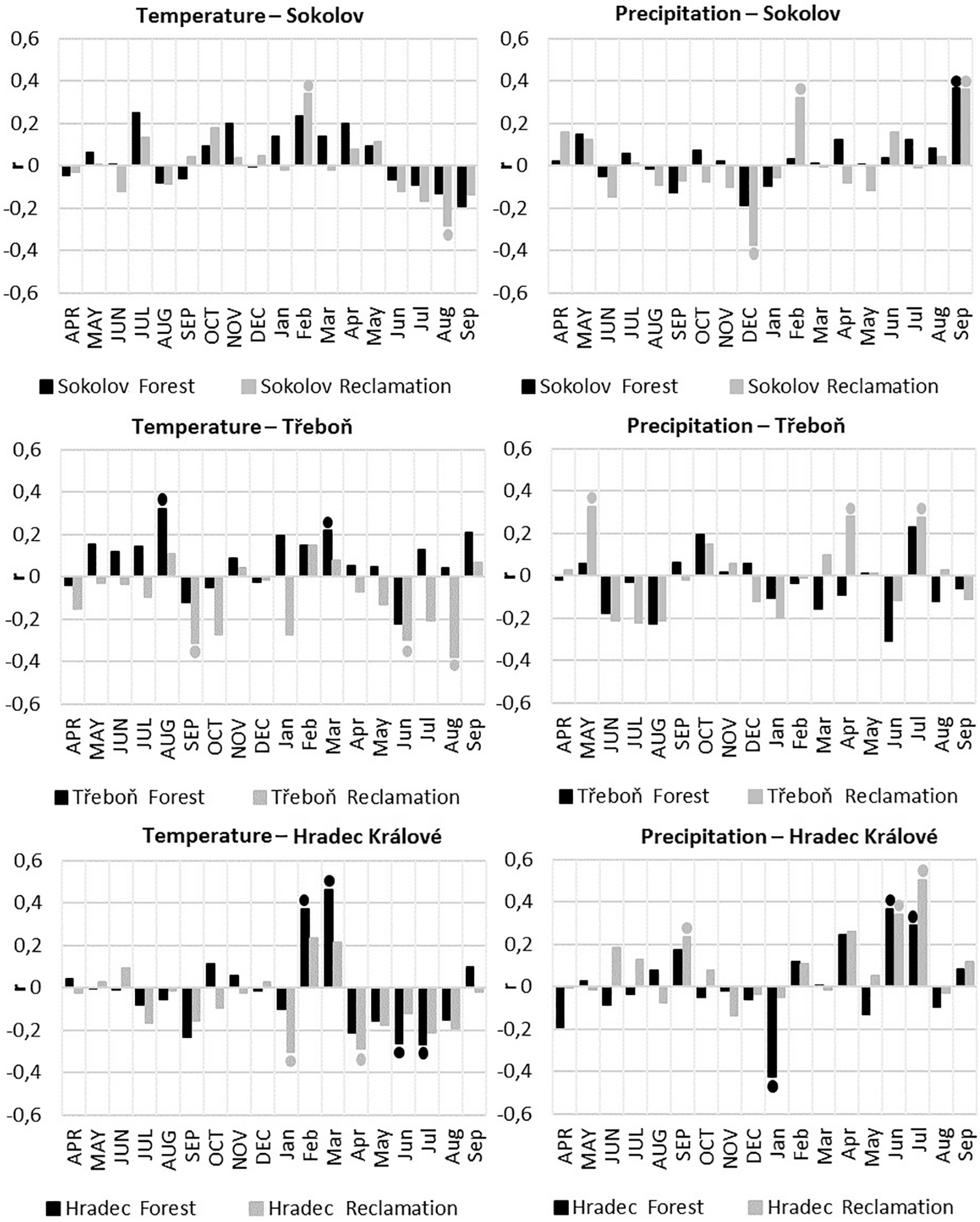

Fig. 7. Coefficients of correlation of the regional residual index tree-ring chronology of Scots pine with the monthly average air temperature, and the sum of precipitation from April of the previous year (capital letters) to September of the current year (lower-case letters) on forest (black) and reclamation sites (grey) in the studied areas (Sokolov, Třeboň and Hradec Králové) in 1985–2019; statistically significant ($p < 0.05$) values are shown by dot.

