# Regeneration of forest stands on permanent research plots in the Krkonoše Mts.

**S. Vacek[1], I. Nosková[1], L. Bílek[1], Z. Vacek[1], O. Schwarz[2]**

[1]*Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic*
[2]*Krkonoše National Park Administration, Vrchlabí, Czech Republic*

**ABSTRACT**: The article describes natural, combined and artificial regeneration on 38 permanent research plots in both Czech and Polish part of the Krkonoše Mts. The attention is paid to species composition, spatial (horizontal and vertical) and age structure of forest regeneration according to different stand and site conditions. Concerning the structure and dynamics of forest stands and their regeneration, the potential and prospects of regeneration according to particular developmental stages and stand types (beech stands; mixed stands: spruce-beech, fir-beech, spruce-fir-beech; spruce stands, stands in the ecotone of the upper forest limit and relict pine woods) were evaluated. In many aspects the plots show several similarities, nevertheless the regeneration in different site and stand conditions show clear differences in dynamics of development. The main differences are result of different ecological conditions, environmental limits and biological characteristics of dominant tree species.

**Keywords**: forest ecosystem; forest regeneration (natural, combined, artificial); Krkonoše Mts.; site and stand conditions; structure and development of forest stands

Increasing the ratio of natural regeneration is in present days considered as one of the main challenges of the Czech forestry and nature protection. The use of natural regeneration is commonly accepted as essential part of close-to-nature forest management based on ecological principles. Beside lower establishment cost, natural regeneration is important measure in conservation of forest genetic resources and establishment of forest stands with appropriate tree species composition and ecological stability. In the Krkonoše National Park the ratio of natural regeneration is constantly increasing (Fig. 1) with simultaneous decrease of artificially regenerated areas, usually of conifers (mainly spruce).

### Issue analysis

Natural regeneration, its age, species and height structure have a key role in regeneration of tree layer in forest ecosystems. Regeneration processes and their dynamics largely influence stability and functionality of forest stands. The advantages of natural regeneration lie mainly in maintaining of autochthonous or well-established allochthonous populations of forest woody plants with presupposition of preserving desirable qualities of maternal forests, i.e. individuals of regeneration that well adapted to more extreme site conditions; it enables to use effectively differences in site conditions (Korpeľ et al. 1989; Vacek et al. 2010a).

The regeneration development in forests with natural or near-natural structure is related to the occurrence of disturbances in the forest development. The success of natural forest regeneration depends on a number of factors. Worsening conditions for existence of a forest in mountain areas (climatic and soil extremes) result in decreasing generative reproduction ability of forest woody plants. Continuous regeneration is dependent on

Supported by the Ministry of Education, Youth and Sports of the Czech Republic, Project No. MSM 2B06012, and by the Ministry of Environment of the Czech Republic, Project No. SP/2d3/149/07.

