

Managed vs. unmanaged. Structure of beech forest stands (*Fagus sylvatica* L.) after 50 years of development, Central Bohemia

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Abstract

In this study, the structure and spatial patterns of adjacent beech (*Fagus sylvatica* L.) forest stands, both those having undergone intensive management and those without management intervention over the last 50 years were analyzed. Data was collected from six 1ha permanent research plots. Four plots were established in varying parts of the reserve, comprising entirely of even-aged managed forest stands; two 1-ha permanent plots were located in a non-interventional stand. For each woody stem, basic dendrometrical data and coordinates were measured. The total volume of dead wood (standing and fallen) and its classes of decay were recorded. The structure and species diversity of forest stands were analyzed using skewness and the coefficient of variation of dbh distribution, the Gini index, the Shannon index, the mingling index, the Pielou index of segregation and the Hopkins-Skellam, Pielou-Mountford, Clark-Evans aggregation indices, the diameter differentiation index and Ripley's *K* function. The diameter distribution of the managed stands was generally normal, albeit with a large diameter range and with a typical flat diameter curve. A general lack of giant trees, lower rates of coarse woody debris (from 0.2 to 0.5% of the total living volume) and random tree distribution were also confirmed. Within the investigated area, the diameter differentiation and Gini indices along with the degree of skewness and the coefficient of variation made it possible to monitor the shift from even-aged forest management to spontaneous forest development. In general, spontaneous development was marked mainly by aggregated tree distribution in the middle and lower layer, and a shift from normal to reversed J-shaped dbh distribution. The total volume of deadwood in one of the unmanaged plots amounted to $48.10 \text{ m}^3 \cdot \text{ha}^{-1}$ (9.5% of living wood volume). The use of adequate structural and spatial analysis as indicators of natural forest development are discussed.

Key words: forest reserve; forest management; stand structure; tree diversity indices; Ripley's *K* function; dead wood.

Resumen

Gestión versus no gestión. Estructura de bosque de hayas (*Fagus sylvatica* L.) al cabo de 50 años de crecimiento, Bohemia Central

En el presente trabajo se ha estudiado la estructura y patrón espacial de rodales de hayas (*Fagus sylvatica* L.) gestionados y no gestionados al cabo de 50 años de crecimiento. Los datos han sido recopilados en seis parcelas de medición permanente de una hectárea, de las cuales cuatro fueron establecidas en masas de bosque coetáneo intensivamente gestionado y dos en la parte de la reserva sin intervención forestal. Se midieron las variables básicas dasométricas y las coordenadas de cada árbol. Se evaluó el volumen total de madera muerta (en pie y caída) y sus grados de descomposición. La estructura y diversidad de las especies se describen en base a la asimetría y el coeficiente de variación de la distribución del diámetro normal, los índices Gini, Shannon, Mingling, índice de segregación de Pielou, índices de variabilidad (Hopkins-Skellam, Pielou-Mountford, Clark-Evans), índice de diferenciación diamétrica y la función *K* de Ripley. La distribución diamétrica de rodales gestionados corresponde a la distribución normal, con una curva típicamente achatada, y una amplia dispersión de valores. En los rodales gestionados los resultados también confirman un patrón espacial de árboles aleatorio, una deficiencia general de madera muerta (0,2-0,5% del volumen total de madera viva) y un número bajo de árboles gigantes. En los dos rodales no gestionados ya se muestran diferencias en la desintegración del dosel en pequeña y gran escala con impacto sobre la estructura diamétrica y patrón espacial del rodal. En el área de estudio, se muestra que el índice de diferenciación diamétrica, el índice Gini, la asimetría y el coeficiente de variación son eficaces para monitorear el cambio de las masas regulares gestionadas frente a las masas no gestionadas. En general, el crecimiento del bosque no gestionado se distingue por la distribución agregada de árboles en

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los estratos medio y bajo, y por transición de la distribución diamétrica normal hacia la distribución en forma de J invertida. El volumen total de madera muerta en una de las parcelas no manejadas alcanzó $48.10 \text{ m}^3 \cdot \text{ha}^{-1}$, que equivalen al 9,5% del volumen total de la madera viva. A partir de esta investigación se discute el uso de los diferentes métodos de evaluación estructural y espacial como indicadores del desarrollo espontáneo del bosque.

Palabras clave: reserva forestal; manejo de bosques; estructura del rodal; índices de variabilidad; función K de Ripley; madera muerta.

Introduction

In Central Europe there are currently no forest ecosystems that have been excluded from human impact. Old-growth deciduous forests in western and central Europe, for the most part, consist of small tracks that may often be atypical due to human disturbance, poor soil productivity or inaccessibility. In addition, very little information concerning tree age distribution, structural heterogeneity and tree spatial patterns appears to be available for these forests (Rademacher *et al.*, 2001; Rozas, 2006; Schnitzler and Borlea, 1998). Studies that investigate natural stand dynamics in Central Europe are hampered by the lack of large tracts of old-growth forests, making it particularly difficult to understand spatial and temporal variation in disturbance regimes at the landscape scale (Nagel *et al.*, 2006), and consequently the specification of «authentic» forest structure at the landscape level may be loaded with a high degree of uncertainty.

A general definition of old-growth for temperate forests includes a relatively high degree of patchiness and heterogeneity, dead trees and logs, relatively old age, reverse-J shaped size distribution and multi-cohort age distribution, but not necessarily without demonstrating any evidence of human activity (Foster *et al.*, 1996). It is commonly accepted that old-growth temperate forests are largely structured by disturbances, where major disturbances can initiate new forest stands, but that only small-scale disturbances are evident in a near-steady state (*e.g.* Leibundgut, 1982; Meyer *et al.*, 2003; Nagel *et al.*, 2006; Standovár and Kenderes, 2003). The smaller the scale and higher the frequency of disturbances, the more diversified the horizontal and vertical forest structure should be. The patches forming the mosaic are distinguishable on the basis of their stand volume accumulation, age and size structure, canopy openness, occurrence of regeneration, and/or eventually, species composition (Korpel', 1995). Nevertheless, Paluch (2007) stated that the occurrence of diversified vertical structures should not be related to the lower levels of the basal area. In his study the struc-

tural diversity of individual patches may depend more on the resistance to disturbance of large canopy trees than on the competitive levels of stress to which the sub-canopy tree and under-canopy tree are subjected. Thus, the study results are incompatible with models that anticipate a stage of beech forest development characterized by high biomass accumulation and a more or less homogeneous vertical structure. Accordingly, the natural beech stands may exhibit a more or less diversified vertical structure and spatial texture depending upon the site- and location-specific disturbance regime. The ecological features of beech alone should not preclude the shaping of a stand of a given structure type.

Moreover, as almost all forests in Europe have 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 wooded area which is to be treated as a natural reserve and restored will inherit a structure created by past management that should be preserved as a starting point for the future forest structure.

The maintenance of many natural ecosystems requires the protection not only of current old-growth areas, but also of naturally disturbed forests that represent future old-growth (Foster *et al.*, 1996). According to Schnitzler and Borlea (1998), sustainable forest management depends on two complementary actions: (i) protection of remnant areas of a high degree of naturalness and/or their extension to areas compatible with the viability of all populations of both plants and animals; (ii) definition of criteria for management which remains as close as possible to the natural models of the forest dynamic.

In this field, the forest structure described from small unmanaged stands (with no management intervention for the last 50 years) and adjacent forest stands with intensive forest management may prove an interesting source of knowledge. The aim of the current study is to investigate the influence of management interventions, respectively the absence of forest mana-

gement during the last several decades concerning forest structure and forest dynamics in similar stand conditions. An important question in this regard is how quickly the forest structure changes towards a higher degree of «naturalness», and what the best indicators of this process are. The present paper discusses only the structure of trees. Aspects such as ground vegetation cover, seedbed type and the influence of herbivores on the regeneration establishment of the same plots are described in Bílek *et al.*, 2009. The dynamics of gap regeneration in the unmanaged part of the reserve, including the description of the herbal and shrub layer, is also beyond the scope of this article and forms part of individual research.