growth was observed in March (r = 0.22–0.46), and a negative effect in the period from July to August (r = −0.26 to −0.37) of the current year. With regard to the precipitation sum, the radial growth was most affected in the period from May to June. Specifically, the highest positive correlation to the monthly sum of precipitation and radial growth was observed in July of the current year (r = 0.50). Overall, the temperature and precipitation had the same effect on radial growth in relation to the same number of significant months. The main limiting factors of pine growth was the lack of precipitation and high temperature, both during the vegetation period.

3.4. Interactions between production, structure, diversity and sites

The results of PCA are presented in an ordination diagram in Fig. 8.

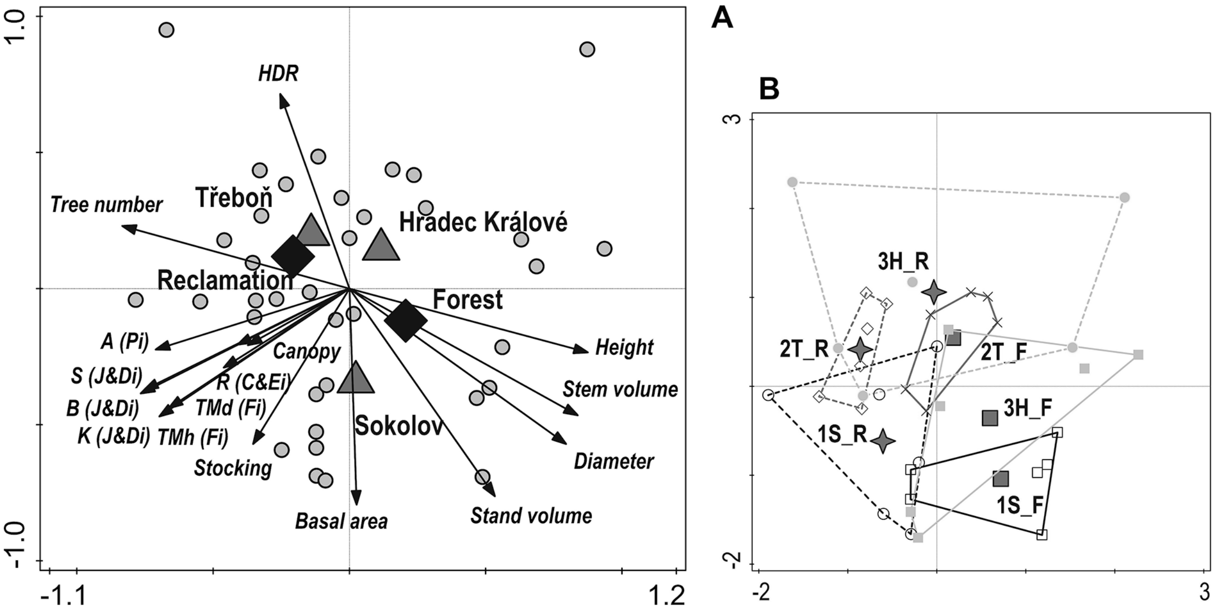

Fig. 8. Ordination diagram showing results of the PCA analysis of relationships between the stand characteristics (stand volume, tree volume, basal area, diameter, height, tree number, canopy – crown closure, stocking – stand density index), structural diversity [*R* (C&Ei), *A* (Pi), *TMd* (Fi), *TMh* (Fi), *S* (J&Di), *K* (J&Di), *B* (J&Di); see Table 2 for notes], variants of sites (R – reclamation site and F – original forest site) and study areas (S – Sokolov, T – Třeboň, H – Hradec Králové); Symbols indicate in plot A ◆ site variants, ▲ areas and ● 36 permanent research plots, and in plot B ■ original forest sites and ✦ reclamation sites.

