Structure and development of forest stands on permanent research plots in the Krkonoše Mts.

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ABSTRACT: The research is focused on structure and development of forest stands from 5th to 8th forest vegetation zone in the Krkonoše Mts. The forest stand diversity according to tree species composition and representation, horizontal and vertical structure was evaluated by using following indices: Clark-Evans aggregation index (Clark, Evans 1954), standardised Arten-profil index (Pretsch 2005) and index of complex diversity after Jaehne, Dohrenbusch (1997). Growth model SIBYLA (Fabrika, Ďurský 2005) was used for visualizations and growth predictions of forest stands on particular plots. Based on research results, management recommendations were evaluated.

Keywords: forest development; mountain forest; structural diversity

Foresters and naturalists often relate the forest to the idea of steadiness, homeostasis and ecological, production and environmental continuity with respect to particular forest developmental phase. This functional continuity can be negatively influenced by several disruptive factors. For some part of conservationists the natural development of forests and forest stands without any human intervention is the highest priority, nevertheless in the conditions of Central Europe this requirement is often only illusory. In changed ecosystems is than their disturbance considered as part of natural development with no respect to their ecological stability or the level of autoregulation processes. For the reason of rational and permanent forest use, near to nature management demands a vast knowledge of the forest ecosystem and the control of natural processes in the forest (Boncina 2000; Sagheb-Talebi, Schütz 2002). The protection of natural processes in forest ecosystems with no relation to their structural diversity is not based on correct assumptions. Complete die back of woody compartment in forest ecosystem leads for example to different developmental trajectory than that of natural forest ecosystem whose high degree of "naturalness" or "authenticity" was the primary impuls for their protection. In the Krkonoše Mts. these trends occured mainly during the air pollution and following ecological calamity in the 1980s of the last century. In these cases the restoration of forest stands and differentiated forest management enhancing ecological stability, biodiversity and autoregulation processes is the essential tool of nature protection and conservation.

During the last decade in both National Parks (Krkonošský národní park and Karkonoski Park Narodowy) the ecological stability and biodiversity of forest stands was increased due to differentiated management based on stand and site characteristics and new zonation. More emphasis is given to close-to-nature forest management and natural processes, namely spontaneous and controlled natural regeneration, which is of great importance in the genetically most valuable forest stands.

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With the objective to optimize future forest management in both national parks, on 38 permanent research plots (PRP) the structure and development of forest stands were evaluated. The research results represent 30 years of observations. Based on particular site and stand characteristics the prediction of tree component development was done in the horizon of 20 years.

MATERIAL AND METHODS

Characteristics of permanent research plots

In the area of Krkonoše Mts. from 5th to 8th forest vegetation zone 32 permanent research plots were established and market PRP 1–32. All PRP represent beech, mixed (beech spruce and spruce beech forest) and spruce stands on different site conditions, with different levels of air-pollution and subsequent acidification. Most of these plots were established in 1980, PRP 11 to 15 were established already in 1976. These plots were between 1981–2004 completed by another two PRP in the ecotone of the upper forest limit with the objective to study vegetative reproduction of spruce and beech. 4 PRP were newly established in the Polish part of the Krkonoše Mts. in forest types, which do not occur in the Czech Republic (locality Chojnik and the upper watershed of Lomniczka): relict pine woods, silver fir spruce forest, herb-rich beech forest and the highest locality of acidophilus beech forest. Plots are rectangular, mainly 50 × 50 m (area 0.25 ha). Exception are PRP 6 (100 × 50 m), PRP 7 (100 × 100 m), PRP 33 (25 × 35 m), PRP 37 (40 × 60 m) and PRP 38 (40 × 60 m). Detailed description of permanent research plots is given in Matějka et al. (2010).

Methodology

The structure of forest stands was evaluated by standard dendrometric methods. Within each PRP enumerated trees were mapped using the right angle prism and measure tapes. For each stem, the dbh (double measurement with calliper, accuracy 1 mm), the height, the crown height (hypsometer Blume-Leiss, accuracy 0.5 m) were measured. The crown projection of each live stem by measuring four cardinal crown radii per tree was mapped (by using system of measure tapes, ranging poles and swiveling telescope). The repeated horizontal mapping was done with the equipment Field-Map (IFER-Monitoring and Mapping Solutions Ltd.). Within PRP the positions of all woody stems ≥ 5 cm dbh were remeasured. The heights were remeasured with the hypsometer Vertex (accuracy 0.1 m).

Growth model SIBYLA (Fabrika, Ďurský 2005) was used for visualisations and growth predictions of forest stands on particular plots. The results are presented in graphical and numerical way (cf. Minx 2006).

The models of spontaneous development were done for 38 permanent research plots in beech, mixed (spruce beech and silver fir beech forest) and spruce stands. Same simulations were also performed on PRPs located in the ecotone of the upper forest limit and in relict pine wood. For all these PRP structural analyses in steps of five years were done. Under the conditions of spontaneous development in ecologically stable environment the prediction was calculated for period of 20 years. In spruce stands endangered by bark beetle disturbances more precise predictions in 5 year steps were conduced. In selected stands with the absence of silver fir (PRP 6 and 28) virtual underplanting of this species was done and prediction of development after 25 and 50 years performed.

The forest stand diversity according to tree species composition and representation, horizontal and vertical structure was evaluated by using following indices:

– Clark-Evans aggregation index (Clark, Evans 1954);
– Standardized Arten-profil index (Pretzsch 2001) as relative rate of diversity;
– Complex diversity index by Jaehne, Dohrenbusch (1997) – (B > 5 – highly differentiated forest stands).

RESULTS AND DISCUSSION

Structure and development of forest stands

Besides the common characteristics of natural forest development, stand dynamics show more or less expressed differences in relation to site conditions (Korpeľ et al. 1991; Vacek 2000; Vacek et al. 2009). This variance has to be considered as result of different ecological conditions, environmental limits and biological properties of dominant tree species. On extreme sites after air-pollution and ecological calamity still elements of large developmental cycle with higher ratio of pioneer tree species are characteristic. Ecologically stable autochthonous forest stands develop within the small developmental cycle.