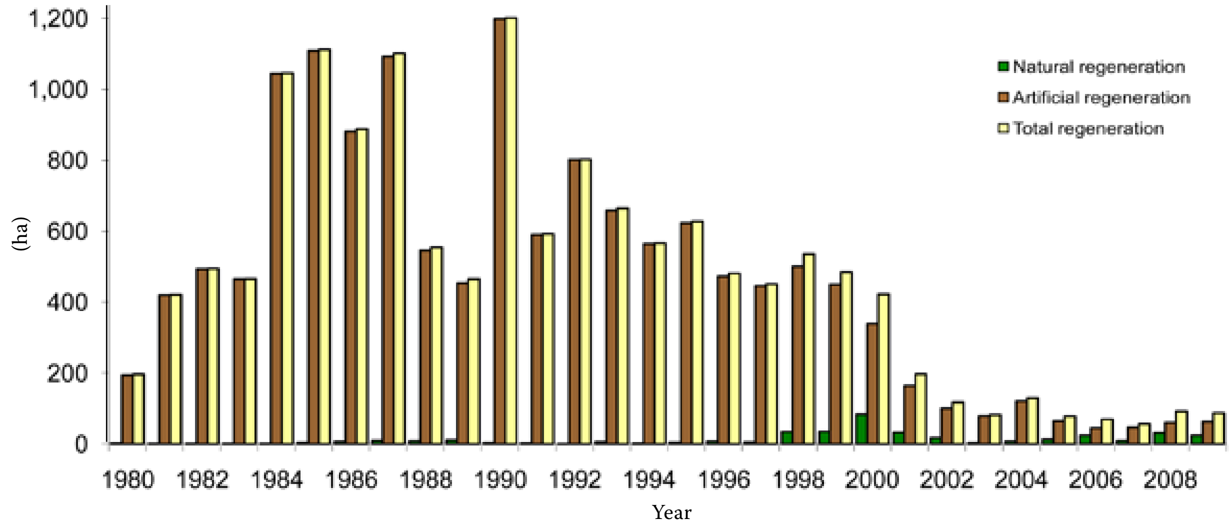


Fig. 1. Natural, artificial and total regeneration in the Krkonoše National Park between 1980 and 2008

favourable constellation of the key site conditions. This issue was studied for instance by Vacek et al. (2009 a,b).

Survival and growth of seedlings or their mortality in natural forests are influenced by many factors. Vacek and Podrázský (2003) report frost, game damage and competition of forest floor vegetation as the most important ones. The process of natural regeneration in mountain areas is further disturbed by an unfavourable effect of climate and a long period of seed years (Šerá et al. 2000).

Seedling survival is affected also by other factors, mainly light conditions, intraspecific competition and competition of other low plants; they lead to high mortality of spruce trees in the youngest age category of 4–5 years (Jonášová, Prach 2004). The influence of forest floor vegetation competition on mainly slow-growing seedlings of some woody species is reported in many works (Canham et al. 1990; Grassi, Bagnaresi 2001; Vacek et al. 2006, 2007, 2009). It is shown that the basis of relatively functional future forest generation are the individuals higher than 20 cm. Korpeľ (1991) estimates the minimal number necessary for regeneration as 150–200 pcs·ha$^{-1}$ of 50–130 cm high individuals; yet, to assess the viability of natural seeding, it is necessary to take into account the chronotopical influence of game as well as other factors (Vacek, Souček 2001; Gubka 2006).

Character and success of the natural regeneration under mountain conditions and in moist spruce stands are related to many factors that mutually influence. The effect of microrelief on the occurrence of regeneration was reported by Vacek (1981); Vacek et al. (1995b); Vacek and Souček (2001); Hanssen (2002, 2003); Kuuluvainen and Kalmari (2003); Diaci et al. (2005); Štícha et al. (2010). These studies imply that the occurrence of natural regeneration of spruce is closely related to sites with a special microrelief, mostly on the elevations. Moreover, a strong influence of other factors is shown, especially sufficient moisture, which is very important for seedlings (Kozlowski 2002). In climax spruce stands, the limiting factors are often light and warm, also in relation to the competition of other plants (cf. Vacek, Souček 2001; Jonášová, Prach 2004); at microrelief elevations it may be the contrary. As to some other factors, let us mention the closure of maternal forest, frost, airflow, snow movement, etc. Influence of forest floor cover type on quantity and growth of regenerating spruce trees is reported e.g. by Vacek (1981); Vacek and Souček (2001); Ulbrichová et al. (2006); the most favourable conditions for seedling regeneration are on dead wood, whereas it is the most difficult in thick ferns (*Athyrium distentifolium*, *Athyrium filix-femina*) and grasses (*Calamagrostis villosa*), and in more humid locations and among bilberry plants.

In mature forests of the optimum stage the emergence and growth of seedlings is completely dependent on the disturbance of closure and dynamics of further development of these gaps. Structure of the maternal forest fundamentally influences number of microclimatic factors and thus significantly affects the beginning and course of the regeneration (Vacek 1990; Coates 2002; Grassi et al. 2004; Hofmeister et al. 2008). Canopy closure regulates to a large extent quantity and character of the light penetrating into the heart of the stand and eventually also on the stand soil. Even the intact closure allows the rays of light to penetrate and create sun-illuminated spots which, if they reach till the forest floor, significantly increase the light interception for all plants that grow there (Chazdon, Pearcy 1991). The main factors determining the survival of seedlings is the quality of substrate in which the seedling has emerged, and its ability to provide sufficient water supply to the plant (Kozlowski 2002).