The first ordination axis explains 39.8% of data variability, the first two axes together explain 62.5% and the first four axes 84.3%. The x-axis illustrates the number of trees along with the mean stand height, while the y-axis represents the height to diameter ratio and basal area (Fig. 8A). Tree characteristics (tree volume, diameter, height) were positively correlated to each other, while these parameters were negatively correlated with the number of trees. The diversity indices showed close positive correlation to each other. The total diversity, vertical structure and structural differentiation increased with stocking (stand density index) and the canopy of trees. The basal area was positively correlated to the stand volume and stocking, while these parameters were negatively correlated with the height to diameter ratio. Aggregation index and canopy were the lowest explanatory variables in the ordination diagram. In terms of the locations, differences among all parameters were remarkable for the Sokolov region in comparison to the other two studied areas, as marks of each record were relatively distant from one another, while the marks representing the areas of Třeboň and Hradec Králové were relatively close to each other. The variants of the two studied sites only have a minor effect on the diversity and structure, but the productivity was significantly influenced by their historical land use. High production parameters (basal area, stand volume etc.) were characteristic of original forest sites, while the high number of trees and low production were a typical feature of reclamation sites. Reclamation sites (compared to original forest sites) had higher stand variability between permanent research plots in one area, especially in the Hradec Králové region (Fig. 8B).

4. Discussion

Our study was focused on Scots pine, the most widespread tree species in Eurasia (Durrant et al., 2016; Farjon, 2018). Due to the very wide ecological amplitude, this species is one of the most important commercial trees in Europe (Forrester et al., 2017; Sharma et al., 2017), even with regard to the ongoing global climate change (Vacek et al., 2019, 2017). For these reasons, Scots pine is often used in the afforestation of post-mining and reclamation areas (Jagodziński et al., 2019; Kompala-Bąba and Bąba, 2013; Kuznetsova et al., 2010; Pietrzykowski, 2008; Pietrzykowski and Socha, 2011), such as in our case (a post-mining coal site, a former sand quarry and a transformed sand dune). Pine stands in the studied afforested reclamation locations were characterized by satisfactory growth parameters, which confirms its high adaptability to post-mining sites (Woś and Pietrzykowski, 2019). The stands compared in our study were 40–46 years old, with the stand volume reaching 318–371 m^3 ha^{-1} on the reclamation sites, and 370–500 m^3 ha^{-1} on the original forest sites (higher by 22.4%). The mean annual increment on the reclamation sites reached 8.0 m^3 ha^{-1} y^{-1}, while it was higher by 25.0% on the original forest sites. A lower value was observed in Estonia, where MAI of pine stands on the spoil of an opencast oil shale mine reached 6.3 m^3 ha^{-1} y^{-1} (Pensa et al., 2004). A similar stand volume of 330 m^3 ha^{-1} with the tree density of 780 trees ha^{-1} was observed in a substantially older (66 years) pine stand on lignite mine spoils in Germany (Knoche, 2005). In our study, the number of trees per hectare was 1689–2822 on reclamation sites, and 1355–1911 trees ha^{-1} on original forest sites (lower by 26.2%). It is in the range (1950–2150 trees ha^{-1}) of another study of a post-mining coal site from the Czech Republic, where the stand volume at a similar age (40 years) reached 294–378 m^3 ha^{-1} (Dragoun et al., 2015).

The divergency in the stand volume and number of trees (forest vs. reclamation sites) might be caused by different soil conditions (texture, nutrition availability etc.; Pietrzykowski 2014) and insufficient thinning interventions influencing the stand density (Bílek et al., 2016; Štefančík et al., 2018; Vacek et al., 2020a), although forest stands in both variants should have the same forest management in study areas. In our case, the most productive reclamation site in relation to timber was the coal spoil heap (Sokolov region). Similarly, the most fertile habitat of reclamation sites in Poland was a lignite spoil heap compared to a sand quarry and a sulfur spoil heap (Pietrzykowski, 2014). The same study documented that the poorest site was the sand quarry. We also confirmed the sand quarry (Třeboň region) as the reclamation site with the lowest stand production. However, all afforested reclamation sites are characterized by a formidable productivity and growth of pine in relation to specific soil conditions. In these extreme sites, Scots pine used the nutrients most efficiently when compared to other tree species commonly grown in post-mining areas, for example, black alder [*Alnus glutinosa* (L.) Gaertn.] or silver birch (*Betula pendula* Roth.) (Kuznetsova et al., 2011).