Material and methods

The area of study

The study area is located 30 km south-east of Prague in the National Nature Reserve (NNR) Beechwood of Voděrády (49° 58' N, 14° 48' E). The parent rock is formed by granite of varying texture. Predominantly cambisols with a low humus content are developed within the forest stands. The mean annual temperature is 7.8°C and mean annual precipitation 623 mm. The lowest point of the area is 345 m a.s.l., and the highest point is the summit of the nearby hill Kobyla, at 501 m a.s.l. The main function of the forest is the protection of wildlife, recreation (being in proximity to highly populated areas) and economic value.

History of the forest

The National Nature Reserve (NNR) Beechwood of Voděrády was established in 1955 with a total area of 658 ha in a former managed forest. In the same year the reserve was divided into two parts, one with total protection (nevertheless, in compliance with the management plan, damaged or uprooted trees and snags could be removed) and the other with forest management aimed at the enhancement of forest structure. In 1971, this two-part arrangement was cancelled and thereafter only the second kind of management was performed. Even so, in smaller selected stands no interventions were carried out and the continuity of spontaneous forest development was fulfilled.

The majority of the stands in the NNR originate from the period between 1810 and 1850, when almost 500 ha of the area (*i.e.* 76% of the surface of the present NNR) was felled and regenerated. After 1838, in accordance with new forest instruction, the three-phase shelterwood felling was implemented. The entire parent stand was thus usually removed within 12-15 years. Release felling was followed by secondary felling, and after 4 or 5 years the process was concluded by final cutting (Šrámek, 1983). This very short regeneration period resulted in almost pure and even-aged beech stands (Pokorný, 1963). This regeneration system was however inappropriate for silver fir (*Abies alba* Mill.), one of the most important natural tree species in the given site conditions (Bílek *et al.*, 2009).

Data collection

Data was collected from six 1 ha (100 m × 100 m) permanent research plots (PRP), including 4 plots established in 1979 (PRP 01, 03, 04, 05) in a part of the reserve comprising entirely of even-aged beech old-growth forest stands. All four plots possessed similar stand structures and all had been managed through shelterwood cutting. They varied slightly in regard to canopy closure with respect to the differing intensity of cutting. For these plots, exact data about the forest structure from 1980 and 1997 were available. To determine the difference between stand structures in managed forests and near natural beech stands in the NNR, in 2005 two additional 1-ha (100 m × 100 m) permanent plots were established in a non-interventional stand in the so-called locality «Virgin forest» (PRP 06 and 07).

Within each PRP all woody stems = 3 cm dbh using Field-Map (IFER-Monitoring and Mapping Solutions Ltd.) were mapped. For each stem, the dbh (double measurement in NS and EW), the total height and the crown height (hypsometer Vertex, accuracy 0.1 m) were measured. The crown projection of each live stem was mapped by measuring a minimum of five cardinal crown radii per tree. The volume of dead wood = 10 cm (log volume – dead fallen trees and stumps; snag volume – dead standing trees) was estimated by complete enumerations undertaken within the permanent plots. For logs, the length and diameter of the butt and the small end were measured. Deadwood was classified according to decay classes (1 = hard, branches present, bark present on more than 50% of the surface, section

oval; 2 = hard, branches present, bark present on less than 50 % of the surface, section oval, 3 = soft, cut in 1-5 cm of depth, section oval; 4 = soft, small parts missing, section elliptical; 5 = soft, contour deformed, section elliptical; 6 = soft, reduced, no contours, Coarse Woody Debris/CWD/covered with soil). According to the forest management plan, the age of the main canopy ranges from 155 to 189 years.

Data analysis

Stand density, volume and stand basal area were calculated by standard dendrometric methods using volume equations (Petráš and Pajtík, 1991). The volume of deadwood was estimated separately for fallen dead wood (logs) and standing dead wood (snags). For logs, Smalian's formula was used, which calculates the area of the butt end (S0) and top end (S1) of the section of a respective length (h) $[(S0 + S1)/2 \times h]$. The volume of snags was estimated using the formula after Atici *et al.* (2008). The same methods were used for older measurements in order to allow comparison with new results. The total volume of particular PRPs was calculated as the sum of the volume of all trees, and the total basal area as the sum of the tree sections at breast height ($d \geq 7$ cm over bark).

Spatially explicit indices of structural diversity are given in this order:

Hopkins-Skellam aggregation index (Hopkins and Skellam, 1954). This is defined by the equation:

$$A = \frac{\sum_{i=1}^N \omega'_i}{\sum_{i=1}^N \omega'_i + \sum_{i=1}^N \omega_i} \quad [1]$$

Here ω'_i is the quadratic distance from sample point to the nearest tree and is the quadratic distance from tree to the nearest neighbouring tree.

Pielou-Mountford aggregation index (Pielou, 1959; Mountford, 1961). This is defined by the equation:

$$\alpha = \frac{1}{N} \pi \left(\frac{n}{P} \right) \sum_{i=1}^N \omega'_i \quad [2]$$

where n is the stem number per plot, N is the number of sample points, P is the plot area and ω'_i is the quadratic distance from sample point to nearest tree.

Clark-Evans aggregation index (Clark and Evans, 1954), which is defined as:

$$R = \frac{\bar{\delta}}{E(D)} \quad [3]$$

Here $\bar{\delta}$ is the empirical mean of the distance from trees to their nearest neighbours, while $E(D)$ is the mean nearest neighbouring distance in a Poisson forest of the same intensity λ as the forest under analysis.

The dbh differentiation was used as other spatially explicit structural index. For the i th reference tree and its $n=3$ nearest neighbour j ($j=1 \dots n$) the diameter differentiation T_{ij} is defined as:

$$T_{ij} = 1 - \frac{\min(DBH_i, DBH_j)}{\max(DBH_i, DBH_j)}; \quad T_i \in [0, 1] \quad [4]$$

where dbh = breast height diameter (Füldner, 1995; Pommerening, 2002). The index values increase according to the larger the difference between the dimensions of the reference tree and its neighbours, with an index of 1 the highest possible differentiation.

The spatial structure of forest stands was also tested using Ripley's K -function (Penttinen *et al.*, 1992; Ohser, 1983):

$$K(r) = \sum_{0 < \|x_i - x_j\| \leq r} \frac{1}{\lambda^2 s(\|x_i - x_j\|)} \quad [5]$$

where λ is the stand density (number of trees per unit area),

$$s(r) = \frac{ab - r(2a + 2b - r)}{\pi} \quad [6]$$

is the correction of the edge effect, where a, b are dimensions of the rectangular plot and $\|x_i - x_j\|$ is the distance between tree i and j .

For calculation, the software PointPro 2.1, developed at the Department of Forest Management at CULS Prague (D. Zahradník, unpublished) was used. The Monte Carlo technique was used to simulate random data sets. For each investigated plot, 4,000 simulations of the Poisson forest with the same stand density as the investigated stand were performed. The confidence limits were estimated as 95% confidence interval. The same technique was used to estimate the upper and

Table 1. Overview of the spatially explicit aggregation indices included in the study and their common interpretation

Index	Mean value	Aggregation	Regularity
Hopkins-Skellam	$A = 0.5$	$A > 0.5$	$A < 0.5$
Pielou-Mountford	$\alpha = 1$	$\alpha > 1$	$\alpha < 1$
Clark-Evans	$R = 1$	$R < 1$	$R > 1$

lower bounds for spatially explicit aggregation indices of structural diversity. The respective expected values of these indices were computed by means of numerical simulations for each specific case separately. In tables describing the particular PRP the column of expected values shows the value of the index for pure random distribution. When the value of the index exceeds the upper or lower limit of the interval (at significance 0.05), the point structure is aggregated or regular. The statistically significant values are marked by an asterisk, and the upper and lower bounds are not shown (Table 5, 6).

As examples of spatially inexplicit structural indices, the coefficient of variation, skewness and the Gini Index (Gini, 1921) were computed. The Gini Index was obtained from the area under the Lorenz curve, which in turn was derived by plotting the cumulative basal area proportions of trees per hectare against the cumulative proportions of the number of stems per hectare, after sorting the sample trees according to ascending dbh (Sterba, 2008).

As a measure of spatially inexplicit species diversity the Shannon Index (Shannon and Weaver, 1949) was used.

$$Shann = -\sum p_{spec} \cdot \ln p_{spec} \quad [7]$$

In this study it is calculated for both basal area (G) and stem number (N) proportions. Both indices are zero, if there is only one species in the sample and (Y) for Y species with equal relative proportions.

