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Stanislav Vacek [1], Zdeněk Vacek [1], Lukáš Bílek [1], Jaroslav Simon [2], Jiří Remeš [1], Iva Hůnová [3], Jan Král [1], Tereza Putalová [1] and Miroslav Mikeska [4]

Structure, regeneration and growth of Scots pine (*Pinus sylvestris* L.) stands with respect to changing climate and environmental pollution

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Highlights

- Pine forest stands showed positive development of stand structural characteristics related to their diversity, number of regeneration individuals and growth characteristics.
- Tree-ring width was positively correlated with precipitation, while it was negatively correlated with temperature in growing seasons.
- Mean NO_x concentrations showed positive effect on radial growth of pine.
- Serious defoliation was caused by SO_2 concentrations and N deposition in combination with extreme climate events.

Abstract

Changes in the structure and development of managed Scots pine (*Pinus sylvestris* L.) stands with respect to changing environmental conditions were set for the period 1979–2015. The study was conducted in conditions of natural pinewoods and pine-oak sites on five permanent research plots (0.25 ha) in Eastern Bohemia, Czech Republic (CR). Studied forest stands showed positive development of stand structural characteristics related to their diversity, number of regeneration individuals and growth characteristics. The standing volume of regularly distributed tree layer in 2015 was in the range of 320–434 m^3 ha^{-1}, which indicates an increase by 5.9–20.0% over 10 years. Correlation between pine radial increment and the amount of precipitation was generally the strongest one. Positive statistically significant correlation between diameter increment and temperature was demonstrated only for the average March temperature of the current year. Within the CR, study site can be characterised as a medium polluted area both for sulphur and nitrogen, despite this SO_2 concentrations and N deposition in combination with extreme climate events caused severe defoliation in pine stands. Conversely, radial growth was positively significantly correlated with mean NO_x concentrations. Drought mainly in combination with even medium environmental pollution can further worsen the health status of pine stands in lowland areas of Central Europe. Thus, formulation of silvicultural techniques able to mitigate the impact of these stress factors is needed.

Keywords *Pinus sylvestris*; stand development; natural regeneration; air-pollution; climate; production

Addresses [1] Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, 165 21 Prague, Czech Republic; [2] Mendel University in Brno, Faculty of Forestry and Wood Technology, Zemědělská 3, 613 00 Brno, Czech Republic; [3] Czech Hydrometeorological Institute, Na Šabatce 17 143 06 Prague, Czech Republic; [4] University of Hradec Králové, Faculty of Science, Rokitanského 62, 500 03 Hradec Králové, Czech Republic
E-mail remesj@email.cz
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1 Introduction

Pinewoods take up a special position in vegetation development and zonality of the Czech Republic (Chytrý et al. 2010). These soil-exposed sites overshadow climate differences by their typical nature and strongly restrict the competitive capability of the major part of vegetation (Mikeska et al. 2008). Scots pine (*Pinus sylvestris* L.) as a pioneer tree species has relatively high requirements for light and its natural regeneration under the canopy of other tree species is relatively rare (Carlisle and Brown 1968; Richardson 1998; Poleno and Vacek 2009; Gaudio et al. 2011).

Pinewoods in lowland areas of Central Europe are often situated on poor and dry sandy soils while in these conditions expected climate changes can even result in more extreme dry and warm periods within the growing season (Briffa et al. 2009; Dubrovský et al. 2009). This may have further negative ecological impact on these sites with low water availability (Slodičák et al. 2011).

Species diversity, variability of tree size and heterogeneity in the spatial pattern of trees belong among the main factors of the forest stand structure (Pommering 2002; Puettmann et al. 2008; Vacek et al. 2014). The analysis of spatial pattern can provide a valuable information about intraspecific and interspecific competition or tree species responses to changing conditions of the environment (Nicotra et al. 1999; Keitt et al. 2002). The spatial structure can help to explain micro-climatic changes, the origin of natural regeneration and the role of gap dynamics in this process (Zenner and Hibbs 2000; Bílek et al. 2014). Information on the stand structure also contributes to the better understanding of history, forest functions and future development of forest ecosystems (Franklin et al. 2002; Moser et al. 2002). Variability in the spatial pattern is a result of interacting biotic and abiotic ecological processes (Gholz et al. 1990; Franklin and Van Pelt 2004; Tuten et al. 2015), and is determined especially by relations between neighbouring trees and their groups (Hui et al. 2011). Spatial variability is also important for the development of ecosystem communities in the understorey (Fahey and Puetmann 2008; Bulušek et al. 2016).

Currently, small-scale close-to-nature forest management gains more and more attention among forest managers and researches as a management system that increases resistance of forests and their capacity of adapting to ongoing climate changes (Franklin et al. 2007; Allen et al. 2010; Smith 2011; Lloret et al. 2012; Cavin et al. 2013; Churchill et al. 2013; Reynolds et al. 2013; Merlin et al. 2015). Although pinewoods are an important component of Central European forest ecosystems, little attention has been paid to possibilities of creating more complex forest structures in this type of forest dominated by light demanding pine, oaks (*Quercus* spp.) and birch (*Betula* spp.) (Kint et al. 2009; Orczewska and Fernes 2011; Matuszkiewicz et al. 2013).

The aim of the present study was to monitor changes in the structure and development of managed Scots pine stands on their natural sites with respect to changing climate as well as air-pollution characteristics during the last decade. We hypothesise that climatically extreme periods characterized by extremely low precipitation and above-average temperatures in the vegetation period have negative effect on the radial growth and foliation of pine, while lower deposition of pollutants has an opposite effect. Better knowledge of these processes may be important for the formulation of best silvicultural techniques in lowland pine regions in Central Europe.

2 Materials and methods

2.1 Description of the territory of interest

The study was conducted in conditions of managed Scots pine stands on natural pinewoods and pine-oak sites on five permanent research plots (PRP) in the Třebechovicko microregion in the northeast of the Czech Republic. PRP are 50 × 50 m in size (0.25 ha) and are situated on a flat relief. Fig. 1 shows PRP localization while Table 1 documents basic data on PRP. These PRP are typical of Scots pine natural sites in conditions of central Europe (Mátyás et al. 2004).

According to Quitt (1976) the climate is characterized with long, warm and dry summer, short transition period with moderately warm spring and moderately warm autumn. Winter is short, moderately warm and very dry, with short duration of snow cover. Average annual temperature is 6.9 °C according to the 1961–1990 climate normal, in the studied period it was 8.3 °C; average annual normal of precipitation amount is 774 mm, in the studied period it was by 5.9% lower (728 mm); the vegetation period is around 160 days (meteorological station Hradec Králové – GPS 50°12´N, 15°51´E).

The PRP order 1–5 classifies plots from the relatively most favourable to the most unfavourable ones in terms of site and stand conditions. It cannot be excluded that PRP 4 and 5 were degraded by litter raking in the past because these are small farm forests not too far from human dwellings.