Dynamics of formation and changes of the canopy closure in the maternal stand is object of intensive studies and conception of numerous modified gap models that try to involve basic predominant variables (Kaufmann, Linder 1996; Yaussy 2000; Bugmann 2001; Allen et al. 2010). These relations also significantly affect spatial structure of newly forming stands. In localities of large-area stand decline, the site conditions significantly change and approach those of open space, which may lead to re-creation of even-aged stands on large surfaces. On the contrary, the situation of local windthrows and other small-scale disturbances of – mostly mountain – forests, is an occasion for formation of desirable mosaic-like structure of stands (Zukrigl 1991; Vacek, Lepš 1996; Vacek et al. 2010b).

## 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. Detailed description of permanent research plots is given in Matějka et al. (2010) and Vacek et al. (2010).

### Methodology

The structure of forest stands was evaluated by standard dendrometric methods; the horizontal structure was mapped using the equipment Field-Map (IFER-Monitoring and Mapping Solutions Ltd.). Within each plot one transect 50 × 5 m (250 m$^2$) in size was established. Only on larger plots 6 and 7 (area 0.5 ha and 1.0 ha) we increased the number of transects to 2 and 4, respectively. Transects were placed in such a way that they represent the number and character of the regeneration within the whole research plot. All transects are stabilised by wooden sticks. We mapped all individuals with dbh superior to 12 cm, the spatial, species, age, dbh and height structure was evaluated. Following indices of forest structure and spatial patterns were calculated: Hopkins-Skellam aggregation index, Pileou-Mountford aggregation index, Clark-Evans aggregation index. The spatial structure of regeneration was also tested using the Ripley's *K*-function (Ripley 1981; Lepš 1996). The results are presented in graphical form, $x$-axis showing the distance of individuals of regeneration, $y$-axis indicates the value of *K*-function. Further we recorded the value of mensurational and biological crown covers for each transect (value 1 represents 100% crown cover). For particular stand types we present only one model permanent research plot.

## RESULTS AND DISCUSSION

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 characteristics. 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 from zonal central European natural forests. These developmental trends are result of maximal shade-tolerance and relatively shorter life span of this tree species (cf. Vacek et al. 1988).

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

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 storey and understorey 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%). The density and size of regeneration is strongly influenced by the canopy of lower tree layers and of the overstorey.

Total number of trees in regeneration layer is 13,320 ind. per ha. Beech forms almost 100%; rowan and spruce are only individually admixed. As result of very slow disruption of the parent stand, also in the following generation high diversification of dbh and height structure occurs. Beech regeneration is predominantly clumped in bio-groups under gaps and in the proximity of logs of dead trees.

Number of seedlings can be regarded as sufficient for successful forest regeneration; approximately 20% of the area is covered by advanced bio-groups of beech regeneration. In localities with coarse woody debris of higher decay stages favourable site conditions for germination and establishment of seedlings occur. Nevertheless, according to present developmental stage of the forest their number is very low (17 ind.).

Height structure of the natural regeneration on transect (ind. per ha) shows Fig. 2. Individuals higher than 1.5 m amount 26% of the total number of individuals (3,520 ind. per ha). Highly represented are trees lower than 30 cm (40%), lowest number of individuals is found in the height class 80.1–90 cm (240 ind. per ha).

Table 1 gives diameter structure of natural regeneration on the transect. Mostly represented are plants older than 1 year with dbh lower than 4.0 cm (88%; 12,000 individuals per ha). Considerably lower represented are individuals in dbh class 4.1–8.0 cm (6%; 840 ind. per ha), seedling (5%; 680 individuals per ha) and dbh class 8.1–12.0 cm (1%; 120 individuals per ha).