In a number of studies, biomass is evaluated as an important production parameter. In southern Finland, Vanninen et al. (1996) presents an average amount of pine tree biomass at a comparable age (41–44 years) reaching 164 kg, while in our study, the amount of biomass reached an average 197 kg per tree. When converted to all stand per hectare, the biomass of pine stands at the age of 50 reached an average of 170 t ha^{-1} in the Polish lowlands (Orzeł et al., 2005). In our study, it was significantly higher; the amount of biomass reached 287–324 t ha^{-1} on reclamation sites, and 332–422 t ha^{-1} on original forest sites (higher by 19.1%). In southern Poland, research on a pine stand of 21–30 years documents biomass higher by 48.9% in forest stands compared to post-mining sites (Pietrzykowski and Socha, 2011). The available data show that the biomass of pine is lower on reclamation sites than on original forest sites. These results are always more or less influenced by the given habitat and stand conditions, especially the stand density, genetic characteristics of trees, forest management, and last but not least, the method of biomass determination (Jagodziński and Kałucka, 2008; Orzeł et al., 2005; Poorter et al., 2015; Rademacher et al., 2009). Castedo-Dorado et al. (2012) and Jagodziński et al. (2019) consider the stand density to be the weakest factor in determining the stand biomass of the Scots pine. In our paper, SDI reached 0.94–1.09 on reclamation sites and 0.96–1.10 on original forest sites. Pietrzykowski and Socha (2011) quote SDI 0.68–0.89 in Scots pine post-mining stands, and 0.74–1.04 in forest stands.

In terms of diversity, the differences were not as significant as in the case of production parameters, yet the diversity was predominately higher on original forest sites compared to reclamation sites. The significant difference was observed in the species profile index A; the vertical diversity was higher on reclamation sites (A = 0.38–0.49) compared to original forest sites (A = 0.24–0.38), especially in the case of the Třeboň region. A similar value of A index was found in the pine stands of the post-mining area (A = 0.38–0.67). This case study also reports that the complex total diversity B index was in the range of 3.96–4.43, characterizing an even structure. A lower total diversity was observed, in favor of reclamation sites, but there was no significant difference between both variants (B = 2.60 vs. 3.08). Similar total diversity (B = 3.01) was observed in a Scots pine forest of the age 35 in an arboretum in Central Bohemia (Podrázský et al., 2020). A similar or higher diversity from Scots pine stands are reported in other studies from different parts of the Czech Republic and Spain (Bílek et al., 2016; Gallo et al., 2020; Vacek et al., 2016a,b; 2019, 2017).

Regarding dendrochronology, the highest radial growth on reclamation sites was also observed in the coal spoil heap (the Sokolov region). The occurrence of NPY showed small differences between original forest sites and reclamation sites. In the Sokolov location (the coal spoil heap), extreme low radial growth in 1992 was caused by an above-average warm beginning of the year, long-term droughts, and intensive sunshine throughout the vegetation period. Similarly, a study from lowland relict pine forests showed that the lack of precipitation in the vegetation period, and high temperatures in winter were the main limiting factors for radial growth (Vacek et al., 2019). Also, NPY 2013 in the Sokolov region was caused by an extremely dry vegetation period with a lack of sunshine. Apart from precipitation and temperature, the length of sunshine and overcast weather during the vegetation period can significantly affect the radial growth of trees (Vacek et al., 2020b; Williams et al., 2008). Negative pointer years 2018 for both variants in the Hradec Králové region were caused by synergism of the historically driest and warmest year, especially climate extremes in the beginning of the vegetation period.