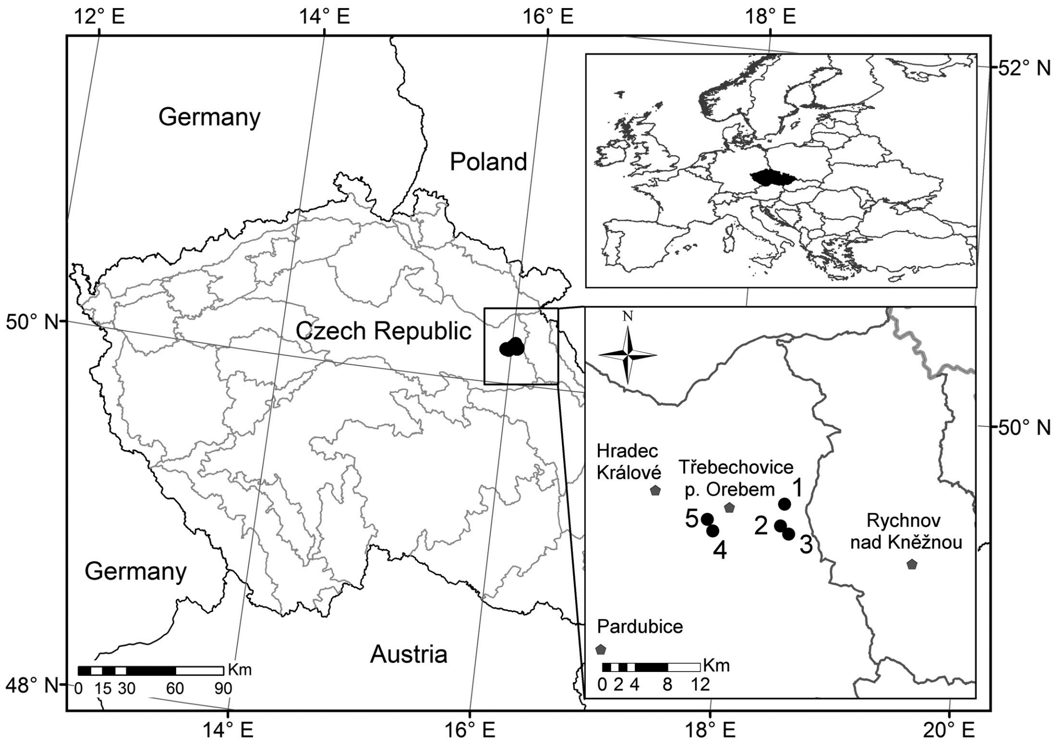

Fig. 1. Location of the permanent research plots 1–5 (black dots) in which the pine stands were investigated.

Table 1. Overview of the basic characteristics of permanent research plots in 2015.

Plot name	GPS	Age	Height m	DBH cm	Volume m^3 ha^{-1}	Altitude m a.s.l.	Forest site type	Soil type
1 Třebechovice 1	50.202°45´N 16.059°01´E	90	21	27	410	267	1M7 - *Pineto-Quercetum oligotrophicum arenosum*	Dystric Arenic Cambisol
2 Třebechovice 2	50.196°27´N 16.056°46´E	80	23	27	380	260	0K1 - *Querceto-Pinetum acidophilum*	Dystric Arenic Cambisol
3 Třebechovice 3	50.196°80´N 16.056°97´E	80	26	21	300	260	0K1 - *Querceto-Pinetum acidophilum*	Podzol Arenic
4 Třebechovice 4	50.192°23´N 15.963°74´E	140	22	30	400	245	0M2 - *Querceto-Pinetum oligotrophicum*	Podzol Arenic
5 Třebechovice 5	50.193°34´N 15.961°96´E	130	24	28	430	245	0M2 - *Querceto-Pinetum oligotrophicum*	Podzol Arenic

2.2 Data collection

To determine the tree layer structure of woody plants of forest ecosystems the FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.) was used for establishment and repeated measurement of five PRP in 2005 and 2015. During measurements the position of all individuals of the tree layer with breast height diameter (dbh) larger than 7 cm was localized. In the tree layer heights of the live crown base and crown perimeter were also measured, minimally at 4 directions perpendicular to each other. Breast height diameters of the tree layer were always measured with a metal calliper to the nearest 1 mm, and tree heights and heights of the live crown base were measured with a laser Vertex hypsometer to the nearest 0.1 m. The tree layer was divided according to tree classes into upper storey (dominant and codominant trees) and lower storey (intermediate and suppressed trees). For individuals of natural regeneration above 1.5 m the same parameters as in the tree layer were measured. In natural regeneration below 1.5 m numbers and heights of individuals of particular tree species were determined in a 5 × 50 m transect on each plot. In deadwood tree species was identified and degree of decomposition was evaluated by a five-point scale according to Fridman and Walheim (2000). Total volume of deadwood and its proportion in the total standing volume were evaluated. Foliation and defoliation was annually estimated with an accuracy of 5%, according to the methodology applied by the ICP-Forests project in period 2005–2015 (Vacek et al. 2015). In 2015 in 30 mainly above-height and next uniform-height pine (dominant and codominant) trees on each PRP increment cores were taken at breast height (130 cm) perpendicularly to the stem axis in the north-south direction using a Pressler borer.

2.3 Data analysis

In all individuals of the tree layer structural and growth parameters, production quantity and quality, horizontal and vertical structure and biodiversity were evaluated on the particular plots. Tree volume was calculated using volume equations published by Petráš and Pajtík (1991).

To determine spatial distribution, index of non-randomness (Hopkins and Skellam 1954), aggregation index (Clark and Evans 1954) and pair correlation function (Stoyan and Stoyan 1992) were computed. The index of cluster size (David and Moore 1954) was used as a distribution index based on tree frequency in the particular quadrats. The size of quadrats on PRP was 10 × 10 m. The PointPro 2.2 program (Copyright 2010 Zahradník, CULS) and the R 3.1.2 software (Copyright 2014 The R FSCP) was used to calculate these characteristics describing the horizontal structure of individuals across the plot. The test of the significance of deviations from the values expected for random distribution of points was done using Monte Carlo simulations. Structural characteristics were computed using the SIBYLA growth simulator (Fabrika and Ďurský 2005). Stand density index (SDI), crown projection area (CPA; the sum of all individual crown projection areas on PRP converted per 1 ha) and crown closure (CC; the horizontal area of PRP covered by crown projections without computing crown overlaps according to Crookston and Stage /1999/) were derived during the study of horizontal structure on PRP. Situational maps were created in the ArcGIS program (Copyright 1995–2010 Esri).

For biodiversity evaluation these indices were computed: diameter differentiation index, height differentiation index (Füldner 1995), species heterogeneity index (Shannon 1948), species evenness index (Pielou 1975), Arten-profil index (Pretzsch 2006), crown differentiation index and stand diversity index (Jaehne and Dohrenbusch 1997). The criteria of the structure indexes are given in Table 2.