The mingling index was used as measure of spatially explicit species diversity (Gadow, 1993, 1999). It gives the proportion of the $n=3$ nearest neighbours j ($j=1 \dots n$) of the i th reference tree, which do not belong to the same species as the reference tree i .

$$M_i = \frac{1}{n} \sum_{j=1}^n 1(\text{species}_i \neq \text{species}_j); \quad [8]$$

$$1(A) = 1 \text{ if } A \text{ is true, otherwise } 1(A) = 0$$

Values range between 0, for stands with no intermingling, and 1, when every neighbour belongs to a different species from the reference tree i .

As another spatially explicit species diversity measure, Pielou's Index of Segregation (Pielou, 1961) was computed for beech and hornbeam (the two main tree species based on tree population) on plots in the unmanaged part of the reserve, as all managed plots included in the study were almost pure beech stands.

$$Seg = 1 - \frac{\text{number of observed mixed pairs}}{\text{number of expected mixed pairs}} \quad [9]$$

where the number of pairs is weighted by the number of the stems per hectare of the respective sample trees. The algorithm to calculate the number of expected mixed pairs was taken from Pommerening (2002). Zero indicates complete randomness of species distribution, -1 indicates association and 1 the segregation of both species.

In the case of near-natural forest stands (PRP 06 and 07) the spatial patterns of the entire plot and in particular layers (trees lower than 10 m, trees from 10 to 20 m and trees higher than 20 m) were investigated. In managed stands (PRP 01, 03, 04, 05) the spatial patterns at the beginning of observation in 1980 and in 2005 were compared.

Results

Tree species composition, the occurrence of dead wood

Across all PRP, beech was the dominant tree species. On PRP 06 beech was represented by 94.0%, on PRP 07 by 64.2% (based on basal area). On PRP 06 other tree species were (composition: basal area): larch - *Larix decidua* Mill. (3.4%), hornbeam - *Carpinus betulus* L. (1.7%), spruce - *Picea abies* (L.) Karst (0.6%), and birch - *Betula pendula* Roth (0.3%). On PRP 07 the other tree species were: larch - *Larix decidua* Mill. (13.6%), spruce - *Picea abies* (L.) Karst (10.7%), hornbeam - *Carpinus betulus* L. (10.6%), sycamore maple - *Acer platanoides* L. (0.6%) and birch - *Betula pendula* Roth (0.4%). PRP 01 was an almost pure beech stand with only one full-canopy larch tree (2.0%). PRP 03 and 04 are pure beech stands with no admixed species. On PRP 05 two oaks - *Quercus petraea* (Matt.) Liebl. were present (1.2%). Based on stem numbers, beech and hornbeam were the main tree species on PRP 06 (90.3%-5.3%) and 07 (71.7%-15.8%).

The total amount of log volume in research plot 06 was $21.5 \text{ m}^3 \cdot \text{ha}^{-1}$. The second decay class was represented by 67%. In general, only lower decay classes were present. The 4th decay class amounted to only 0.2% of CWD. On PRP 07 the volume of snags was presented by only one standing death beech. By contrast, the volume of logs was higher than PRP 06 and reached in total $46.3 \text{ m}^3 \cdot \text{ha}^{-1}$. The 2nd, 3rd and 4th decay classes were for the most part represented (32%, 28% and 24% of total CWD volume). On PRP 01, 03, 04 and 05 the occurrence of dead wood was restricted to

Table 2. Characteristics of dead wood on unmanaged plots

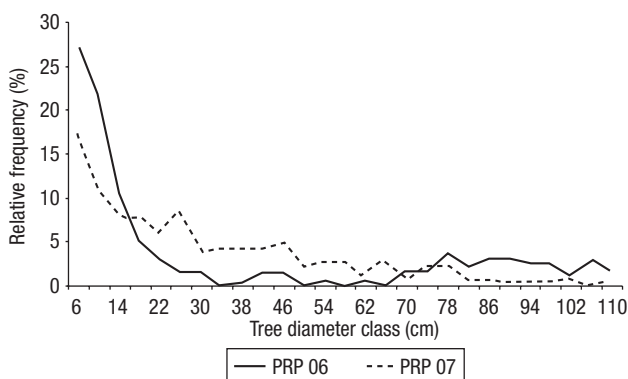
Plot (PRP)	Logs ($\text{m}^3 \cdot \text{h m}^{-1}$)				Snags ($\text{m}^3 \cdot \text{ha}^{-1}$)	Total dead wood ($\text{m}^3 \cdot \text{ha}^{-1}$)
	Beech	Birch	Hornbeam	Larch		
06	20.0	1.1	0.4	—	12.2	33.7
07	42.7	2.3	1.0	0.2	1.8	48.0

felling debris of a diameter of less than 10 cm. There were no logs recorded. On PRP 01 volume of snags amounted to $1.0 \text{ m}^3 \cdot \text{ha}^{-1}$, on PRP 03- $3.3 \text{ m}^3 \cdot \text{ha}^{-1}$, on PRP 04- $1.6 \text{ m}^3 \cdot \text{ha}^{-1}$ and on PRP 05- $3.0 \text{ m}^3 \cdot \text{ha}^{-1}$. The basic characteristics of deadwood are given in Tables 2 and 4.

Structural and species diversity

The diameter distribution on PRP 06 shows the presence of an upper layer and an understorey in the stand (two peaks in the frequency of tree diameter classes, Fig. 1). The quadratic mean diameter was 48.8 cm. The top diameter (represented by the 10 thickest trees) was 103.9 cm. The total basal area of the stand was $35.6 \text{ m}^2 \cdot \text{ha}^{-1}$, the beech amounted to $33.4 \text{ m}^2 \cdot \text{ha}^{-1}$, larch $1.2 \text{ m}^2 \cdot \text{ha}^{-1}$, hornbeam $0.6 \text{ m}^2 \cdot \text{ha}^{-1}$, spruce $0.2 \text{ m}^2 \cdot \text{ha}$ and birch $0.1 \text{ m}^2 \cdot \text{ha}^{-1}$.

On PRP 07 the diameter distribution can be characterized by using a reversed J-shaped curve (Fig. 1). The quadratic mean diameter of the stand on PRP 07 was 38.0 cm. The highest diameter was 84.8 cm. Both values are lower than those of PRP 06, with its considerable number of full-size canopy trees in the upper layer. On PRP 07 the number of these trees is distinctly lower; on the contrary, a middle layer formed by beech and other tree species is present. On both plots many

**Figure 1.** Diameter structure on PRP 06 and 07.

small recruits in the understorey still await release from suppression. The total basal area of the stand was $30.8 \text{ m}^2 \cdot \text{ha}^{-1}$, with beech amounting to $19.7 \text{ m}^2 \cdot \text{ha}^{-1}$, larch $4.2 \text{ m}^2 \cdot \text{ha}^{-1}$, hornbeam $3.3 \text{ m}^2 \cdot \text{ha}^{-1}$, spruce $3.3 \text{ m}^2 \cdot \text{ha}$, birch $0.1 \text{ m}^2 \cdot \text{ha}^{-1}$ and sycamore maple $0.2 \text{ m}^2 \cdot \text{ha}^{-1}$.

The coefficient of variation reaches the highest value on PRP 06 and 07 (with high diameter differentiation, due to the high number of trees in undergrowth) and the lowest on PRP 05. Other managed plots show very similar values to that of PRP 05, with a slightly higher value for PRP 01 (Table 3). The biggest shift of the frequency curve on the axis x to the right was recorded on this PRP by two diameter classes. A similar development was also recorded on other plots but to a lesser extent (Fig. 2).

The frequency of large trees defined as trees with a dbh > 80 cm (Meyer *et al.*, 2003) was highest on PRP 06 (36 ha^{-1}), followed by PRP 07 with 10 ha^{-1} . On managed plots the frequency of large trees ranged from 1 to 8 ha^{-1} and was at its highest point in 2005.