Beech stands

Natural beech stands in the Krkonoše Mts. are marked by high age heterogeneity, low volume and structure variability and small-scale texture – the smallest of the zonal Central European natural forests. These developmental trends are result of maximal shade-tolerance and relatively shorter life span of this tree species. The duration of one mosaic cycle is normally not longer than 230–250 years. The optimal stage is relatively short (max. 40 years), and is characterized by lower dbh variability of the upper layer and reduced number of trees in the lower layer. The shade tolerance of beech results in two and three layered beech stands during important part of the whole life cycle. Simple structures with only one storey are rather exceptional and occur only in the optimal stage. Developmental independence is due to fine grained mosaic reached already within areas of 25–30 ha. Number of trees in the optimal stage varies between 350 and 550 per 1 ha (50%), the volume varies in the range of 30% and reaches on average sites values between 400 and 600 $m^3 \cdot ha^{-1}$, on better sites then 550–800 $m^3 \cdot ha^{-1}$ (cf. Vacek et al. 1988).

Abundant natural regeneration occurs in the interval 100–120 years, which corresponds to the early destruction phase of mature stands. For natural beech stands is typical the occurrence of overtopping trees that locally survive in more favorable site conditions. They develop after sporadic natural regeneration, which precedes abundant natural regeneration after expressed gap formation in forest stands.

Forest stands are mainly described from following localities: river valley of Jizera, Boberská stráň, Rýchory (Czech Republic), Chojnik, Szklarka, Nad Jagnadkówem and river valley of Lomniczka (Poland).

PRP 29 – U Bukového pralesa B

Site and stand characteristics

Forest stand 536 A17/2/1b with PRP 29 – U Bukového pralesa B is located on gentle slope with SE exposition. The stand can be characterized as overmatured with relatively opened canopy and abundant beech regeneration of different size and age. Within the forest cycle the prevalent aggradation stage is accompanied by fragments of destruction stage. The stand is classified as phenotype category B with above average production and good health status. The age of the upper storey is 173 years and is formed by dominant beech (93%) and spruce (7%). The middle layer and lower layer are completely formed by beech of age 23 and 9 years, respectively. Individually admixed trees species are rowan and spruce. Middle height of the upper storey is 25 m, stocking is 6. Low canopy cover of the upper storey (55%) results in higher radiation in the inner of the stand forming suitable conditions for development of natural regeneration. The stand belongs to target management set 546 and air-pollution zone C.

PRP 29 was established in 1980, the forest type is determined as nutrient-medium spruce-beech stand with *Oxalis acetosella* (6S1). Soil type is modal Cambisol. The ground vegetation cover is very low (5%).

Forest structure

Autochthonous beech forest stand on PRP 29 – U Bukového pralesa B (admixed spruce, rowan and Sycamore maple less than 3%) can be characterized as three-storeyed stand with partial selection structure. The distribution of natural regeneration is mainly influenced by the canopy cover of middle and upper storey. Total number of trees in regeneration layer is 13,320 ind. per ha. Beech forms almost 100%, rowan and spruce are only admixed. Trees of the main canopy are distributed randomly.

In the upper layer mainly trees of dbh > 50 cm are represented. Relatively frequent are also trees with lower dbh and very thick trees. High number of relatively thin trees (dbh around 10 cm) and the absence of lower dbh classes reflect former natural regeneration of the stand ceased in the past. The occurrence of new regeneration will depend on the creation of new canopy openings in the upper layer. The green crown height of the upper storey is relatively variable reaching values between 8 m and 16 m. The crown length is proportional to tree height in all storeys, the h:d ratio is in lower storey extremely variable and shows no relation to dbh. The *h:d* ratio of larger trees in the middle and upper storey reaches constantly values around 50 and shows only slight decrease with increasing dbh.

Growth visualizations and forest structure simulations

Main characteristics used for simulation on PRP 29 – U Bukového pralesa B:

- altitude: 950 m,
- forest type: 6S1,
- natural tree species composition: Beech 4, Spruce 4, Silver fir 2, Sycamore maple,
- average age: 142 years,
- vegetation period: 110 days,
- precipitation of the vegetation period: 640 mm,
- annual temperature amplitude: 18°C,

– mean temperature of the vegetation period: 10°C,
– water saturation: 0.50,
– nutrients saturation: 0.50.

Main forest characteristics:

– Beech 98, *h*:*d* – 21:44, 471 $m^3 \cdot ha^{-1}$, 252 $N \cdot ha^{-1}$,
– Spruce 2, *h*:*d* – 13:27, 7 $m^3 \cdot ha^{-1}$, 16 $N \cdot ha^{-1}$,
– Rowan 0, *h*:*d* – 10:15, 2 $m^3 \cdot ha^{-1}$, 56 $N \cdot ha^{-1}$,
– Sycamore maple 0, *h*:*d* – 11:24, 1 $m^3 \cdot ha^{-1}$, 4 $N \cdot ha^{-1}$,
– Mixture: individual,
– Texture – distribution: regular.
  At present (2010) the beech stand shows high structural and age diversification. Rowan, spruce and sycamore maple are only individually admixed.
– Age of storeys: 9/23/173 years,
– tree species composition: Beech 98, Spruce 2, Rowan, Sycamore maple.

Forest dynamics

The autochthonous beech forest stand (admixed spruce, rowan and sycamore maple less than 3%) is located in the 1st zone of the National Park. The tree species composition can be characterized as natural. The actual stand corresponds to shift between tree species within the small developmental forest cycle. The spatial and age differentiation is very high; the destruction stage of the upper storey is accompanied by aggradation stage of the middle layer. Advanced natural regeneration of beech, rowan and spruce occurs on areas with lower canopy (Vacek et al. 2009). Maximal use of production potential is accompanied by intense autoreduction of tree numbers in lower layers (Fig. 1). The forest dynamics are typical for small developmental cycle with high autoregulation potential. The stand can be left for spontaneous development.