Fig. 3 shows the horizontal structure of natural regeneration on transect with mensurational and biological crown covers and the tree position of the parent stand. Mensurational crown cover amounted to 0.25; biological crown cover reached the value 0.51. The natural regeneration occurs mainly in small groups regularly distributed around

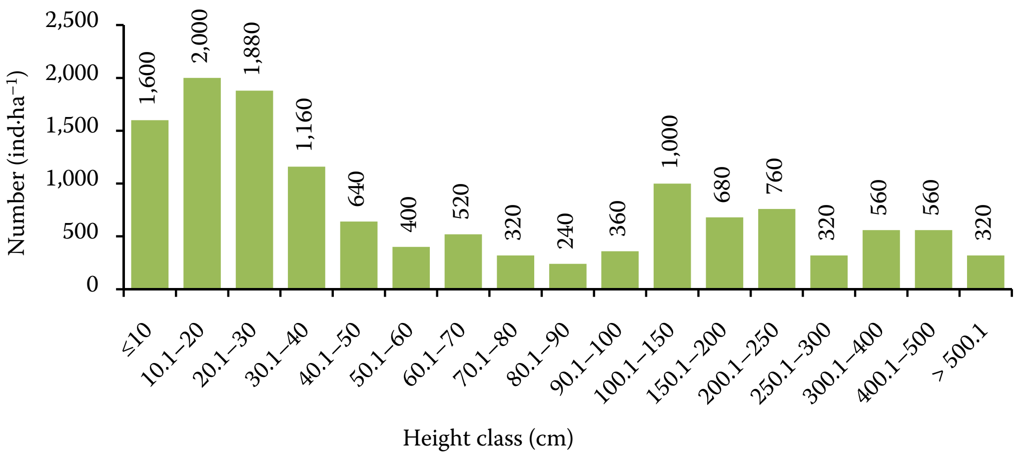


Fig. 2. Height structure of the natural regeneration on the transect of PRP 29 – U Bukového pralesa B (individuals per ha)

Table 1. Diameter structure of lower tree storeys on the transect of PRP 29 – U Bukového pralesa B (ind. per ha)

| Diameter class (cm) | Tree species | | | Total |
|---|---|---|---|---|
| | beech | rowan | spruce | |
| Seedlings | 680 | – | – | 680 |
| ≤ 4 | 11,920 | 40 | 40 | 12,000 |
| 4.1–8.0 | 840 | – | – | 840 |
| 8.1–12.0 | 120 | – | – | 120 |
| Total | 13,560 | 40 | 40 | 13,640 |

Table 2. Indices of spatial patterns of natural regeneration on PRP 29 – U Bukového pralesa B

| Index | Value | | Bound | |
|---|---|---|---|---|
| | observed | expected | lower | upper |
| Hopkins-Skellam | 0.667 | 0.499 | 0.454 | 0.555 |
| Pielou-Mountford | 1.874 | 1.103 | 0.957 | 1.276 |
| Clark-Evans | 0.840 | 1.038 | 0.976 | 1.098 |

the area of the whole transect. Smaller individuals of tree regeneration are more abundant on places without these advanced groups. Rowan and spruce are individually admixed.

According to all three structural indices (Hopkins-Skellamov, Pielou-Mountford and Clark-Evans) the pattern of natural regeneration is aggregated (Table 2). The Ripley's K-function gives similar results showing aggregation of regeneration on PRP 29.

## 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 influenced 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 5$^{th}$ and 6$^{th}$ forest vegetation zone (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 7 – Bažinky 1

The forest stand 311 A17/4/1a with PRP 7 – Bažinky 1 is located on middle slope with E exposition. The stand can be characterized as mature overstorey with locally broken canopy with abundant natural regeneration of beech and spruce of different size and age.Within the forest cycle the prevalent destruction stage is followed by regeneration phase. The stand is classified as phenotype category A, autochthonous forest stand with high management value, above-average production and resistance. In the upper storey (age 223 years) the dominant beech (90%) is accompanied by spruce (10%). In the middle storey (age 39 years) beech amounts 95% and spruce 5%. The understorey (age 17 years) is formed by beech (94%), spruce (5%) and rowan (5%). The middle height of the overstorey is 30 m, stocking is 6. The stand belongs to target management set 546 and air-pollution zone C. Reduced crown cover of the overstorey creates favourable conditions for establishment and growth of natural regeneration. The forest stand shows very high potential for natural regeneration development and can be regarded as optimal model for shelter wood management system mimicking natural forest development in the conditions of the Krkonoše Mts.