Tree-ring width increment series were individually cross-dated (removal of errors connected with the occurrence of missing tree-ring widths) and for determining the degree of similarity a statistical test in the PAST application programme was used (Knibbe 2007) and subsequently subjected to visual inspection according to Yamaguchi (1991). If a missing tree-ring width was found out, a tree ring of 0.01 mm in width was inserted in its place, in this place the increment was probably narrow and was not detected. The ring-width series from PRP were detrended and ring-width chronologies were created from them in the ARSTAN programme. The modified negative exponential function was applied (Grissino-Mayer et al. 1992) because of its capacity to determine short-term trends in past climate. The analysis of negative pointer years was done according to Schweingruber et al. (1990). For each tree the pointer year was tested as an extremely narrow tree-ring that does not reach 40% of the average of increments from previous 4 years. The occurrence of negative year was proved if such a strong reduction in increment occurred at least in 20% of trees on the plot. The standardized ring-width chronologies from PRP were correlated with climatic data (precipitation, temperatures; 1961–2014 from meteorological station Hradec Králové) and with air-pollution data (concentrations SO_2, NO_x, AOT40F /ozone exposure/, S and N deposition /1979–2014/ from meteorological station Svratouch – GPS 49°44´N, 16°02´E) according to the particular years. The DendroClim software was used for modelling diameter increment in dependence on climatic characteristics (Biondi and Waikul 2004). Variances are shown by standard deviation (±SD).

Table 2. Overview of indices describing the stand structure and their common interpretation.

Criterion	Quantifiers	Label	Reference	Evaluation
Horizontal structure	Index of non-randomness	*A* (H&Si)	Hopkins, Skellam (1954)	mean value $A=0.5$; aggregation $A>0.5$; regularity $A<0.5$
	Aggregation index	*R* (C&Ei)	Clark, Evans (1954)	mean value $R=1$; aggregation $R<1$; regularity $R>1$
	Index of cluster size	*CS* (D&Mi)	David, Moore (1954)	mean value $CS=1$; aggregation $CS>1$; regularity $CS<1$
Vertical diversity	Arten-profil index	*Ap* (Pri)	Pretzsch (2006)	range 0–1; balanced vertical structure $Ap<0.3$; selection forest $Ap>0.9$
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)	minimum $K=0$, higher K=higher values; low $K<1.5$; high differentiation $K>2.5$
Species diversity	Heterogeneity	*H´* (Shi)	Shannon (1948)	minimum $H'=0$, higher H'=higher values
	Evenness	*E* (Pii)	Pielou (1975)	range 0–1; minimum $E=0$, maximum $E=1$
Complex diversity	Stand diversity	*B* (J&Di)	Jaehne, Dohrenbusch (1997)	monotonous structure $B<4$; uneven structure B=6–8; very diverse structure $B>9$

Table 3. Detailed overview of stand characteristics of the tree layer on PRP 1–5 in 2005 and 2015.

PRP	Year	Age y	dbh cm	h m	v m^3	N trees ha^{-1}	BA $m^2\ ha^{-1}$	V $m^3\ ha^{-1}$	PAI $m^3\ ha^{-1}\ y^{-1}$	MAI $m^3\ ha^{-1}\ y^{-1}$	CC %	CPA ha	SDI
1	2005	68	25.8	19.90	0.536	644	33.5	345	8.0	4.42	80.2	1.62	0.66
	2015	80	27.1	21.44	0.627	660	38.1	414	8.1	5.18	77.1	1.47	0.73
2	2005	59	26.3	21.33	0.531	644	35.1	342	7.5	4.96	80.2	1.61	0.70
	2015	70	27.3	23.05	0.621	620	36.4	385	7.0	5.50	72.7	1.30	0.72
3	2005	59	24.7	19.76	0.455	656	31.5	299	8.0	4.33	80.2	1.62	0.65
	2015	70	26.0	20.60	0.523	612	32.5	320	7.0	4.57	69.3	1.18	0.65
4	2005	120	31.2	22.63	0.798	472	36.2	377	6.5	2.90	76.2	1.44	0.68
	2015	130	30.5	22.42	0.791	508	37.2	402	6.4	3.08	74.8	1.38	0.70
5	2005	117	26.4	22.40	0.564	728	39.9	410	8.5	3.23	81.1	1.67	0.80
	2015	128	27.8	23.91	0.662	656	39.7	434	7.1	3.39	70.4	1.22	0.78

Age average stand age, *dbh* mean quadratic breast height diameter, *h* mean height, *v* average tree volume, *N* number of trees per hectare, *BA* basal area, *V* stand volume, *PAI* periodic annual increment; *MAI* mean annual increment, *CC* canopy closure, *CPA* crown projection area, *SDI* stand density index

3 Results

3.1 Tree layer structure and development

The basic structural parameters of tree layer on PRP 1–5 in 2005 and 2015 are documented in Table 3. In 2015 the share of Scots pine ranged from 93.4–100.0%. Norway spruce (*Picea abies* (L.) Karst.) was represented by 2.4% on PRP 1, silver birch (*Betula pendula* Roth.) reached 2.1% on PRP 2 and 5.4% on PRP 3 and on other PRP these two tree species with durmast oak (*Quercus petraea* (Matt.) Liebl.) reached less than 1%. During the dynamics SDI (0.65–0.78) increased by 0.1–10.1%, only on PRP 5 stand density decreased by 2.5%. The crown projection area decreased by 4.2–26.5% on all plots in the studied period.

Average basal area in 2015 ranged from 32.5 to 39.7 $m^2\ ha^{-1}$, which suggests an increase by 2.8–13.7%, only on PRP 5 basal area decreased by 0.5% as a result of salvage felling. The standing volume in 2015 was in the range of 320–434 $m^3\ ha^{-1}$, which indicates an increase by 5.9–20.0% over 10 years. Scots pine accounted for a dominant proportion in the standing volume on all PRP (93.1–100%).

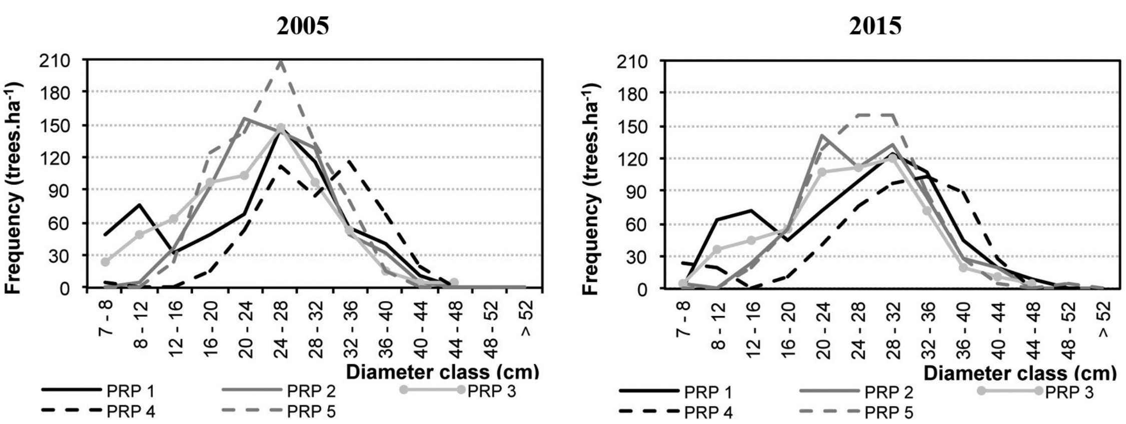

Fig. 2. Diameter distribution on the permanent research plots (PRP) 1–5 converted per ha in 2005 and 2015.