Structural differentiation of the forest stand

Table 1 gives overview of all three structural indices used in the study. The horizontal structure of the forest stand was from the first year of observation till 2010 random; in following years the stand tends to more aggregation. The spatial diversity of the stand is medial with slight increase as result of ongoing destruction of the parent

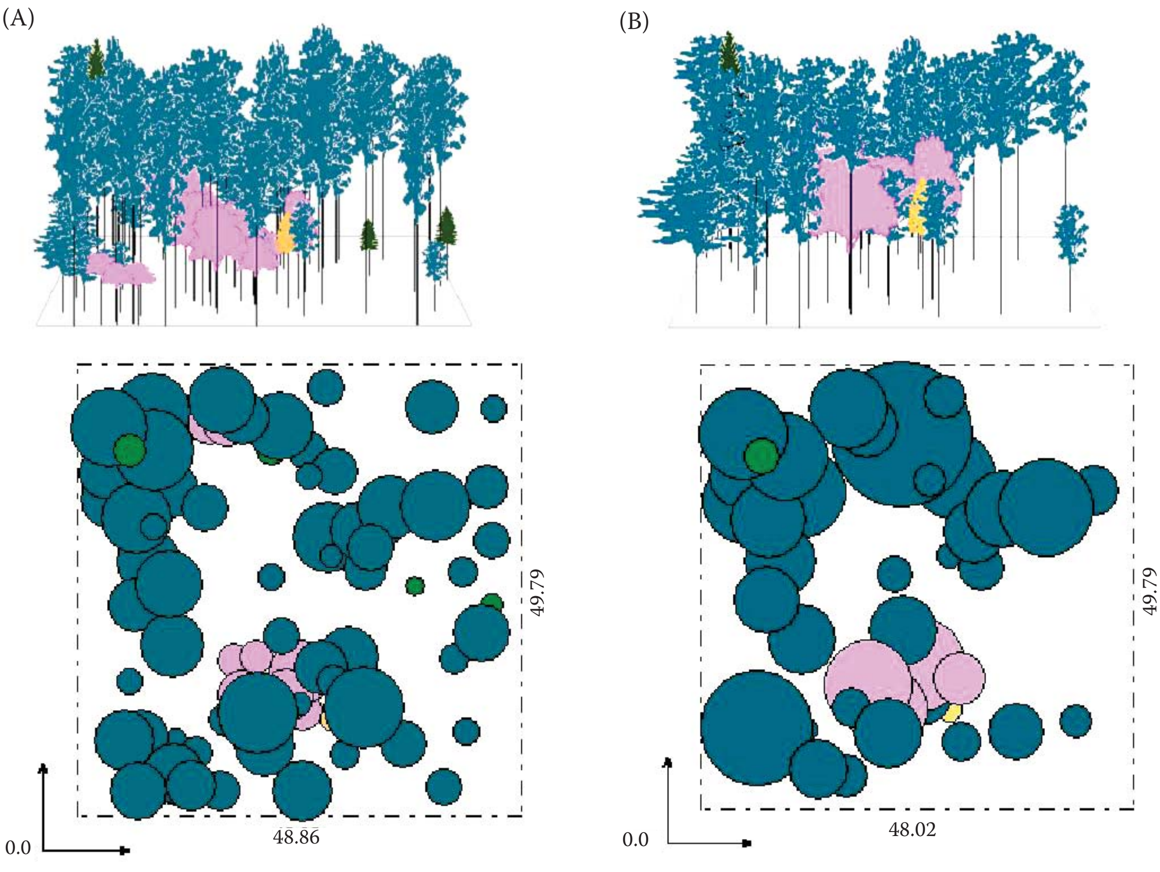

Fig. 1. (A) Visualization of forest structure in 1980 and (B) forest structure prediction in 2030 on PRP 29 – U Bukového pralesa B

Picea abies, *Abies alba*, *Pinus sylvestris*, *Pinus mugo*, *Fagus sylvatica*, *Sorbus aucuparia*, *Acer pseudoplatanus*, *A. platanoides*, *Ulmus glabra*, *Quercus petrae*, *Betula pendula*

Table 1. Indices prediction on PRP 29 – U Bukového pralesa B after spontaneous development

Year	Index		
	R (C&Ei)	A (Pi)	B (J&Di)
1980	1.122	0.367	6.086
1990	1.163	0.366	5.868
2000	1.066	0.366	5.751
2010	0.987	0.354	5.599
2020	0.914	0.376	5.601
2030	0.885	0.428	5.531

stand and establishment of natural regeneration. The complex diversity of the stand was in the first year of measurement also medial, but shows slight decrease during following decades as result of destruction of the ageing stand. Table 2 presents growth variables after spontaneous development for the whole stand and beech as dominant tree species.

Mixed stands

Mixed forest stands of beech, fir and spruce are marked by long developmental cycle lasting over 350–400 years. This very long period is mainly determined by long life span of silver fir. The life span of spruce is 300–350 years, of beech 200–250 years. These differences in developmental cycles of particular tree species result in high variability and complexity of natural forest dynamics in the 5th and 6th forest vegetation zone. It can be generally stated that during one generation of fir or spruce, beech normally changes two generations. Thus, tree species composition and their volume can change dramatically during the developmental cycle. Almost pure forest stands with increased ratio of coniferous species on the one hand or with beech on the other hand are not exceptional. Higher portion of beech is related to shorter optimal stage; on the contrary higher portion of spruce results in to longer optimal stage with horizontal canopy. The optimal stage repeats after 220–260 years, dominance of particular tree species

Table 2. Growth tables for beech stand on PRP 29 – U Bukového pralesa B based on the simulation of spontaneous development (values for admixed tree species are not included)

Period	Year	Stand – including dead individuals											
		t	*d*	*h*	*f*	*v*	*N*	*G*	*V*	*h*:*d*	TCI	TAI	TPV
Total													
1	1980	246	39.6	19.01	0.628	1.470	328	40.3	482	0.480	0.0	1.96	482
3	1990	259	42.6	20.30	0.600	1.737	288	40.9	500	0.477	5.2	2.07	537
5	2000	266	45.2	21.40	0.575	1.976	220	35.2	435	0.473	4.3	2.19	583
7	2010	278	48.4	21.67	0.567	2.260	176	32.3	398	0.448	4.1	2.25	626
9	2020	290	49.9	21.56	0.571	2.407	156	30.3	375	0.432	3.6	2.29	664
11	2030	283	49.9	21.52	0.568	2.392	144	28.0	344	0.431	3.7	2.48	701
Beech													
1	1980	250	44.1	21.48	0.57	1.870	252	38.4	471	0.487	0	1.88	471
2	1985	254	45.2	21.70	0.569	1.981	252	40.3	499	0.480	5.3	1.96	499
3	1990	262	46.5	22.14	0.561	2.108	232	39.2	489	0.476	5.0	2.00	524
4	1995	265	47.1	22.66	0.554	2.186	208	36.2	455	0.481	4.5	2.07	549
5	2000	269	48.3	22.83	0.549	2.298	184	33.6	423	0.473	4.2	2.12	569
6	2005	274	49.4	22.94	0.550	2.417	180	34.4	435	0.464	4.2	2.16	591
7	2010	283	50.8	22.59	0.553	2.533	152	30.7	385	0.445	3.9	2.16	611
8	2015	287	51.6	22.49	0.556	2.614	144	30.0	376	0.436	3.6	2.20	630
9	2020	295	52.6	22.47	0.560	2.736	132	28.5	361	0.427	3.4	2.19	647
10	2025	288	51.9	22.47	0.561	2.669	124	26.1	331	0.433	3.4	2.31	664
11	2030	289	52.6	22.39	0.561	2.732	120	26.0	328	0.426	3.4	2.36	681