According to the height distribution of PRP 06 and 07, the stands can be described as multi-layered. The frequency curve on Figure 3 has in both cases two peaks reflecting the dbh distribution. On PRP 06 the middle layer was almost missing, with only few individual examples firstly of admixed tree species, whereas the

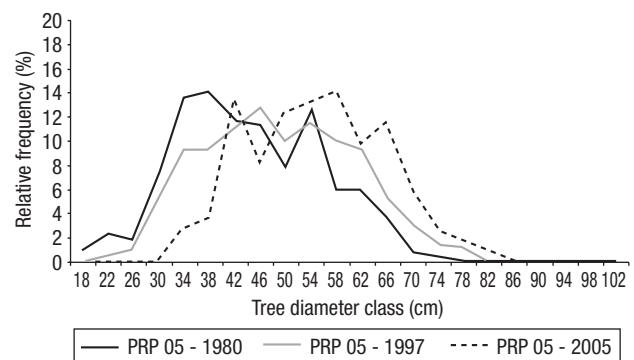
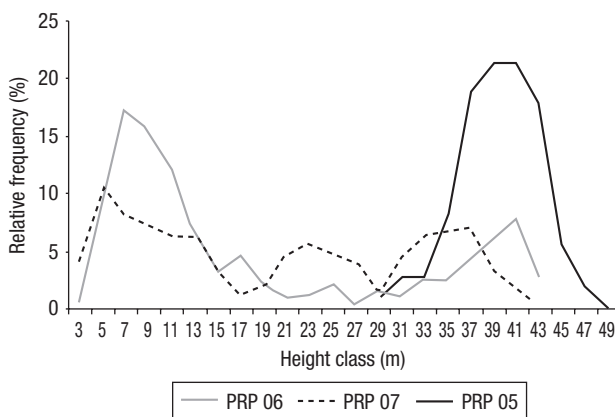
**Figure 2.** Diameter distribution on PRP 05 in a managed stand and its evolution over time (other managed plots show a similar development of dbh distribution).

Table 3. Statistic characteristics of diameter distribution in partial plots

Characteristics	Permanent research plot/Year															
	06		07		01			03			04			05		
	2005	2005	1980	1997	2005	1980	1997	2005	1980	1997	2005	1980	1997	2005		
Mean value (cm)	31.9	29.6	51.3	55.2	59.6	55.4	60.1	62.5	53.2	57.8	60.5	44.6	49.1	55.2		
Count	203	272	170	149	93	149	138	126	139	127	110	221	194	113		
Minimum (cm)	3.6	3.1	24.5	25.6	28.8	26.6	32.3	33.0	27.6	28.6	31.5	18.9	22.0	35.2		
Maximum (cm)	110.2	108.2	93.0	91.8	95.6	81.0	87.4	95.0	87.2	91.7	102.1	72.2	78.7	83.2		
Stand. dev. (cm)	34.93	23.78	12.49	13.70	13.43	11.74	12.60	12.98	10.66	11.72	12.25	11.31	11.92	10.55		
Kurtosis	2.50	3.42	2.99	2.62	2.83	2.56	2.37	2.54	3.00	2.78	3.34	2.36	2.35	2.43		
C. of variation (%)	109.57	80.28	24.33	24.84	23.94	21.18	20.96	20.78	20.04	20.29	20.25	25.38	24.30	19.12		
Skewness	1.10	1.06	0.19	0.15	0.06	-0.23	-0.20	-0.17	0.13	-0.01	0.17	0.13	0.16	0.20		

overstorey and understorey were dominated by beech. Similar to dbh distribution, the distribution of height on PRP 07 showed the presence of an abundant middle layer (formed mainly by admixed tree species). On managed plots with the exception of PRP 03 the heights were normally distributed (Fig. 3).

**Figure 3.** Height distribution in managed (on example of PRP 05) and unmanaged (PRP 06 and 07) stands.

The height curve for the managed stands moved upwards, probably due to the felling of thinner trees and the absence of management interventions in the unmanaged stands where subcanopy trees remain in the stand, thus lowering the arithmetical mean of tree height for the entire stand and in particular diameter classes (not displayed).

According to the stability of individual trees, the critical value of h/d ratio for beech is given in the range 1.8-2.2 (Korpel' *et al.*, 1991). On PRP 06, the values ranged from 0.28 to 1.89. On PRP 07 the h/d ratio ranged between 0.35-1.75. Extreme values were reached only in the dimensions of the small pole stage on unmanaged plots, making the understorey more susceptible to abiotic agents (especially snowbreak) familiar from young managed stands.

In all managed plots, the width of crowns in relation to dbh was very similar. The mean value of the crown projection area reached from 70.0 m² to 85.4 m². On PRP 06 the size of crowns (mean 73.9 m²) for the given dbh overreached the values of managed plots, but also that of PRP 07 (mean 49.1 m²). On PRP 07, a high

Table 4. Basic stand characteristics (2005)

PRP	N (ha ⁻¹)	G (m ² /ha)	Crown cover (%)	V (m ³ ·ha ⁻¹)	V _{cwd} (m ³ ·ha ⁻¹)	V _{cwd} /V (%)	d _{1,3} ** mean stem (cm)	h mean stem (m)
01	93	27.2	78.2	597.5	1.0	0.2	61.1	41.2
03	126	40.3	107.7	863.7	3.3	0.4	63.8	40.3
04	110	32.9	81.8	704.0	1.6	0.2	61.7	40.4
05	113	28.0	77.0	583.2	3.0	0.5	56.2	39.8
06	203	35.6	146.1	707.2	33.7	4.8	48.8	30.5
07	272	30.8	132.8	505.6	48.1	9.5	35.9*	26.4*

* Due to high stand diversification and species richness value takes into account only beech trees (hornbeam /d_{1,3} and h of mean stem/: 31.10 cm-24.2 m, larch: 59.5 cm-36.9 m, spruce: 49.7 cm-33.9 m). ** Quadratic mean diameters.