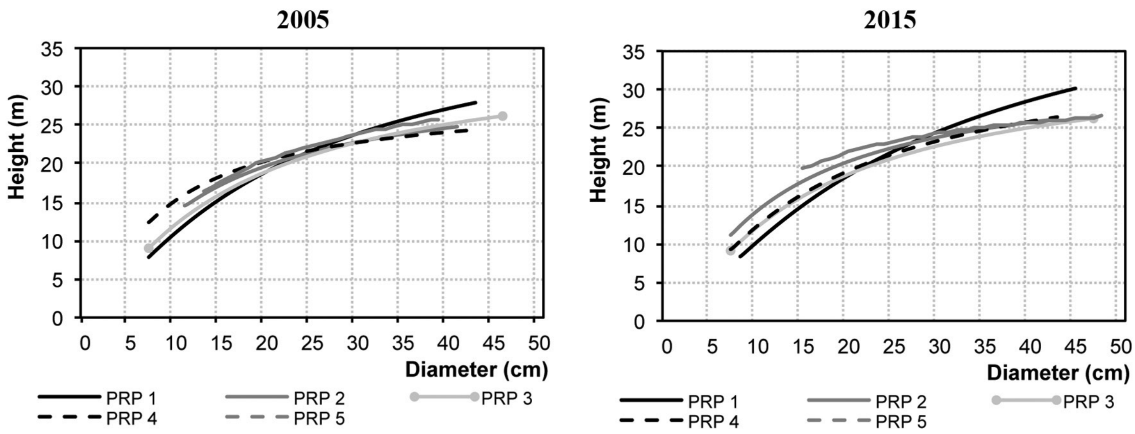

Fig. 3. Relationship between the height and diameter for the permanent research plots (PRP) 1–5 in 2005 and 2015.

Mean annual increment in 2015 was 3.08–5.50 m^3 ha^{-1} $year^{-1}$, which indicated an increase by 5–17% in the last 10 years while total periodic annual increment in 2015 ranged from 6.4 to 8.1 m^3 ha^{-1} $year^{-1}$, and on all plots except PRP 1 (an increase by 1%) there was a decrease by 2–17% (Table 3). The volume of salvage fellings over the studied period was from 11.1 to 34.2 m^3 ha^{-1} (on average 22.5 m^3 ha^{-1}), when the highest volume was recorded on PRP 5.

Fig. 2 represents diameter frequencies of the tree layer in 2005 and 2015. On all PRP there was a considerable shift of trees to higher diameter classes, and especially on PRP 1 and 4 there was a somewhat more pronounced increase in the thinnest diameter classes, not only in Norway spruce but also in silver birch and Scots pine. Fig. 3 shows height curves in 2005 and 2015.

3.2 Tree layer biodiversity

The indices describing the tree layer diversity on PRP 1–5 are shown in Table 4. Horizontal structure of the tree layer in 2015 is shown in Fig. 4. In the tree layer the individuals were distributed

Table 4. Indices describing the structural, species and complex diversity of the tree layer on PRP 1–5 in 2005 and 2015.

PRP	Year	Indices									
		R(C&Ei)	*A*(H&Si)	*CS*(D&Mi)	*Ap*(Pri)	TM_d(Fi)	TM_h(Fi)	*K*(J&Di)	*H´*(Si)	*E*(Pii)	*B*(J&Di)
1	2005	1.105	0.496	–0.048	0.400	0.349	0.304	2.809	0.163	0.271	8.022
	2015	1.230*	0.402*	–0.469*	0.241	0.328	0.273	1.718	0.174	0.289	6.694
2	2005	1.248*	0.366*	–0.399*	0.333	0.219	0.107	1.034	0.081	0.269	4.500
	2015	1.264*	0.350*	–0.604*	0.269	0.229	0.099	2.310	0.062	0.130	6.469
3	2005	1.198*	0.403*	–0.378*	0.407	0.289	0.191	1.486	0.145	0.241	6.211
	2015	1.216*	0.427	–0.268	0.375	0.305	0.195	2.485	0.165	0.274	7.011
4	2005	1.225*	0.373*	–0.429*	0.360	0.204	0.091	2.692	0.001	0.003	6.454
	2015	1.205*	0.419*	–0.271	0.322	0.307	0.187	1.706	0.012	0.025	5.791
5	2005	1.268*	0.345*	–0.496*	0.595	0.194	0.094	0.579	0.000	0.000	2.923
	2015	1.308*	0.359*	–0.459*	0.216	0.205	0.074	0.615	0.000	0.000	2.449

R aggregation index, *A* index of non-randomness, *CS* index of cluster size, *Ap* Arten-profil index, TM_d diameter differentiation index, TM_h height differentiation index, *K* crown differentiation index, *H´* index of species heterogeneity, *E* index of species evenness, *B* stand diversity index; *statistically significant for horizontal structure ($P<0.05$)