t – average age of stand; *d* – the average diameter at breast height (cm); *h* – mean stand height (m); *f* – form factor; *v* – average tree volume (m^3); *N* – number of trees per 1 ha; *G* – basal area per hectare ($m^2 \cdot ha^{-1}$); *V* – volume of growing stock ($m^3 \cdot ha^{-1}$); *h*:*d* – slenderness ratio; TCI – total current increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$); TAI – total average increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$); TPV – total production volume ($m^3 \cdot ha^{-1}$)

repeats after 130 years as result of changing generations of beech. In Krkonoše Mts. the largest reported tree is silver fir with 182 cm of dbh and 58 m of height. Total volume of forest stands varies between 500 and 900 $m^3·ha^{-1}$. The regeneration occurs exclusively under the shelter of parent stand, coniferous tree species regenerate rather in groups, beech on larger continuous areas. During the last decades the ratio of fir in natural regeneration significantly decreased, on the other hand we observe increasing vital regeneration of beech. (cf. Vacek et al. 1987).

Natural spruce beech forest stands with admixed fir are mainly described from following localities: river valley of Jizera, Boberská stráň, Rýchory, V Bažinkách (Czech Republic), Nad Jagnadkówem, Szklarka, river valley of Lomniczka and Pod Kociołom Szrenickim (Poland).

PRP 36 – Chojnik – silver fir beech stand

Site and stands characteristics

The forest stand 213f with PRP 36 – Chojnik – silver fir beech forest is located on gentle slope with S exposition. The stand can be characterized as matured with abundant natural regeneration of shade tolerant tree species (beech and silver fir) accompanied by more light demanding tree species of different age and size. The stand is classified as phenotype category B. The upper storey (118 years) is formed by spruce (40%), silver fir (30%), beech (20%) and pine (10%). In the middle- and understorey (27 and 10 years) the beech is represented by 75%, silver fir 15%, sycamore maple 5% and Norway maple 5%. Middle height of the stand is 25 m, stocking is 9. The canopy cover of the upper layer is relatively high (95%), thus the conditions for successful development of natural regeneration are rather limited. The stand belongs to target management set 452 and air-pollution zone D.

PRP 36 was established in 1980, the forest site type is determined as las mieszany górski świeży (LMwyż-św) (forest type 4S1 – nutrient medium beech stand with *Oxalis acetosella*). Soil type is modal Cambisol. The ground vegetation cover is low (30%) and is dominated by *Oxalis acetosella*. Thus, the competition of herbal vegetation for resources is rather low with suitable conditions for natural regeneration.

Forest structure

Highly differentiated autochthonous silver fir beech forest stand on PRP 36 – Chojnik (admixed spruce, sycamore maple, Norway maple and Scotch elm 20%) can be characterized as three-storeyed stand with partial selection structure.

Number of tree regeneration strongly depends on the canopy cover of the parent stand, on the soil surface conditions and ground vegetation and moss cover. Total number of trees in regeneration layer is 90,200 ind. per ha. Beech forms 91%, silver fir 6%, other tree species are represented by less than 1% (sessile oak, *Crataegus monogyna*, rowan, sycamore maple, Norway maple, small-leaved linden, spruce and *Sambucus recemosa*). Individuals of the parent stand are distributed randomly.

The dbh structure of the forest stand is highly differentiated. Mostly represented are lowest diameter classes (beech with admixed sycamore maple). Diameter classes between 15 and 30 cm are strongly underrepresented. Silver firs of dbh around 35 cm form an important part of the stand, in higher dbh classes the number of individuals constantly decreases, the thickest trees are exclusively beeches. The height of trees increases rapidly up to dbh 40 cm, after this value the increase is rather slow. In the upper storey the height of green crowns is between 10 and 20 m, in the understorey between 1 m and 3 m. The crown length is proportional to tree height in all storeys. In the case of silver fir this relation is more obvious than in the case of beech. The h:d ratio is in lower storey extremely variable and shows no relation to dbh (values are from 70 to 150). On the contrary, by trees thicker than 25 cm the h:d ratio shows decrease with increasing dbh.

Growth visualizations and forest structure simulations

Main characteristics used for simulation on PRP 36 – Chojnik – silver fir beech stand:

- altitude: 940 m,
- forest type: 4S1,
- natural tree species composition: Beech 8, Silver fir 2, Lime tree, Maple, Oak, Hornbeam,
- average age: 118 years,
- vegetation period: 130 days,
- precipitation of the vegetation period: 650 mm,
- annual temperature amplitude: 19.9°C,
- mean temperature of the vegetation period: 12.9°C,
- water saturation: 0.37,
- nutrients saturation: 0.50.

Main forest characteristics:

- Beech 48, h:d – 18:35, 283 $m^3·ha^{-1}$, 192 $N·ha^{-1}$,
- Silver fir 32, h:d – 28:37, 193 $m^3·ha^{-1}$, 144 $N·ha^{-1}$,
- Spruce 18, h:d – 31:42, 108 $m^3·ha^{-1}$, 64 $N·ha^{-1}$,
- Scotch elm 2, h:d – 35:50, 11 $m^3·ha^{-1}$, 4 $N·ha^{-1}$,
- Sycamore maple 0, h:d – 11:11, 2 $m^3·ha^{-1}$, 48 $N·ha^{-1}$,
- Norway maple 0, h:d – 11:11, 0 $m^3·ha^{-1}$, 4 $N·ha^{-1}$,
- Mixture: individual,

– Texture – distribution: random.
At present (2010) the stand shows high structural and age diversification. The stand is formed by beech, silver fir, spruce, sycamore maple with individually admixed elm tree.
– Age of storeys: 10/27/118 years
– Tree species composition: Beech 50, Silver fir 30, Norway spruce 10, Sycamore maple 9, Elm tree 1.