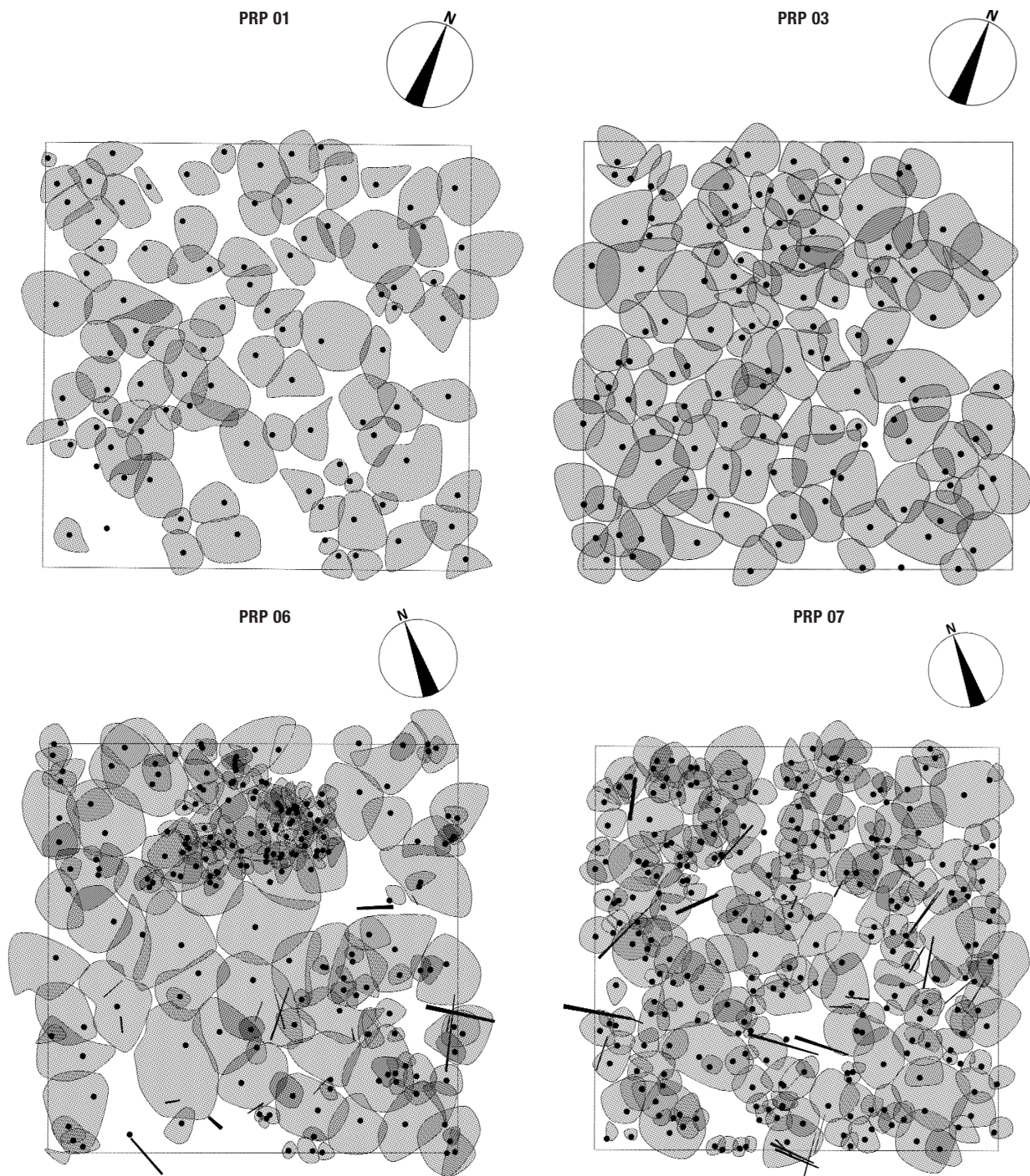


Figure 4. Horizontal structure of forest stands on PRPs 01, 03, 06 and 07 (figures were made in software Forestry GIS (fGIS) Program Copyright 2003-2004 University of Wisconsin).

number of undercanopy trees with small crowns lowered the average value, which was not exactly the case for PRP 06, with a mean value comparable with that of the managed plots. The frequency of tree giants (Rademacher *et al.*, 2001) with a crown area of at least

204 m² was highest on PRP 06 with 22 trees ha⁻¹. On PRP 07, only 7 tree giants were found. On the managed plots, the density of large trees was generally lower (on PRP 01 and 03 identically 3 individuals). Figure 4 shows the horizontal structure of PRP 01 and 03 as

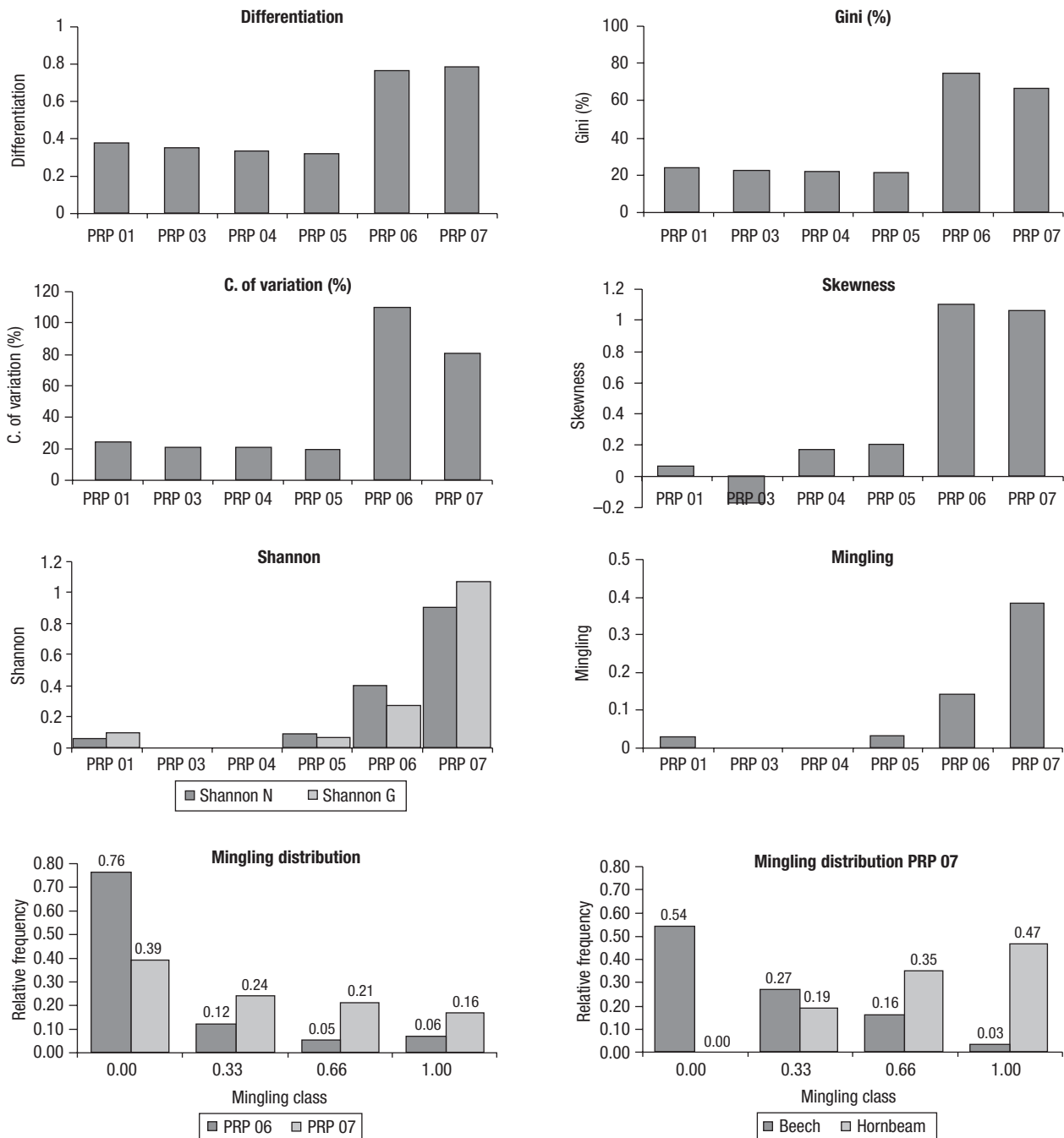


Figure 5. Selected structural and species diversity indices characterizing the sample sites in 2005 and the species mingling distribution on unmanaged sites PRP 06 and 07.

examples of the lowest and the highest basal area of the particular plot and both of the unmanaged PRPs, 06 and 07.

According to dbh differentiation, managed plots show distinctly lower values (average 0.344) than unmanaged forest sites (0.763 and 0.784). The latter are similar to each other in regard to skewness and diame-

ter differentiation, but PRP 07 still has a lower structural heterogeneity according to the coefficient of variation and the Gini index. Only one managed plot was somewhat left-skewed (-0.17), while the three managed plots weakly right-skewed (from 0.06 to 0.20) and both unmanaged sites were heavily right-skewed (1.10 and 1.06). The coefficient of variation of dbh dis-