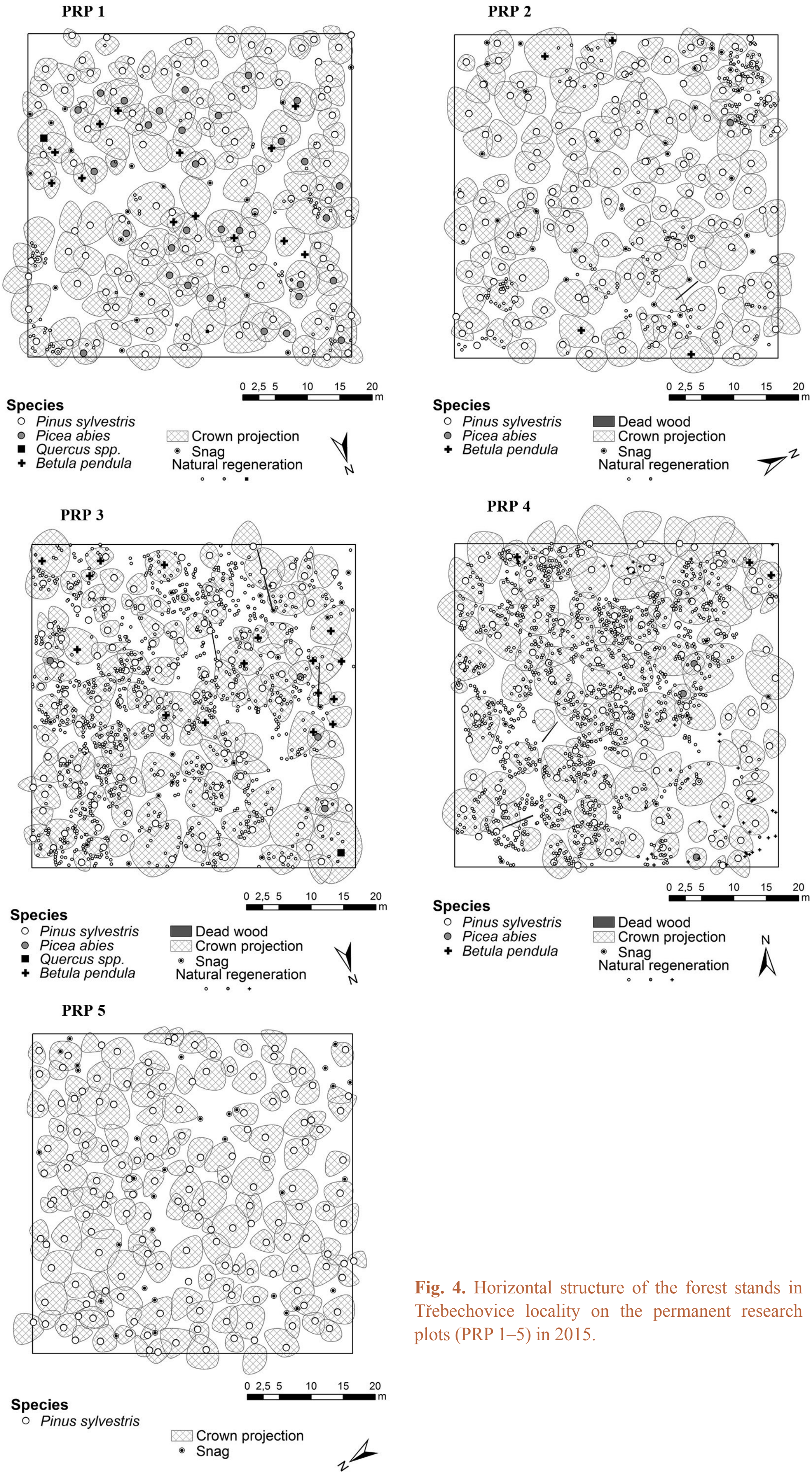

Fig. 4. Horizontal structure of the forest stands in Třebechovice locality on the permanent research plots (PRP 1–5) in 2015.

regularly on PRP according to structural indices, same structural characteristics were recorded for both periods.

Vertical structure (Arten-profil index) was relatively variable on PRP (in 2005 Ap=0.333–0.596 and in 2015 Ap=0.216–0.375), ranging from low to high diversity. In the course of the studied years vertical diversity decreased on all PRP. It was highest on PRP 5 in 2005 (Ap=0.596). The structure differentiation indexes of diameter (TM_d) and height (TM_h) indicated forest stands with mostly low and medium structural differentiation (in 2005 TM_{d}=0.194–0.349, TM_{h}=0.094–0.304 and in 2015 TM_{d}=0.205–0.328, TM_{h}=0,074–0,273). The highest differentiation of diameter and height structure was observed on PRP 1 in the studied years (Table 4).

From the aspect of complex diversity (stand diversity index B), these were plots with monotonous structure (B=2.449–2.923, PRP 5), even to uneven structure (B=4.500–7.011, PRP 2–4) and uneven to heterogeneous structure (B=6.694–8.022, PRP 1). In the course of the studied years, total diversity on PRP 1, 4 and 5 moderately decreased and on the contrary, it increased on PRP 2 and 3. During the studied years crown differentiation (K) increased on PRP 2, 3 and 5 while it decreased on PRP 1 and 4 (in 2005 K=0.579–2.809).

Species diversity of the tree layer (entropy H') was low on PRP 1–3 (H'=0.062–0.174) and minimum on PRP 4 and 5 (H'=0.062–0.174). Species evenness of the tree layer according to E index also suggested low biodiversity on PRP 1–3 (E=0.130–0.274) and very low on PRP 4 and 5 (H'=0.000–0.025).

3.3 Structure and development of natural regeneration

Characteristics of natural regeneration on PRP in 2005 and 2015 are shown in Table 5 and in Fig. 5 (for 2015). At the beginning of observations the numbers of recruits were relatively low (64–1492 recruits ha^{-1}). No regeneration occurred only on PRP 5 in the studied periods. By 2015 there was a considerable increase in the number of recruits (344–4940 recruits ha^{-1}, i.e. 3.2–5.9 times) and substantial enhancement of their maturity. Its highest enhancement was observed on PRP 3 and 4, i.e. on plots with the lowest canopy closure (SDI 0.64 and 0.70). Leading shoot browsing was found out in durmast oak only. Damage to trees by fraying (less than 0.3%) was observed only in 2015 in pine on PRP 3 and 4. Fig. 5 shows the histograms of height frequencies of natural regeneration.

Table 5. Numbers of recruits converted per ha, their percentage ratio and average height differentiated by tree species on the permanent research plots (PRP) 1–4.

Species	Year	PRP 1			PRP 2			PRP 3			PRP 4		
		recruits ha^{-1}	%	cm	recruits ha^{-1}	%	cm	recruits ha^{-1}	%	cm	recruits ha^{-1}	%	cm
Pinus sylvestris	2005	44	69	142	116	94	117	1284	99	138	1448	97	162
	2015	304	89	306	724	98	237	4080	99	298	4732	96	326
Picea abies	2005	12	19	211	8	6	201	12	1	254	16	1	175
	2015	36	10	371	12	2	421	40	1	420	32	1	380
Betula pendula	2005	4	6	-	0	0	-	4	0	245	24	2	182
	2015	0	0	-	0	0	-	4	0	435	176	3	392
Quercus petraea	2005	4	6	122	0	0	-	0	0	-	0	0	-
	2015	4	1	210	0	0	-	0	0	-	0	0	-
∑	2005	64	100	147	124	100	118	1296	100	140	1492	100	167
	2015	344	100	312	736	100	240	4124	100	300	4940	100	330