Forest dynamics

The autochthonous silver beech forest stand (admixed spruce, sycamore maple, Norway maple, Scotch elm 20%) is located in the 1st zone of the National Park. The tree species composition can be characterized as natural. The actual stand corresponds to shift between tree species within the small developmental forest cycle. The spatial and age differentiation is very high; the optimal stage of the upper storey is accompanied by aggradation stage of the middle layer. Advanced natural regeneration mainly of beech and sporadical silver fir, sessile oak, rowan, sycamore maple, Norway maple, small-leaved linden, spruce, *Crataegus monogyna* and *Sambucus recemosa* occur on areas with lower canopy (Vacek et al. 2009). The forest dynamics are typical for small developmental cycle with high autoregulation potential.

Table 3. Indices prediction on PRP 36 – Chojnik – Silver fir beech stand after spontaneous development

Year	Index		
	R (C&Ei)	A (Pi)	B (J&Di)
2007	0.983	0.616	9.260
2012	0.983	0.622	9.239
2017	0.991	0.628	9.109
2022	0.964	0.616	8.881
2027	0.901	0.659	8.296
2032	0.893	0.656	8.197
2037	0.893	0.657	8.099
2042	0.893	0.639	8.037
2047	0.893	0.654	8.000
2052	0.893	0.653	7.952
2057	0.893	0.644	7.874

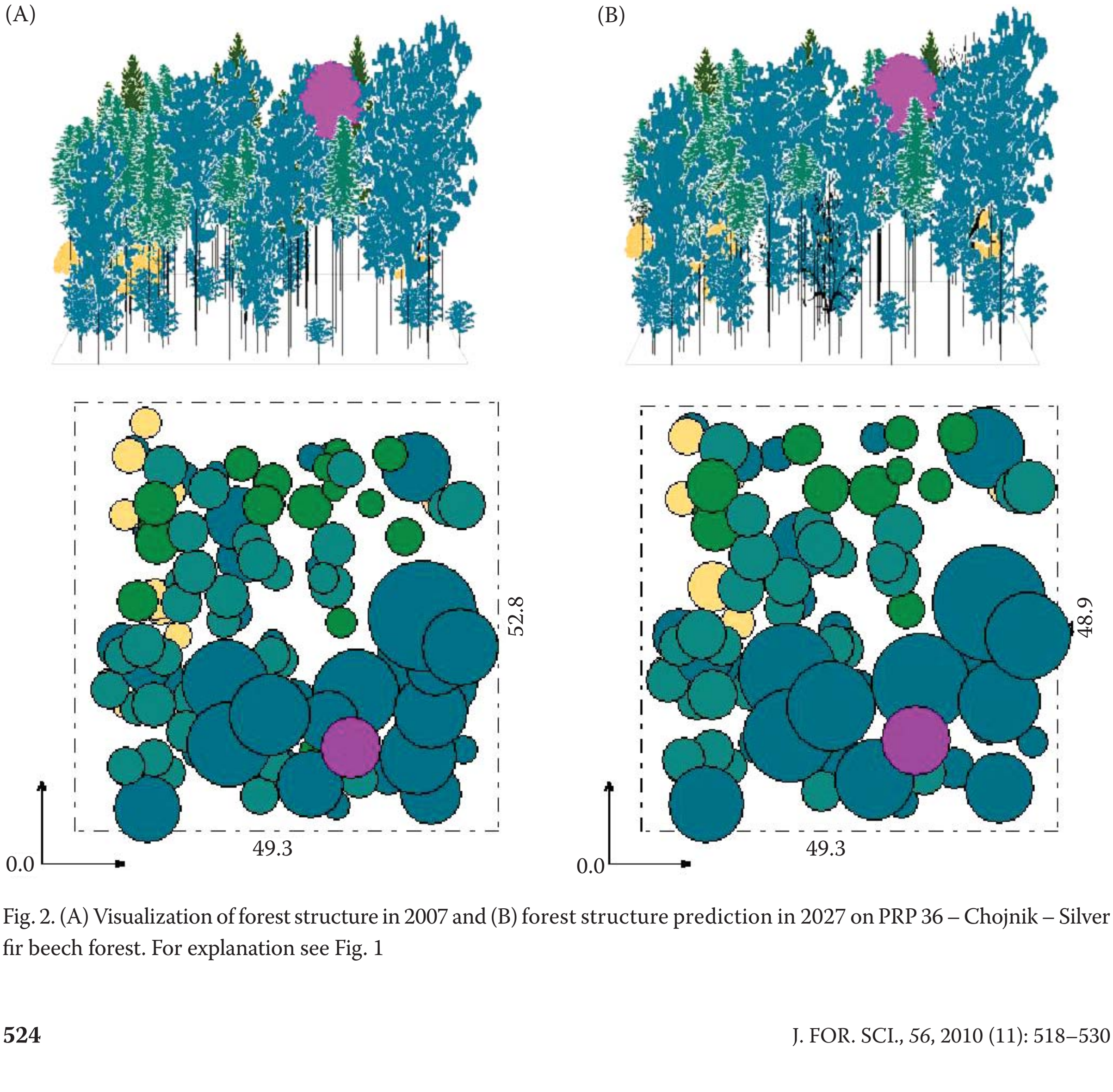

Fig. 2. (A) Visualization of forest structure in 2007 and (B) forest structure prediction in 2027 on PRP 36 – Chojnik – Silver fir beech forest. For explanation see Fig. 1

Structural differentiation of the forest stand

Table 3 gives overview of all three structural indices used in the study. The horizontal structure of the forest stand was from the first year of observation random; in following years the stand tends to more aggregation, after 2022 clumped structure of the stand is predicted. The spatial diversity of the stand is medial with slight increase as result of higher ratio of silver fir in the forest stand. The complex diversity of the stand was in the first year of measurement very high, but shows slight decrease during following years (mainly after 2022).