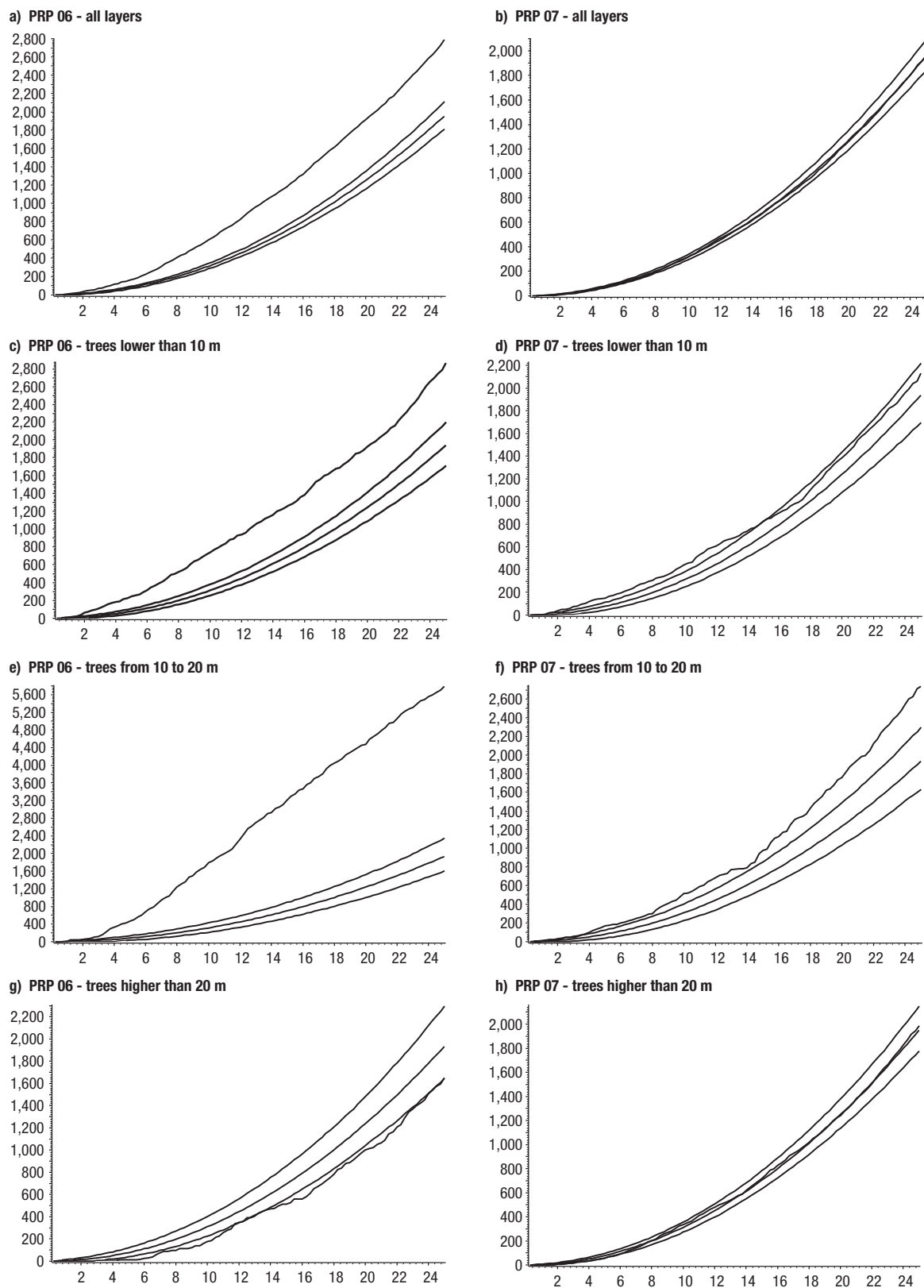


Figure 6. Ripley's K -function - locality «Virgin forest»: permanent research plots PRP 06 and 07 (x-axis: distance /m/, y-axis: Ripley's K -function). Upper and lower bounds show 95% confidence interval.

tribution was low on the managed plots (average 21.02%) and high on the unmanaged plots (109.57 and 80.28%). Considerable diversity confirms also the values of the Gini index for the unmanaged sites (74.70% and 66.74%) and lower diversity on the managed sites (average 22.35%). Spatially inexplicit species diversity indices (Shannon indices both calculated for N and G) exhibit variation ranging from nearly no species diversity with the managed sites and low diversity on PRP 06 (Shannon index N = 0.397 corresponding to 1.5 equally frequent species) to higher species richness on unmanaged PRP 07 (Shannon index N = 0.900 corresponding to 2.5 equally frequent species). With three neighbours, the mingling attribute M_i can assume four values. The distribution of species mingling on PRP 06 indicates that most of the trees belong to the lower mingling class (a structural group of four is formed by only one species in 76% of cases). The mingling distribution on PRP 07 shows that in most cases (61%) the reference tree is surrounded by one to three neighbours that belong to a different species (Fig. 5). Pielou's

index of segregation for both main tree species (beech and hornbeam) indicates a rather random distribution in all tree layers with values ranging from -0.017 to 0.299. Of particular interest is the species-specific mingling distribution for beech and hornbeam also shown in Figure 5 (displayed only for PRP 07). Beech occurs in variety of mingling distributions, but in most cases (about 80%) is surrounded by two or even three trees of the same species. In contrast, hornbeam occurs most frequently as a single tree among other species. This is also the case of all other admixed tree species on both of the unmanaged sites (not shown).

Forest structure-spatial patterns of trees

*Permanent research plots 06, 07-locality
«Virgin forest»*

All three of the aggregation indices on PRP 06 and 07 show trees of the understorey and middle layer

Table 5. Aggregation indices of spatial patterns in unmanaged stand. Permanent research plots PRP 06 and PRP 07

Index	Observed value	Expected value	Observed value	Expected value
	PRP 06		PRP 07	
<i>All trees</i>				
Hopkins-Skellam	0.545	0.499	0.494	0.499
Pielou-Mountford	1.478*	1.076	1.120	1.065
Clark-Evans	0.965	1.031	1.079	1.026
<i>Trees lower than 10 m</i>				
Hopkins-Skellam	0.714*	0.499	0.701*	0.498
Pielou-Mountford	2.759*	1.116	1.909*	1.118
Clark-Evans	0.778*	1.047	0.818*	1.051
<i>Trees from 10 to 20 m</i>				
Hopkins-Skellam	0.736*	0.497	0.574	0.499
Pielou-Mountford	3.745*	1.145	1.524	1.139
Clark-Evans	0.910	1.065	0.939	1.057
<i>Trees higher than 20 m</i>				
Hopkins-Skellam	0.381*	0.497	0.477	0.499
Pielou-Mountford	0.918	1.130	1.147	1.092
Clark-Evans	1.321*	1.057	1.141*	1.037
<i>Trees with dbh > 80 cm</i>				
Hopkins-Skellam	0.420	0.496	0.493	0.485
Pielou-Mountford	1.117	1.174	1.227	1.257
Clark-Evans	1.352*	1.081	1.162	1.168

* Statistically significant.

clumped according to random patterns. Trees taller than 20 m have a random to regular distribution over the area. All layers as whole on PRP 06 incline to a clumped structure, and on PRP 07 to more random distribution. Tree giants (trees with dbh > 80 cm) are rather randomly distributed over the forest stands with a slight tendency to a regular pattern (Table 5). The Ripley's *K*-function gives similar results with a pronounced tendency to the aggregation of trees between 10 to 20 m height on both plots. Nevertheless, on PRP 07 the tree layer up to 10 m height shows a tendency to a rather random distribution (Fig. 6). In general, the understorey and middle layer on PRP 07 demonstrate a less-clumped spatial distribution indicating a slower disruption process of the main tree layer on this plot.

Permanent research plots 01, 03, 04, 05-managed stands

Use of the Hopkins-Skellam and Clark-Evans indices demonstrate the regular structure of the managed stands on all PRPs. No significant changes are apparent over the evolution in time. Yet on PRP 01 and 05, a decrease in value is apparent, which means a shift to more regu-

larity. On the contrary, PRP 03 and 04 show a slight increase in the value of the index, which can be interpreted as a shift towards random distribution. This can be explained by the effect of an ongoing border-cutting that has already reached the border of PRPs 03 and 04. The Pielou-Mountford index shows random to regular distribution of the forest stands, with the exception of PRP 04 in 2005, with an aggregated spatial pattern (Table 6). The Clark-Evans index in all cases shows regularity in the forest structure. The Ripley's *K*-function gives similar results with a slight aggregation (not significant) on PRP 03 and 04 in 2005 (Fig. 7). On these plots the shelterwood management system combined with border-cutting, results in more clumped structures. PRP 01 and 05 show a random spatial distribution of trees over the full duration of the observation period.

Discussion

The main structure of managed beech stands in the area is regular, with the wide stands being uniform in size and age. According to the forest management plan of 2001, the rotation of beech is 130 years (without any difference among forest types); in reality most beech

Table 6. Aggregation indices of spatial patterns in managed stands (period 1980 and 2005). Permanent research plots PRP 01, 03, 04 and 05

Index	Observed value	Expected value	Observed value	Expected value
	1980		2005	
<i>PRP 01</i>				
Hopkins-Skellam	0.368*	0.499	0.336*	0.500
Pielou-Mountford	0.884	1.083	0.764*	1.113
Clark-Evans	1.341*	1.033	1.328*	1.044
<i>PRP 03</i>				
Hopkins-Skellam	0.370*	0.499	0.405*	0.498
Pielou-Mountford	0.875	1.087	0.886	1.093
Clark-Evans	1.294*	1.036	1.208*	1.039
<i>PRP 04</i>				
Hopkins-Skellam	0.426	0.498	0.484	0.499
Pielou-Mountford	1.063	1.088	1.235	1.103
Clark-Evans	1.308*	1.037	1.249*	1.042
<i>PRP 05</i>				
Hopkins-Skellam	0.433*	0.499	0.374*	0.498
Pielou-Mountford	1.001	1.075	0.845*	1.101
Clark-Evans	1.227*	1.031	1.294*	1.043

* Statistically significant.