On the other hand, significant differences between the sites (reclamation vs. forest) were observed through the effect of monthly climatic factor on radial growth. Reclamation sites were more sensitive to climatic factors' influence on radial growth compared to original forest sites, especially the lack of precipitation. Other studies from the Mediterranean and the boreal regions confirm that drought is a determining factor in the radial growth of Scots pine (Augustaitis et al., 2007; Bogino et al., 2009; Oberhuber et al., 1998). In terms of temperature, the highest positive effect of temperature on radial growth was observed in March. Similarly, Vacek et al. (2017) showed March as the most important month, temperature-wise, for pine growth. As confirmed by our study, precipitation had the highest effect from June to September. Generally, June and July were observed to be the most significant months in relation to the effect of climate. Such findings were also confirmed by other studies dealing with radial growth of pine forests (Vacek et al., 2016a,b; Vacek et al., 2019). This is caused by the climatic conditions in those two months, when the fastest xylem formation and radial increment were recorded (Mäkinen et al., 2003; Putalová et al., 2019).

Afforestation plays a very important role in restoration of the damaged landscape. In Poland, for example, the area of post-mining lands – reclaimed and managed as commercial forests – amounts to 60% of all land restored (Pajak et al., 2016). The above results show that Scots pine is a very suitable tree species for afforestation of reclamation sites. This is the reason why Scots pine is frequently used for afforestation of reclaimed areas in Europe (Knoche, 2005; Likus-Cieślik and Pietrzykowski, 2017; Pietrzykowski, 2014), such as in the Czech Republic (Šebelíková et al., 2016). However, we must not forget other suitable trees for afforestation of reclamation sites. Apart from Scots pine, there are also silver birch, black alder, European larch (*Larix decidua* Mill.), small-leaved lime (*Tilia cordata* Mill.), poplars (*Populus* spp.) and oaks (*Quercus* spp.), the stands of which are characterized by good growth parameters, confirming high adaptability of these tree species to post-mining sites (Kuznetsova et al., 2011; Vacek et al., 2018, Woś and Pietrzykowski, 2019). Introduced tree species such as black locust (*Robinia pseudoacacia* L.), ponderosa pine (*Pinus ponderosa* Douglas ex C. Hawson), black pine (*Pinus nigra* J. F. Arnold) and Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] can also be an appropriate choice for afforestation in relation to production, good stability and growth adaptation to these specific sites (Pająk et al., 2004; Podrázský et al., 2020). However, it is important to use a suitable tree species for the given habitat and soil conditions (Pietrzykowski, 2014), preferably in a mixture that can increase the productivity of stands in the reclamation areas (Dragoun et al., 2015).

5. Conclusion

Research has shown that Scots pine at this particular stage of the stand development adapts well to new environmental conditions on post-mining sites. On the afforested reclamation sites, the productivity and growth of pine are relatively high compared to the stands on the original forest sites. At the same time, a higher stand volume and overall production were observed on all forest soils in comparison to reclamation sites (by 9–32%). The stand characteristics of the compared variants of forest stands were influenced by the methods of forest management. In particular, thinning operations were less intensive on reclamation sites, which resulted in higher numbers of trees compared to original forest sites. However, structural parameters and diversity indicators were mostly higher for reclaimed areas. On the other hand, climatic factors had a higher effect on radial growth in the case of reclamation sites compared to forest sites, especially in terms of precipitation. Moreover, there was no significant difference between the two variants in terms of extreme fluctuations in radial growth (negative pointer years). The analyses show that Scots pine has a favorable adaptability potential to the climate factors and habitat of the given soil conditions. Due to its undemanding nature, Scots pine is recommended for afforestation of reclamation sites, especially on poor and dry sandy soils, exacerbated by the ongoing climate change.

CRediT authorship contribution statement

Zdeněk Vacek: Conceptualization, Data curation, Resources, Writing - original draft, Writing - review & editing, Methodology. **Rostislav Linda:** Conceptualization, Data curation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Jan Cukor:** Data curation, Funding acquisition, Resources, Project administration, Validation, Writing - original draft, Writing - review & editing. **Stanislav Vacek:** Conceptualization, Methodology, Validation, Supervision, Writing - original draft. **Václav Šimůnek:** Data curation, Writing - original draft. **Josef Gallo:** Data curation, Writing - original draft. **Karel Vančura:** Data curation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.118951.

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