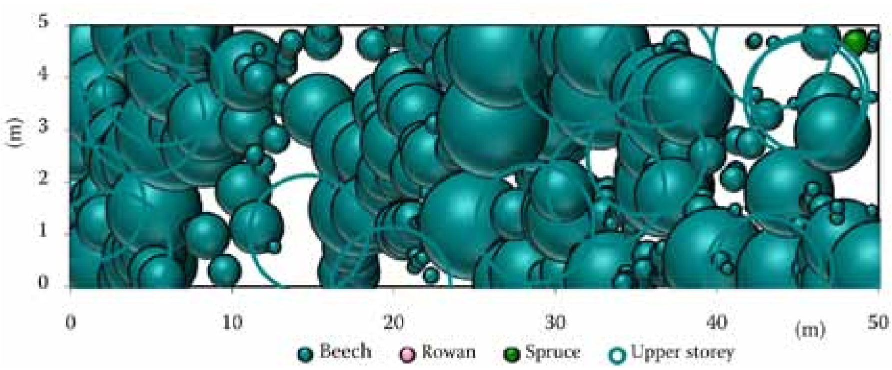


Fig. 3. Horizontal structure of natural regeneration on the transect of PRP 29 – U Bukového pralesa B

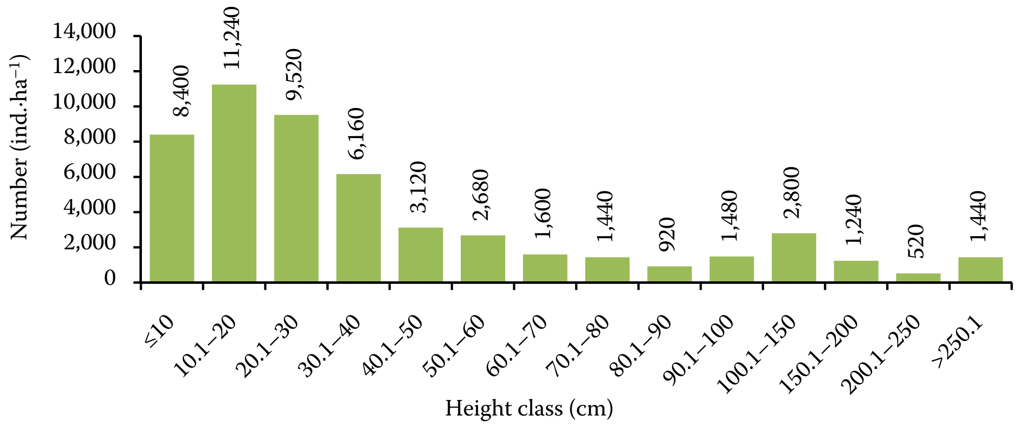


Fig. 4. Height structure of the natural regeneration on the transect of PRP 7 – Bažinky 1 (ind. per ha)

PRP 7 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 medial (50%) and is dominated by *Calamagrostis villosa* and *Prenanthes purpurea*. Competition of ground vegetation layer is rather low, the distribution of natural regeneration is influenced mainly by the canopy of overstorey, soil surface characteristics and the cover of herbs and mosses. Total number of trees in regeneration layer is 52,560 ind. per ha. Beech forms 84%, spruce 14%, other tree species (silver fir, rowan, sycamore maple, goat willow) are individually admixed. Similarly to previous plot, as result of very slow disruption of the parent stand, also in the following generation high diversification of dbh and height structure occurs.

Height structure of the natural regeneration (ind. per ha) on the transect 1c of PRP 7 is shown in Fig. 4. The structural differentiation of the regeneration layer is very high with more or less continuously decreasing tree number in more advanced height classes with the only distinct exception in the lowest height class. Individuals lower than 30.1 cm amount 55%. Mostly represented is regeneration in the class 10.1–20.0 cm (11,240 ind. per ha), 20.1–30.0 cm (9,520 ind. per ha) and lower than 10.0 cm (8,400 ind. per ha). On the contrary the lowest number of tree regeneration is in height class 200.1–250.0 cm (520 individuals. per ha). Most of the individuals in height classes 90.1–200.0 originate from the mast year 1993.