Table 4. Growth tables for silver fir beech stand on PRP 36 – Chojnik based on the simulation of spontaneous development

Period	Year	Stand – including dead individuals											
		t	*d*	*h*	*f*	*v*	*N*	*G*	*V*	*h*:*d*	TCI	TAI	TPV
Total													
1	2007	117	34.8	22.44	0.614	1.310	456	43.3	597	0.645	0	5.10	597
2	2012	121	36.1	23.00	0.603	1.420	456	46.6	648	0.637	10.4	5.36	648
3	2017	126	37.6	23.40	0.599	1.557	444	49.3	691	0.622	10.0	5.56	701
4	2022	131	37.5	23.67	0.572	1.495	420	46.3	628	0.631	9.4	5.71	748
5	2027	135	38.1	23.90	0.556	1.514	380	43.2	575	0.627	9.4	5.89	795
6	2032	140	39.8	24.57	0.547	1.672	372	46.3	622	0.617	9.4	6.01	842
7	2037	145	41.2	24.97	0.54	1.798	372	49.4	669	0.606	9.5	6.13	889
8	2042	150	42.5	25.30	0.537	1.927	372	52.7	717	0.595	9.2	6.25	937
9	2047	155	43.7	25.60	0.532	2.044	372	55.7	761	0.586	8.7	6.33	981
10	2052	160	44.8	25.87	0.53	2.162	372	58.6	804	0.577	9.3	6.40	1,024
11	2057	165	46.1	26.13	0.527	2.296	372	62.0	854	0.567	9.3	6.51	1,074
Beech													
1	2007	115	34.7	18.29	0.853	1.475	192	18.0	283	0.527	0	2.46	283
2	2012	120	35.7	18.92	0.834	1.580	192	19.0	303	0.530	3.9	2.53	303
3	2017	125	36.6	19.51	0.819	1.681	192	20.0	323	0.533	3.4	2.58	322
4	2022	128	33.2	18.86	0.808	1.319	172	14.7	227	0.568	2.8	2.63	337
5	2027	129	29.5	17.91	0.823	1.007	148	10.0	149	0.607	2.5	2.71	350
6	2032	133	30.8	18.63	0.807	1.120	144	10.6	161	0.605	2.5	2.72	362
7	2037	138	31.8	19.15	0.795	1.209	144	11.3	174	0.602	2.6	2.72	375
8	2042	143	32.7	19.59	0.788	1.296	144	12.0	187	0.599	2.1	2.71	388
9	2047	148	33.4	19.99	0.774	1.356	144	12.5	195	0.599	2.0	2.68	396
10	2052	153	34.2	20.32	0.770	1.436	144	13.1	207	0.594	2.3	2.67	408
11	2057	159	35.0	20.63	0.763	1.514	144	13.7	218	0.589	2.3	2.64	419
Silver fir													
1	2007	118	36.9	28.07	0.446	1.338	144	15.4	193	0.761	0	1.64	193
2	2012	123	38.5	28.54	0.444	1.475	144	16.8	212	0.741	4.1	1.73	213
3	2017	128	40.9	29.12	0.438	1.676	136	17.8	228	0.712	4.2	1.83	234
4	2022	133	42.5	29.50	0.438	1.832	136	19.3	249	0.694	4.3	1.92	255
5	2027	138	44.9	30.20	0.432	2.067	128	20.2	265	0.673	4.5	2.01	277
6	2032	143	46.6	30.61	0.430	2.247	128	21.8	288	0.657	4.6	2.10	300
7	2037	148	48.3	30.97	0.428	2.428	128	23.4	311	0.641	4.7	2.18	323
8	2042	153	50.0	31.26	0.426	2.617	128	25.1	335	0.625	4.7	2.27	347
9	2047	158	51.6	31.50	0.425	2.797	128	26.7	358	0.61	4.5	2.34	370
10	2052	163	53.1	31.74	0.422	2.969	128	28.3	380	0.598	5.0	2.40	392
11	2057	168	54.9	31.98	0.421	3.185	128	30.2	408	0.583	5.0	2.50	420

t – average age of stand; *d* – the average diameter at breast height (cm); *h* – mean stand height (m); *f* – form factor; *v* – average tree volume (m^3); *N* – number of trees per 1 ha; *G* – basal area per hectare ($m^2 \cdot ha^{-1}$); *V* – volume of growing stock ($m^3 \cdot ha^{-1}$); *h*:*d* – slenderness ratio; TCI – total current increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$); TAI – total average increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$); TPV – total production volume ($m^3 \cdot ha^{-1}$)

Table 4 presents growth variables after spontaneous development for the whole stand and particular tree species.

Spruce stands

Also spruce stands have expressed dynamics in higher mountain areas. This tree species has the highest competitive ability in higher elevations and tolerates conditions in the ecotone of the upper forest limit, although its optimal growth and production is reached in the conditions of the 5th and 6th forest vegetation zone. Development and dynamics of natural spruce stands are highly related to altitude and site conditions. In lower elevations on average sites spruce stands have rather homogenous structures with expressed horizontal canopy. These stands however have high age variation between individuals. The developmental cycle completes after 300–400 years. In spruce stands (due to the longevity of this tree species) typically develops structure, which is subject to abiotic (and biotic) disturbances. Large scale forest disruption with subsequent ecological succession is a usual mode of spruce forest regeneration, but normally do not reach the dimensions often seen in boreal regions. In the 8th vegetation zone other tree species occur only sporadically. Within the large developmental cycle the share of pioneer tree species can temporarily increase. Spruce regeneration tends to occur on microsite elevations, mainly on logs. Optimal stage is relatively large but can be shortened by e.g. bark beetle calamity. Similar development occurs also in artificial spruce monocultures outside its natural range with the exception of high age variation. Inclination to catastrophic disturbances is in this case even more expressed (cf. Vacek 1990).

Natural spruce forest stands are mainly described from following localities: Labský důl, Modrý důl, Obří důl, Koule, Střední hora (Czech Republic) Kocioł Lomniczki, Mumlawski Wierch, Kamennik and Maly Staw (Poland).

PRP 24 – Střední hora

Site and stand characteristics

The forest stand 330 D17a/1a with PRP 24 – Střední hora is located on middle slope with SE exposition. The stand can be characterized as matured with partial natural regeneration of spruce. The upper storey (183 years) is formed by spruce (100%). The understorey (15 years) is formed by spruce (99%) and rowan (1%). Middle height of the stand is 21 m, stocking is 7. The canopy cover of the upper layer is relatively high (75%), thus the natural regeneration occurs only in few smaller gaps (Fig. 3). The stand belongs to target management set 21 and air-pollution zone B. The forest stand is during last two years from its SW border attacked by bark beetle.