On PRP 5 no natural regeneration in the study period was present

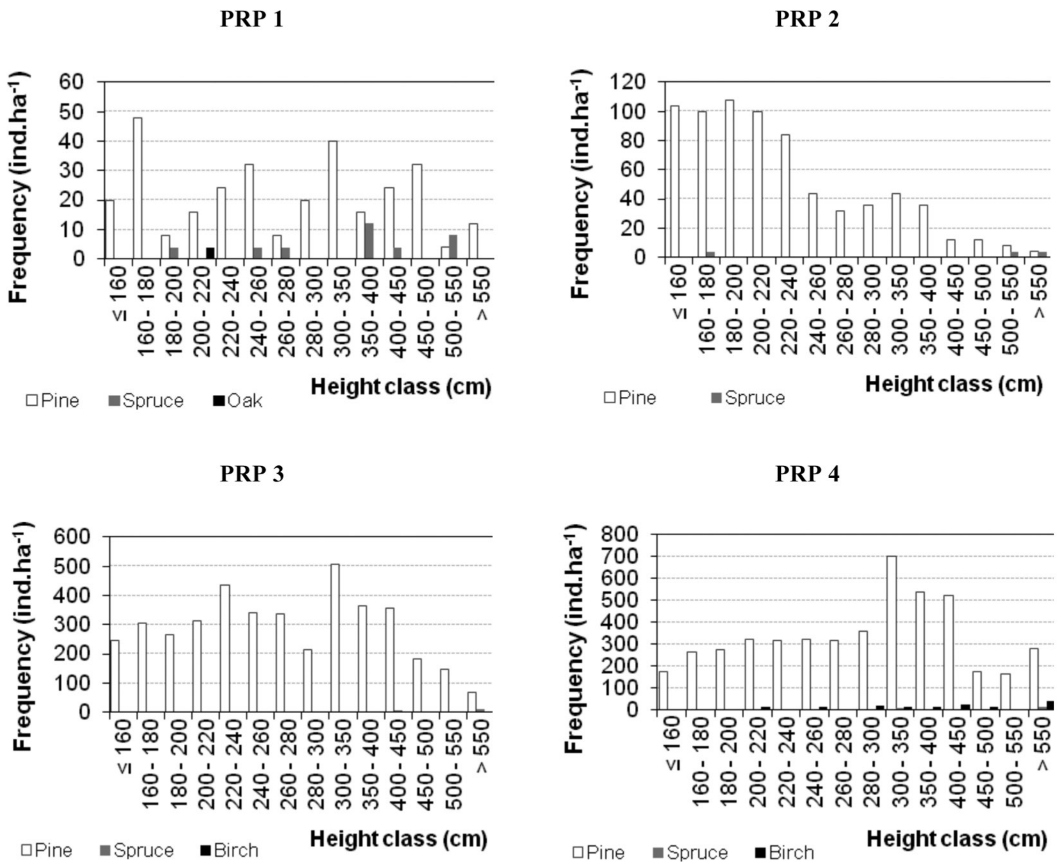

Fig. 5. Histograms of the height structure of natural regeneration on the permanent research plots (PRP) 1–4 differentiated by tree species and converted per ha in 2015.

The horizontal structure of natural regeneration in 2015 in recruits higher than 1.5 m is shown in Table 6 with highly aggregated spatial pattern of natural regeneration on all PRP.

The spatial relations between natural regeneration and tree layer by means of the pair correlation function are shown in Fig. 6. On all PRP the spatial distribution of recruits in relation to the tree layer was evaluated as random at distances longer than 2 m, only on PRP 3 there was a tendency to an aggregated pattern at distances longer than 8 m. At distances within 2 m the relations between recruits and the tree layer showed a significant aggregated distribution on all plots except PRP 1, where the spatial pattern of recruits and the tree layer was random along the entire curve.

Table 6. Indices describing the horizontal structure of natural regeneration on the permanent research plots (PRP) 1–4 in 2015.

Index	PRP 1	PRP 2	PRP 3	PRP 4
Hopkins–Skellam *A*	0.742*	0.923*	0.776*	0.890*
Clark–Evans *R*	0.627*	0.492*	0.783*	0.738*
David–Moore *DM*	3.652*	6.320*	4.140*	5.195*

* Statistically significant (P<0.05)

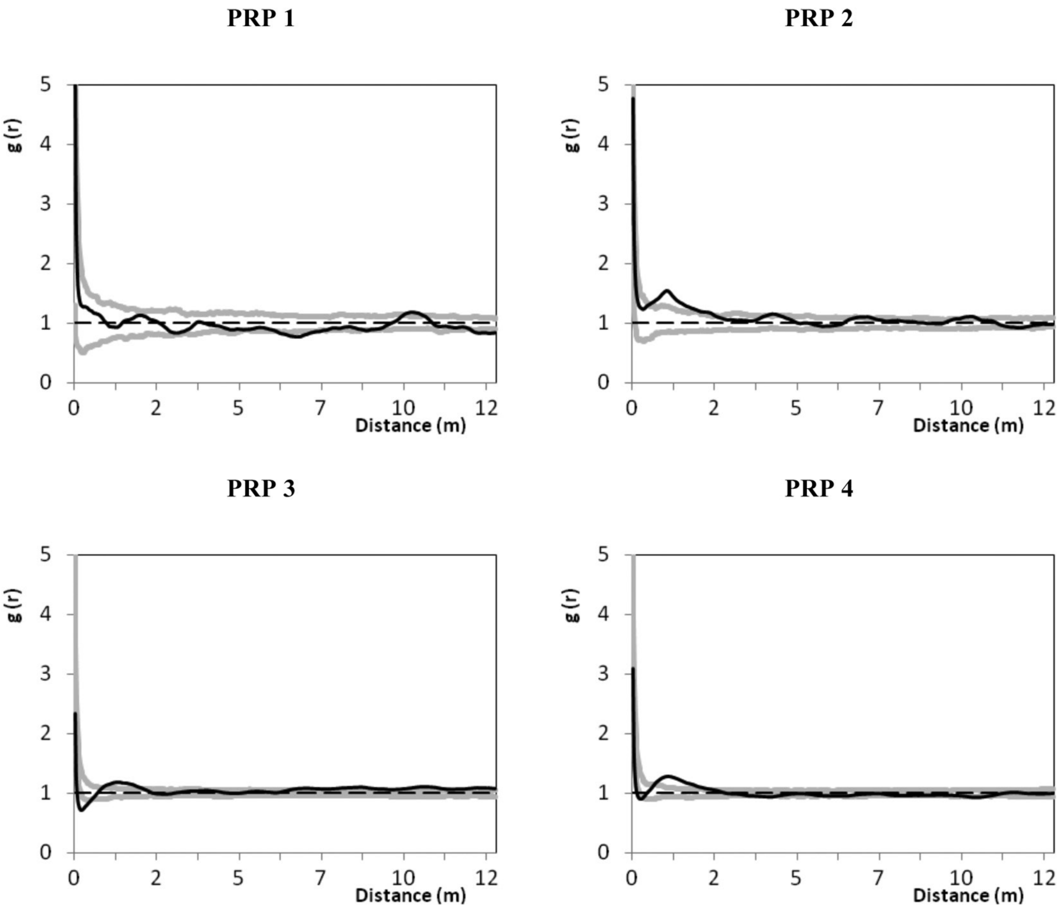

Fig. 6. Spatial relations of natural regeneration and the tree layer on the permanent research plots (PRP) 1–4 represented by the pair correlation function; the black line depicts the pair correlation function *g(r)* for real distances between individuals on the permanent research plots (PRP); two grey curves illustrate the 95% confidence interval for the random spatial pattern; *r* – radius defining distance between the selected points (trees and nature regeneration); *g(r)* > 1 indicates a clustering at distances *r*, while *g(r)* < 1 indicates a regularity in the respective distances *r*.

3.4 Deadwood structure and development

The highest volume of dead standing trees up to 7 cm top diameter was in 2005 on PRP 1 (13.1 $m^3 ha^{-1}$) and 5 (11.0 $m^3 ha^{-1}$); it was minimum on the other plots. In 2015 the volume of dead standing trees was in the range from 0.2 to 9.0 $m^3 ha^{-1}$ when the largest decrease was observed on PRP 1 (12.9 $m^3 ha^{-1}$) while the highest increase was on PRP 4 (7.9 $m^3 ha^{-1}$). As for the degrees of decomposition of dead standing trees, the representation of degree 1 was the highest (65.7%), and that of degree 3 and 4 was lower (15.3% and 10.8%).

The reserve of coarse woody debris on PRP was very low and even zero in 2005. In 2015 it ranged from 0.3 to 0.7 $m^3 ha^{-1}$ and on PRP 1 and 5 it did not occur at all. As for the degrees of coarse woody debris (CWD) decomposition, degrees 2, 3 and 4 were recorded.