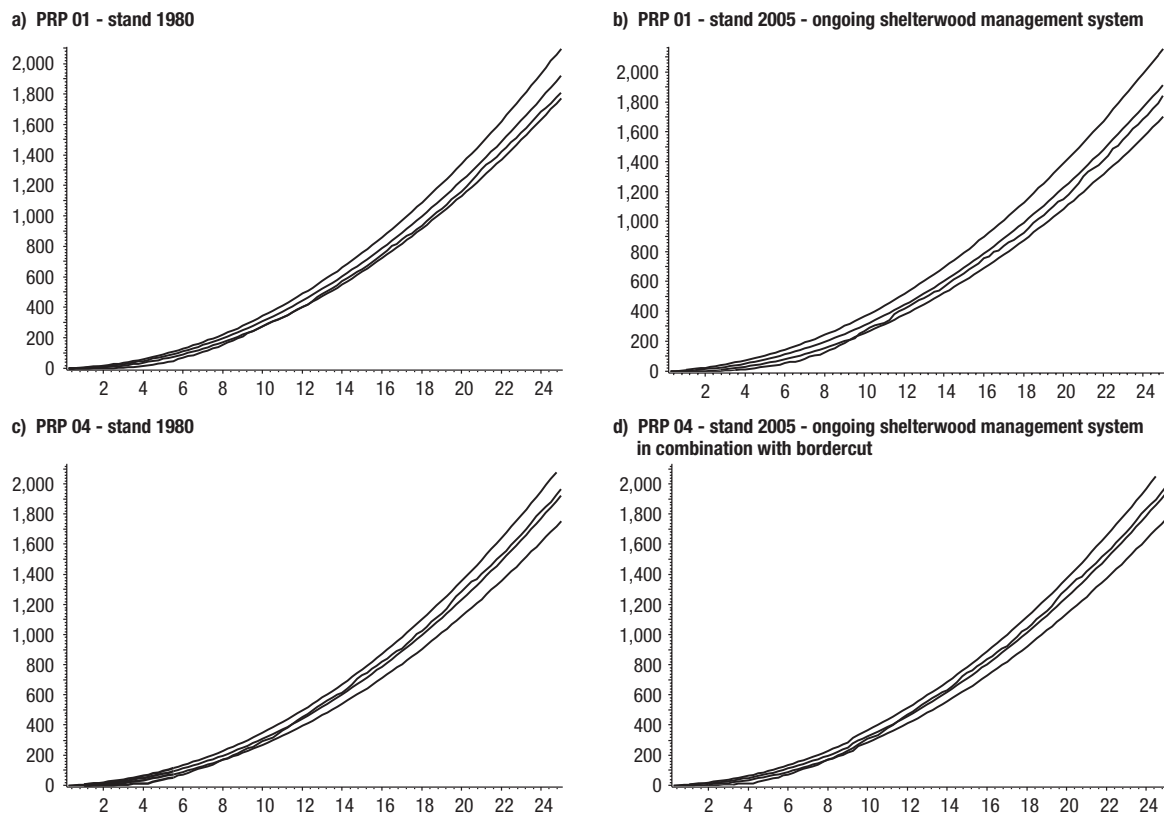


Figure 7. Ripley's K -function - managed forest stands: permanent research plots PRP 01 and 04 (x-axis: distance /m/, y-axis: Ripley's K -function). Upper and lower bounds show 95% confidence interval.

stands in the area are far behind this rotation period. For managed plots size-class distribution with normal distribution of diameter classes was recorded. With a relatively closed canopy during the evolution of managed stands, and due also to high competition between trees, diameter distribution is generally symmetrical, yet with a large range in diameter (common for beech and other shade tolerant species: from 28.8 cm to 102.1 cm in 2005) and with a typical flat diameter curve. Similar results were obtained from all years, indicating that present management does not contribute to higher stands diversification (the harvest rates were in general low and retained dense canopy closure and horizontal uniformity). The changes in dbh distribution for the managed stands were of two kinds: mechanical-caused by thinning and shelterwood cutting, and dynamic-caused by diameter increase as a consequence of tree growth. In the unmanaged forest stands, we see higher structural differentiation, yet with differences in structural characteristics within the same old-growth depending on the initial structure and the prevalent disruption dynamic, on both PRP 06 and PRP 07. Diffe-

rences between fine-scale tree falls (PRP 07) and a more pronounced gap formation on PRP 06, which in turn influenced both diameter distribution and spatial patterns, were apparent. According to Pommerening (2002) the class of dbh differentiation on the unmanaged sites can be interpreted as being very high, meaning that the tree with the smallest dbh is less than 30% of the neighbouring tree's size, and average for unmanaged plots. Heavily right-skewed dbh distribution is also typical for uneven-aged forests (Sterba 2008). For the investigated area, the differentiation and Gini indices along with the skewness and the coefficient of variation make it possible to monitor the shift from even-aged forest management to spontaneous forest development. Analogically, Sterba and Zingg (2006) found significant differences in the mentioned indices of even-aged management and individual tree selection system. In their study, the lowest Gini index was 21% and the lowest coefficient of variation 20% for large number of different stand conditions, indicating also for our conditions (with almost identical values for both indices) a very low diversification for the mana-

ged sites. From the viewpoint of time, a decline of the values of the coefficient of variation occurred only on PRP 05. The time dependency was not found on other plots. According to Barna and Marušák (2003) the dynamic changes are quicker if more intensive cutting is applied and the coefficient of variation drops according to the increase in cutting intensity. This was exactly the case of PRP 05, where intensive cutting from 1997 to 2005 resulted in a decrease of the coefficient of variation.

The majority of stands in both managed and unmanaged sites show a generally high degree of artificiality for species composition in trees (lack of silver fir and presence of non-native species or species not appropriate for given forest types). According to Meyer *et al.* (2003) a high portion of admixed tree species is not a natural feature of beech forests. Under mostly good site conditions, nature develops towards domination with only a very few competitive species, and forms relatively un-mixed forests with more or less uniform stand structures (Schütz, 1999, 2002). Therefore, a conflict could arise between the goals of enhancing tree species diversity and of emulating natural patterns. In this aspect, the possible dependency between higher structural heterogeneity and species richness on unmanaged sites needs to be studied in greater detail. Heterogeneous microclimatic conditions as a result of higher structural differentiation probably allow more room for other tree species to establish in the subcanopy (hornbeam, spruce, birch). On the contrary, altered species composition may also have an impact on the dynamics of the forest. Larch is under the given conditions mainly a full-canopy tree of higher dimensions.

In managed stands a general lack of woody debris was confirmed. According to many authors, the average dead wood volume in present day production forests is less than $10 \text{ m}^3 \cdot \text{ha}^{-1}$ (cf. UNECE/FAO, 2000; Green and Peterken, 1997). By contrast, it has been shown that in mature stands, which have not been managed for half a century, the volume of dead wood was significantly higher. As a stand progresses into maturity the volume of dead wood tends to increase rapidly. Earlier research demonstrated that there is no one standard level of natural dead wood, but rather that the level differs greatly from site to site. This is related to the general cycle of dead wood levels in natural stands. Christensen *et al.* (2005) reported the mean volume of total dead wood in beech forest reserves at $130 \text{ m}^3 \cdot \text{ha}^{-1}$. The variation among reserves was high, ranging from almost 0 to $550 \text{ m}^3 \cdot \text{ha}^{-1}$. The greatest difference between the

managed and unmanaged PRP was the amount of lying and standing dead trees. In any case the ratio of living trees volume and the volume of CWD did not exceed 1.0% on the managed plots and 10.0% on the unmanaged plots. The rapid increase of dead wood on unmanaged plots has to be related to the terminating life cycle of old beeches and decreasing growing stock. A high number of tree giants and the presence of fungal pathogens on a high portion of trees suggest that the proportion of CWD will increase further in the coming decades. Nonetheless, not only the total volume of dead wood is important for the maintenance of biodiversity and natural cycles, but also its quality. Dead wood of different types (tree species, decay classes), dimensions and long-term continuity in forest stands are of great importance. The highest portion of dead wood in the second decay class, which accumulated mainly during the last few decades and the general lack of higher decay classes on unmanaged plots clearly shows this time dependency of dead wood occurrence and the importance of a continuous cycle of CWD.