PRP 24 was established in 1980, the forest type is determined as 8Z4 – rowan-spruce stand with *Calamagrostis*. Soil type is modal Podsol. The ground vegetation cover high (85%) and is dominated by *Calamagrostis villosa* and *Avenella flexuosa*. Thus, the competition of herbal vegetation for resources is rather high with less suitable conditions for natural regeneration.

Forest structure

Almost on the entire area of the autochthonous spruce stand prevails single storeyed stand with low degree of differentiation with partial natural regeneration of spruce. Number of tree regeneration is differentiated according to canopy cover of the parent stand, soil surface characteristics (with clear preference of elevations including CWD) and ground vegetation and moss cover (preference of mosses and *Avenella flexuosa*). Total number of trees in regeneration layer is 4,640 ind. per ha. Spruce forms 83%, rowan 17%. The natural regeneration of both species occurs mainly in small groups and is bound to elevations and areas with lower canopy cover. The horizontal structure of the forest stand is shown on Fig. 3.

The dbh diversification of the forest stand is low indicating optimal stage of the forest developmental cycle. Mostly represented are diameter classes around 35 cm. The representation of individuals in lower and higher dbh classes constantly decreases. The height of trees is rather independent on their dbh, the stand forms expressed horizontal canopy. The height of trees is between 20 and 25 m. Also crown height and crown length have no dependency on the dbh. On the other hand, the h:d ratio is closely correlated with dbh (with the exception of the smallest trees). By trees thicker than 40 cm the ratio decreases slower.

Growth visualisations and forest structure simulations

Main characteristics used for simulation on PRP 24 – Střední hora:

– altitude: 1,250 m,

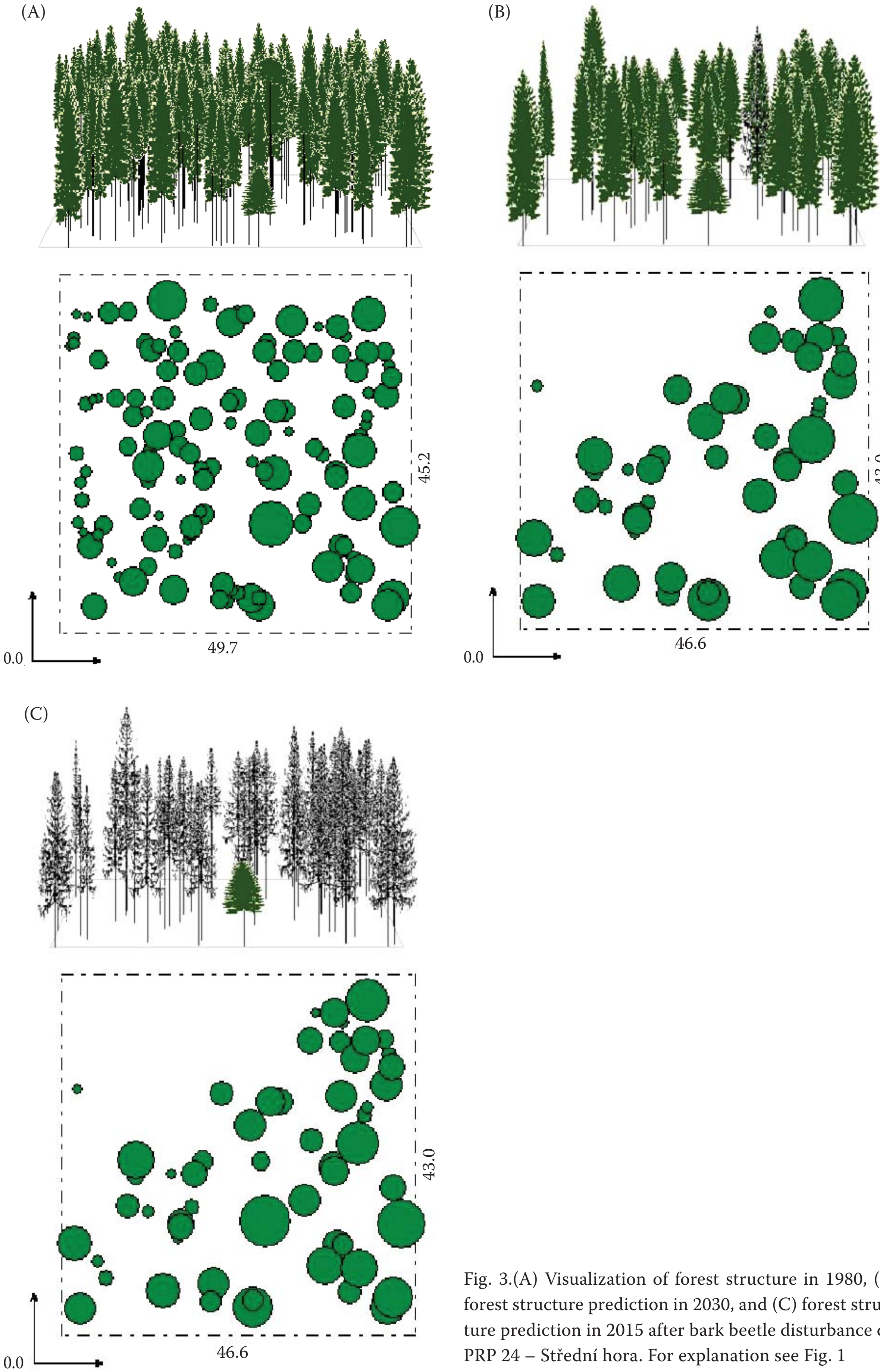

Fig. 3.(A) Visualization of forest structure in 1980, (B) forest structure prediction in 2030, and (C) forest structure prediction in 2015 after bark beetle disturbance on PRP 24 – Střední hora. For explanation see Fig. 1

– forest type: 8Z4,
– natural tree species composition: Spruce 9, Rowan 1, *Betula pubescens*, Dwarf pine, *Betula carpatica,*
– average age: 164 years,
– vegetation period: 70 days,
– precipitation of the vegetation period: 690 mm,
– annual temperature amplitude: 17.6°C,
– mean temperature of the vegetation period: 7.5°C,
– water saturation: 0.115,
– nutrients saturation: 0.125.

Main forest characteristics:

– Spruce 100, *h*:*d* – 21:39, 532 m^3·ha^{-1}, 528 *N*·ha^{-1},
– Texture – distribution: clumped.
At present (2010) the stand shows slight structural and age diversification. The stand is dominated by spruce.
– Age of storeys: 15/183 years
– Tree species composition: Spruce 100.