Table 7. Chronologies characteristics including mean increment, Explained proportion of Signal (EPS) autocorrelation values before and after standardization and dendrometric characteristics of sampled trees on the permanent research plots (PRP) 1–5.

PRP	Mean increment (mm)	Explained proportion of signal	Autocorrelation value before standardization	Autocorrelation value after standardization	Length in age 80 (cm)	Min. dbh* (cm)	Max. dbh* (cm)	Min. height (m)	Max. height (m)
1	1.88516	0.874	0.7738	0.5116	11.38	24.2	33.3	24.9	27.5
2	1.65091	0.864	0.7481	0.5098	11.75	21.6	35.7	22.0	26.4
3	1.61937	0.685	0.7059	0.5577	11.40	20.0	36.7	20.4	25.5
4	1.07536	0.885	0.7123	0.6065	7.84	22.6	36.9	21.2	25.1
5	1.25056	0.879	0.7288	0.6109	8.46	24.1	36.4	24.8	26.9

* Breast height diameter without bark

3.5 Diameter growth with respect to environmental conditions

The mean tree-ring width ranged on PRP from to 1.08 mm (±0.31 SD) to 1.89 mm (±0.48 SD). Summary of chronologies including mean increment, explained proportion of signal (EPS), autocorrelation values before and after standardization and dendrometric characteristics of sampled trees is given in Table 7.

The regional standardized tree-ring chronology in 1960–1991 indicates a relatively balanced radial increment, subsequently followed by a trend of its decrease (Fig. 7). The years 1980, 2005 and 2014 with low radial increment were confirmed as negative pointer years.

A comparison of average tree-ring curves for the particular PRP showed goodness of fit between them, their t-test values above 3.4 documented synchronization reliability. Thanks to it, it was possible to construct the regional standardized ring-width chronology for pinewoods in the Třebechovicko microregion.

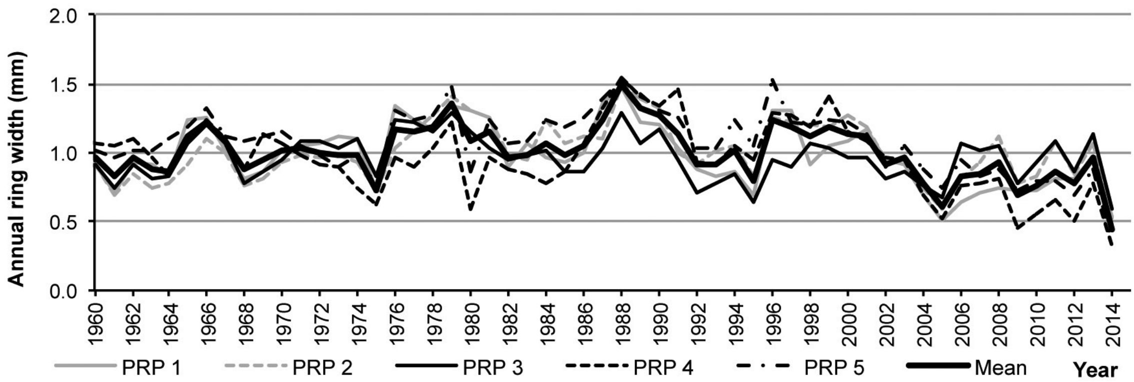

Fig. 7. Average tree-ring series from the permanent research plots (PRP) 1–5 and in total after age detrending.

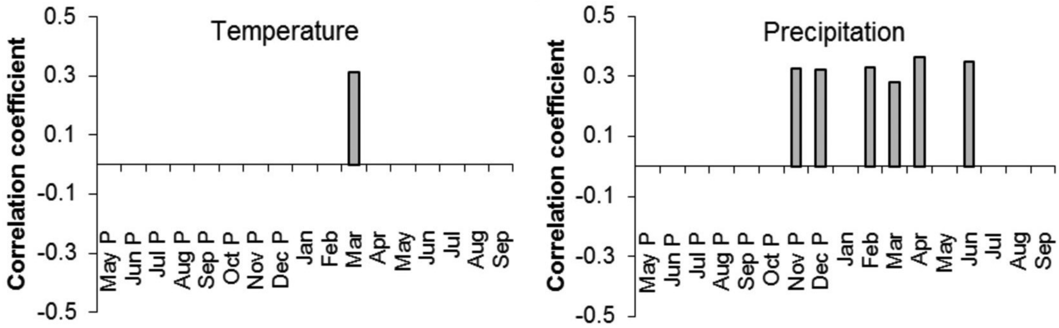

Fig. 8. The values of correlation coefficients of the regional standardized tree-ring chronology with the monthly temperature (left) and precipitation (right) from May of the previous year (P) to September of the current year for the period 1963–2014. Only correlation coefficients with statistically significant values (α=0.05 %) are displayed.

Correlations of standardized diameter increment with average monthly temperatures and precipitation indicated some statistically significant values. In the Třebechovicko microregion there were positive statistically significant correlations of diameter increment in 1962–2014 with temperature in March of the current year (r=0.31; Fig. 8). Statistically significant positive correlations were also found out with precipitation amount in November and December of the previous year (r=0.33 and 0.32) and in February, March, April and June of the current year (r=0.33, 0.28, 0.36 and 0.35, respectively; Fig. 8).

Diameter increment was negatively significantly correlated with temperature in vegetation season of the current year and previous year and temperature in May–August of the previous year, while radial growth was positively significantly correlated with mean NO_x concentrations and mean foliation of living trees (Table 8). In addition mean foliation was negatively correlated with mean SO_2 concentrations and N deposition and positively correlated with climatic factors in May–August of the previous year.

Table 8. Correlations between radial growth increment with climatic data (1963–2014) and air pollution factors (1984–2014; AOT40F 1996–2014) and health status (2005–2014). Significant correlations (P<0.05) are indicated in bold.

	SO_2 mean	SO_2 veg	SO_2 nonveg	NO_x mean	NO_x veg	NO_x nonveg	AOT40F	S depos	N depos	Temp ActAnn	Temp ActVeg	Temp PrevVeg
Foliation	**–0.66**	–0.46	–0.29	–0.29	–0.35	–0.24	–0.49	–0.45	**–0.69**	–0.01	0.08	0.60
Increment	0.17	0.11	0.22	**0.42**	0.19	0.04	0.37	0.24	0.27	–0.26	**–0.34**	**–0.33**

	Temp ActV-VIII	Temp PrevV-VIII	Temp ActI-III	Temp Nonveg	Prec ActSum	Prec ActVeg	Prec PrevVeg	Prec ActV-VIII	Prec PrevV-VIII	Prec ActI-III	Prec Nonveg	Incre-ment
Foliation	0.50	**0.71**	0.13	–0.10	–0.15	–0.03	0.48	–0.13	**0.63**	–0.25	–0.12	**0.88**
Increment	–0.22	**–0.29**	–0.00	–0.87	0.17	0.01	0.17	–0.07	0.10	0.11	0.09	**1.00**