On plots with no silvicultural interventions in the last 50 years, overstorey trees show random (PRP 07) to regular (PRP 06) spatial patterns. The spatial patterns of beech understorey trees on both PRP 06 and 07 (locality «Virgin forest») is rather clumped, which corresponds with observations from Nagel *et al.*, (2006) made in regard to the old-growth *Fagus sylvatica*-*Abies alba* forest in south-eastern Slovenia. PRP 06 is marked by a faster break-up of the upper layer of dominant beeches, creating larger gaps and a high number of trees in understorey. Comparing both unmanaged plots, due to the slower degradation of the parent stand on PRP 07 (with a less pronounced gap formation), the spatial patterns of understorey and middle storey are not as clumped as on PRP 06. The dbh distribution shows an absence of a middle layer on PRP 06. On PRP 07 the dbh distribution is closer to that of selection forests showing a typical reverse-J shaped size distribution. A bimodal pattern as on PRP 06 was observed for some near-natural forests in Central Europe, with a second maximum ranging from 100 to 180 years (Emborg *et al.*, 2000). The author suggests that the bell-shaped section of the diameter distribution at these ages reflects large-scale beech regeneration due to a natural phase of decline and regeneration, or after cattle-grazing ceased. Mature managed stands are in some structural aspects similar to forests in their optimal phase during the forest cycle (closed canopy and the absence of undergrowth); nevertheless the area

of the given developmental phase covers almost the entire area of the reserve with only a few forest stands having more diversified structures. Oheimb *et al.* (2005) stated that even though the individual structural features may be similar to those of virgin beech forest (in his study in Serrahn beech forests), a temporary phenomenon and the regeneration gap between the dominant trees and the lower canopy trees may result in a shortage of large trees for approximately 100 years. In this regard the presence of diversified structures of the aggregation, innovation and degradation phases are exceptional in the reserve and are thus related to a higher amount of deadwood and the presence of tree giants, but not necessarily to lower basal area. This observation may be in agreement with results of Paluch (2007), who stated that the basal area of the under-canopy trees is more crucial for the presence of the beech regeneration bank than the basal area of the surrounding stand and the closure of the canopy trees. Locally, this factor has a greater influence on light conditions on the forest floor than on the tree fall of a canopy tree in patch with sub-canopy trees. This event may not improve conditions for the emergence of regeneration and its subsequent recruitment in the long term. Typical for small-scale disturbances is the diameter distribution of beech, with many small recruits and also a considerable number of full-size canopy trees. However, it seems that the presence of sub-canopy trees on PRP 07 decreased in terms of the number of trees of lower diameter classes.

In general, younger trees in forests driven by spontaneous development start off clumped, and the populations become more uniform as the forest ages. According to Wolf (2005), two contrasting sets of processes affect the spatial structure of natural forest stands. Direct density-dependent competition between neighbouring individuals in a clumped stand should progressively lead to a more regular pattern. Opposed to this are processes that tend to create mosaics and clumped distribution. These processes might be influenced by microsites, mosaics, canopy gaps and the history of the area. In general, the regular pattern shows evidence for competition playing the major role, whereas clumping suggests that gap dynamics and favourable microsites are more important. In managed even aged-stands, the optimal growth for all trees may be obtained by equal spacing. Hanewinkel (2004) revealed that in all investigated stands, clustering decreased with increasing heights of understorey trees, indicating that trees of the understorey suffer from competition not only from the crown cover but also from neighbouring small trees.

Similarly, our results showed that during the regeneration period the parent stand became more clustered (especially with trees of the understorey and middle layer), on PRP 06 with a limited number of trees in the middle layer and less clustered, and on PRP 07 with a dbh distribution closer to that of forest selection. Wolf (2005) stated that when management ceased, recruitment changed the pattern towards more randomness, with the gap regeneration being the main driving force behind the changes. Although it seems that in temperate deciduous forest on mesotrophic sites the gap formation and gap regeneration plays a very important role in determining the spatial patterns of forests, no general thresholds of «randomness» or «regularity» of near-natural forest stands can be given. According to Wolf (2005), monitoring the changes in a spatial pattern is a comparatively fast indicator for following up the achievements of conservation, which aims to bring the forest back to a natural state. The diversity measures and forest summary characteristics of selected stands can help to monitor the influence of both natural processes and modern silviculture which employs methods of near-natural forestry on forest development (Motz *et al.*, 2010). Examples of modern approaches and concepts, and of ways to characterize forest or stand structures, can be found in Pommerening (2002) or Aguirre *et al.* (2003). In any event, the structural characteristics of the stand should include summary forest characteristics, tree (spatial patterns) and tree attributes diversity (dbh and species diversity). Moreover, in forests left to spontaneous development the initial structure of the stands may also be of great importance. In the case of a faster disruption of the overstorey related to gap formation, clumped structures may outweigh discrete patterns of regeneration induced by the death of single trees. Nevertheless, Meyer *et al.* (2003) reported from an Albanian virgin beech forest the occurrence of gaps smaller than the mean crown size of older trees. The presence of wide crowns of dominant beeches on PRP 06 indicate a longer continued period with lower stand density in the overstorey relative to gap formation with sufficient time to develop such extensive crowns. It is also possible that initial gaps in this case were formed mainly by the death of single trees of large dimensions with their further extension. It is probable that already before the area was declared to be non-interventional, the locality «Virgin forest» showed some indicators typical for near natural stands (tree giants, gap formation, natural regeneration, and structural differentiation) becoming the effective im-

pulse for their protection. However, the observer should not be misled by the impression that the entire area of natural beech forests may be covered by undergrowth and therefore difficult to penetrate. Virgin forests generally show regular structures, at least during an essential part of their development. From the phase of «aggradation» to the end of the «optimal» phase, the process of homogenization (*i.e.* the creation of regular stands) can be observed as a dominating principle (Schütz, 1999). Tabaku (1999) reported 2.6%-7.6% of the area with the destruction phase occurring within the mosaic cycle, Emborg *et al.* (2000) reported in his model 6% of the forest area covered by a degradation phase (further 2% innovation and 22% aggradation phase). Korpel' (1995) indicates a far higher proportion of the decaying phase (42-45%), which results from a different definition of this stage including more developmental stages (Meyer *et al.*, 2003). The common problem for the comparison of horizontal structures between different authors are discrepancies in definitions and overlaps between particular developmental phases. Generally, for natural beech forests highly diversified structures, usually connected to shifts between forest generations, are just as natural or authentic as with closed stands uniform in structure. Schütz (2002) distinguishes between genuine irregularity within the crown layer, full (vertical) irregularity at stand level (plenter system) and horizontal irregularity («patchiness»). In this aspect, forest management can contribute to both increased uniformity and heterogeneity of forest stands at all three levels.

Conclusions

It should be stated that there is no single key indicator of natural forest dynamics. Broad knowledge of forest summary characteristics, as well as of tree and tree attributes diversity is needed in order to understand the actual stage of forest development at a given site. The diameter differentiation and Gini indices, along with skewness and the coefficient of variation, provide a means of monitoring the shift from even-aged forest management to spontaneous forest development. The description of variability via classical variability indices based on pairs can reveal adequate information about the studied forest stand. A disadvantage of these indices is that they are «short-sighted», due to the fact that they only take into account the nearest neighbours. However, these indices are still of value when applied

in situ to a given forest, when only nearest neighbour distances are measured (Stoyan and Penttinen, 2000). All aggregation indices gave similar results, with a slight higher sensitivity of the Pielou-Mountford index for aggregations of trees (see Tables 5 and 6), which is often in accordance with the result of the used correlation function. In our study, spontaneous development was marked mainly by aggregated tree distribution in the understorey and middle layers, an increase of dead-wood volumes and a shift from normal to reversed J-shaped dbh distribution.

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