Forest dynamics

The autochthonous spruce forest stand is located in the 2nd zone of the National Park. The tree species composition can be characterized as natural. The spatial and age differentiation is low; the mature overstorey is dominated by spruce, in the natural regeneration the ratio of rowan slightly increases (Vacek et al. 2009). The production potential of the site is almost completely used, nevertheless with ongoing bark beetle disturbance the use may decrease. The forest dynamics are typical for small developmental cycle with high autoregulation potential (Fig. 3).

Table 5. Indices prediction on PRP 24 – Střední hora after spontaneous development

Years	Index		
	R (C&Ei)	A (Pi)	B (J&Di)
1980	0.924	0.426	3.656
1985	0.924	0.427	3.652
1990	0.939	0.444	3.609
1995	0.901	0.445	3.510
2000	0.908	0.441	3.301
2005	0.935	0.459	3.293
2010	0.943	0.472	3.299
2015	0.924	0.481	3.287
2020	0.960	0.473	3.281
2025	0.939	0.476	3.281
2030	0.939	0.475	3.275

Structural differentiation of the forest stand

Table 5 gives overview of all three structural indices used in the study. The horizontal structure of the forest stand was from the first year of observation slightly aggregated, during the last two de-

Table 6. Growth tables for spruce stand on PRP 24 – Střední hora based on the simulation of spontaneous development

Period	Year	Stand – including dead individuals											
		t	*d*	*h*	*f*	*v*	*N*	*G*	*V*	*h*:*d*	TCI	TAI	TPV
1	1980	164	39.4	21.32	0.388	1.008	528	64.5	532	0.541	0	3.24	532
2	1985	169	40.2	21.38	0.386	1.048	528	67.0	553	0.532	4.1	3.27	553
3	1990	174	41.5	21.68	0.383	1.122	480	64.9	539	0.522	4.1	3.29	573
4	1995	179	42.6	21.93	0.382	1.193	436	62.2	520	0.515	4.1	3.32	594
5	2000	184	43.9	22.11	0.380	1.270	392	59.4	498	0.504	4.0	3.34	614
6	2005	189	45.1	22.18	0.377	1.334	380	60.6	507	0.492	3.6	3.35	634
7	2010	194	46.3	22.29	0.376	1.411	360	60.7	508	0.481	2.9	3.35	650
8	2015	199	49.3	22.21	0.370	1.571	200	38.1	314	0.451	2.3	3.33	663
9	2020	204	50.3	22.25	0.369	1.632	196	38.9	320	0.442	2.1	3.30	673
10	2025	209	51.1	22.29	0.369	1.687	196	40.2	331	0.436	2.1	3.27	684
11	2030	214	52.2	22.31	0.367	1.752	192	41.0	336	0.427	2.1	3.24	694

t – average age of stand; *d* – the average diameter at breast height (cm); *h* – mean stand height (m); *f* – form factor; *v* – average tree volume (m^3); *N* – number of trees per 1 ha; *G* – basal area per hectare (m^2·ha^{-1}); *V* – volume of growing stock (m^3·ha^{-1}); *h*:*d* – slenderness ratio; TCI – total current increment (m^3·ha^{-1}·year^{-1}); TAI – total average increment (m^3·ha^{-1} year^{-1}); TPV – total production volume (m^3·ha^{-1})

cades the spatial pattern of the parent stand moves to more randomness. The spatial diversity of the stand is medial with predicted slight decrease after 2010. The complex diversity of the stand was in the first year of measurement low with decreasing tendency. The downgrading was even faster after 1985. Table 6 presents growth variables after spontaneous development for the whole stand formed exclusively by spruce.

CONCLUSIONS

The presented research on structure and development of forest stands in national parks of Krkonoše Mts. describes the stand of forest ecosystems before during and after the air pollution and subsequent ecological calamity including the regeneration processes. From this point of view the presented results are unique also in pan-European context. The structural dynamics of beech, mixed (fir beech and spruce beech stands) and spruce stands, relict pine woods and stands in the ecotone of the upper forest limit in different site, stand, air-pollution and ecological conditions were examined. The main attention was paid to areas with autochthonous forests stands with lowest human impact in the past and at present. Based on long term observations of vertical and horizontal patterns, structural processes in relation to abovementioned stand types and particular developmental phases were evaluated.

On extreme sites after air pollution calamity, attributes of large developmental cycles still play important role in the development of forest stands (e.g. the presence of pioneer tree species and introduced allochthonous tree species). Ecologically stable autochthonous forest stands regenerate within the small developmental cycle. Natural beech stands are marked by high age heterogeneity, low volume and structure variability and small-scale texture – the smallest of the zonal Central European natural forest. The duration of one mosaic cycle is not normally longer than 230–250 years. Mixed forest stands of beech, fir and spruce are characterized by a very long developmental cycle lasting over 350–400 years. This very long period is mainly influenced by the long life span of silver fir. Spruce stands in higher mountain areas also show pronounce dynamics of structural development. The developmental cycle completes after 300–400 years. In the ecotone of the upper forest limit the cycle is shorter as result of extreme climatic condition and normally does not last longer than 120–200 years. Here, the importance of ecological side cover increases and trees typically build clumped structures. In natural pine stands in the Krkonoše Mts. one developmental cycle completes after 150–240 years as result of fragmentation of these stand types within the zone of species-rich beech forest.

Research results presented here were broadly used for the formulation of management objectives in given conditions. The authors lay emphasis on sustainable forest management and on close-to-nature management. A greater emphasis is placed also on ecosystematic approach to the forest, on transition to the forest of native populations of tree species with natural structures, on individual or group selection management system and maximum use of natural processes (e.g. natural regeneration).

After more than 30 years of observations, valuable findings as base for appropriate management of mountain forests were gathered. Nevertheless, the transition of forest stands after hundreds years of anthropogenic activities to more "natural" structures is very long process far overreaching the horizon of human life. Moreover, as almost all forests in Europe has been managed, forest restoration has always had to deal with stands with a composition, structure and function developed through a history of repeated, intense anthropogenic disturbances (Wolf 2005). Any wood, which is to be treated as a natural reserve and restored, will inherit a structure created by past management. From this point of view this research can be regarded as first step towards abovementioned objectives of close-to-nature management of mountain forest ecosystem not only in Krkonoše Mts., but in similar air-pollution and ecological conditions throughout Central Europe.

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