SO_2mean mean annual SO_2 concentration, *SO_2veg* mean SO_2 concentrations in vegetation season, *SO_2nonveg* mean SO_2 concentrations in nonvegetation season, *NO_x*, *AOT40F* ozone exposure, *Sdepos* annual S deposition, *Ndepos* annual N deposition, *TempActAnn* mean annual temperature, *TempActVeg* mean temperature in the current vegetation season, *TempPrevtVeg* mean temperature in the previous vegetation season, *TempActV-VIII* mean temperature in May–August of the given year, *TempPrevV-VIII* mean temperature in May–August of the previous year, *TempActI-III* mean temperature in January–March of the given year, *TempNonveg* mean temperature in the nonvegetation season; *Prec* sum of precipitation

4 Discussion

Regarding the ambient air pollution, presented results reflect pollution trends in the CR. Ambient air pollution was a major environmental problem in the CR in the past (Moldan and Schnoor 1992). Legislative changes introducing more stringent emission limits in the end of 1990s resulted in significant decrease of major air pollutants and important improvement of situation within the European context (European Environment Agency 2014). This holds for SO_2 in particular, and to a lesser extent also for NO_x. Decreasing trend of both ambient air pollution and deposition fluxes of sulphur and nitrogen is evident to the late 1990s, while these remain about the same since 2000 (Hůnová et al. 2004; Hůnová et al. 2014). Within the CR, the Třebechovicko microregion can be characterised as a medium polluted area both for sulphur and nitrogen (Hůnová 2001; Hůnová 2003), and also for ambient O_3 (Hůnová and Schreiberová 2012). Despite this and in accordance with other research results (Vacek and Podrázský 1994; Augustaitis et al. 2007), SO_2 concentrations and N deposition in combination with extreme climate events causes sever defoliation in pine stands. Since the reaction of trees to the impact of climatic factors in the polluted environment is more sensitive (Juknys et al. 2002), weakened forest stands can react on changing climate conditions characterised by longer drought periods by lowering their ecological stability, however the number of signal years is higher in healthy environmental conditions (Wilczyński 2006). On the other hand, the relation between N concentration and defoliation seemed to be rather weak, while N concentration had positive effect on the growth of the studied stands.

Correlation between pine increment and the amount of precipitation was generally the strongest one. Positive statistically significant correlation between diameter increment and temperature was confirmed only for the average March temperature of the current year. The drought stress shown by the negative correlation between diameter increment and average temperature of both the actual and preceding vegetation period was one of the main environmental stresses affecting the tree growth. Comparing other studies from the Mediterranean environment, from the Alps and from the boreal regions (Augustaitis et al. 2007; Oberhuber et al. 1998; Bogino et al. 2019) drought is a determining factor in the radial growth of Scots pine also in Central European conditions. Similarly, in northeast lowlands of Brandenburg (Germany), for the needle production of Scots pine both autumn precipitation of the previous year and summer precipitation are important predictors, whereas temperature seems to have a minor impact on needle parameters (Insinna et al. 2007).

A comparison of tree density with Sullivan et al. (2009) shows the highest similarity in the number of trees in natural stands (830 trees ha^{-1}), in the other stands studied in the cited paper tree density exceeds 1000 trees ha^{-1}. Similar results of higher density of individuals are reported from natural pine forests in NW Spain (Marcos et al. 2007). The maximum basal area reached on the studied PRP in 2015 was 39.7 m^2 ha^{-1}, quite distinctly exceeding the value of 30.6 m^2 ha^{-1} reported from pinewoods in N Sweden (Mellander et al. 2007). With one exception it increased on all PRP in the studied period. In the future it is expected to approach the value of 41.2 m^2 ha^{-1}, found out on one research plot in the highly productive Valsaín area in central Spain (Montes et al. 2008).

A very important component of forest stands is natural regeneration while the understanding of its crucial factors leads to better knowledge of the whole spatial structure of forest stands (Pardos et al. 2008). Based on the results, by 2015 there was a high increase in the number of recruits compared with 2005 (up to 5.9 times). A comparison of these results with those of Martín-Alcón et al. (2015) shows an opposite trend because a decreasing number of recruits is reported in that paper. Such a trend is observed in other studies (Urbieta et al. 2011; Carnier et al. 2014). Martín-Alcón et al. (2015) explain a decreasing number of recruits by the worse availability of light in forest stands. In other works a negative influence of the competition of herbaceous vegetation is mentioned (Lucas-Borja et al. 2011; Prévosto et al. 2012). Changes in silvicultural practices in several last decades has influenced also the pinewood structure (Montes et al. 2005) and so they could influence conditions for natural regeneration. In our study PRP 5 had the highest initial basal area, number of trees and stand density index and canopy closure. These characteristics probably resulted in lower light intensity, which (in combination with high competition of *Vaccinium myrtillus* L.) strongly limited the number of pine regeneration individuals. Oppositely on PRP with lower stocking the regeneration success was higher. Generally higher thinning intensities in pine stands and ongoing efforts to regenerate pine under the parent stand as often formulated in the theory of close-to-nature silviculture (Bílek et al. 2016) lead not only to better health status of these stands (Prieto-Recio et al. 2015), but also more favourable conditions for their natural regeneration (Berbeito et al. 2009).

Based on the assessment of biodiversity, pronounced variability was revealed among the particular PRP and within them in the studied period. These results are basically consistent with Gao et al. (2014), who reports that mature stands with multi-storey structure usually have higher species diversity. Our study found mostly regular distribution of tree layer with low to medium structural diversity. Similarly results were obtained in managed pine stand in other localities in CR, respectively plots were slightly higher and diameters were more variable compared to Třebechovicko (Bílek et al. 2016). Barbier et al. (2008) and Chávez and MacDonald (2012) consider species diversity as a result of combined effects of several factors such as the influence of age, canopy and the species composition of studied stands. A change in species composition is closely related to differences in light conditions, developmental stages and stand density (Smith et al. 2008; Coote et al. 2013).

Tuten et al. (2015) reports a high degree of aggregation within a tree distance <10 m, similar results from pine stands are also presented by Sánchez Meador et al. (Sánchez et al. 2011), who documents a statistically significant aggregated pattern to a distance shorter than 40 m, with the aggregation peak at a distance of 6–8 m. Lydersen et al. (2013) observes aggregated structure within a distance of 20 m, then the pattern changes to random distribution. This trend is also described in other studies (Youngblood et al. 2004; Sánchez et al. 2009). In accordance with our results, prevailing regular to random distribution of dominant trees is reported by Li et al. (2012), while natural regeneration individuals tend to aggregated spatial pattern.

5 Conclusions

After 10 years, studied forest stands showed positive development of stand structural characteristics related to their diversity, number of regeneration individuals and growth characteristics. Tree-ring curves with goodness of fit between them indicated balanced conditions between the stands and climate and environmental conditions. However, silvicultural techniques should not be focused only at stand productivity, but also at risk prevention against stand disruption by stress factors such as air-pollution and drought periods. Small scale forestry based on the principles of selection harvest allows in this respect higher plasticity and better mitigation of negative impacts related to the climate change.

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