The diameter structure of natural regeneration on the transect 1c is given in Table 3. Mostly represented are plants older than 1 year with dbh lower than 4.0 cm (95%; 49,920 ind. per ha). Considerably lower represented are seedlings (5%; 2,440 ind. per ha), representation of higher dbh classes is negligible.

Fig. 5 shows the horizontal structure of natural regeneration on the transect 1c with mensurational and biological crown covers and the tree position of the parent stand. Mensurational crown cover amounted to 0.45; biological crown cover reached the value 0.78. The natural regeneration of beech occurs mainly in small groups located in small gaps. Spruce regeneration forms clumped structures mainly in larger gaps. Seedlings of rowan, fir, sycamore maple and goat willow are individually admixed. Smaller individuals of tree regeneration are more abundant on places without advanced groups of beech and spruce.

According to all three structural indices (Hopkins-Skellamov, Pielou-Mountford and Clark-Evans) the pattern of natural regeneration is clearly aggregated

Table 3. Diameter structure of lower tree storeys on the transect 1c of PRP 7 – Bažinky 1 (ind. per ha)

| Diameter class (cm) | Tree species | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | beech | fir | rowan | maple | spruce | willow | |
| Seedlings | 2,120 | – | 40 | – | 280 | – | 2,440 |
| ≤ 4.0 | 41,480 | 80 | 1,040 | 40 | 7,200 | 80 | 49,920 |
| 4.1–8.0 | 200 | – | – | – | – | – | 200 |
| Total | 43,800 | 80 | 1,080 | 40 | 7,480 | 80 | 52,560 |

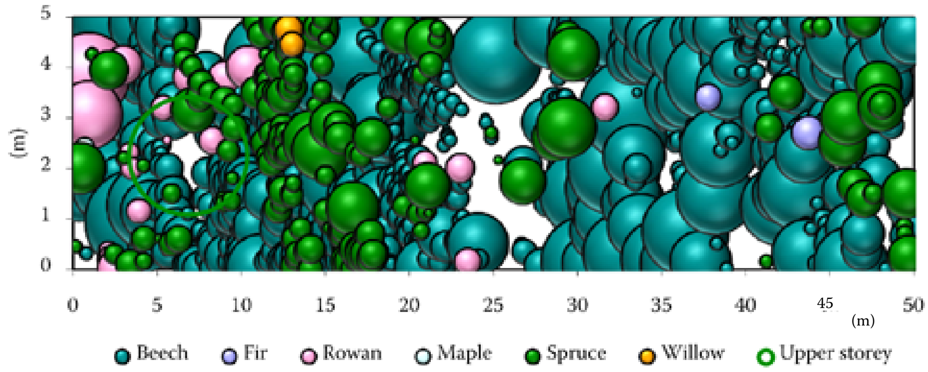


Fig. 5. Horizontal structure of natural regeneration on the transect 1c of PRP 7 – Bažinky 1

(Table 4). The Ripley's *K*-function gives similar results showing aggregation of regeneration on PRP 29.

### 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 the altitude and site conditions. (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 13 – Strmá stráň C

Forest stand 117 C17/1b with PRP 13 – Strmá stráň C is located on middle slope with NE exposition. The stand is overmatured with relatively opened canopy and increasing bark beetle attack during the last five years. The regeneration is dominated by spruce of different age and size with admixed rowan and *Betula carpatica*. Within the forest cycle the prevalent destruction stage is accompanied by regeneration phase. The stand is classified as phenotype category A. The age of the upper storey is 223 years and is formed by dominant spruce (100%). The understorey is 10 years old and is formed by spruce (75%), beech (15%), rowan (6%), *Betula carpatica* (3%) and sycamore maple (1%). Beech, *Betula carpatica* and sycamore maple were regenerated mainly artificially. Middle height of the upper storey is 22 m, stocking is 5. Low canopy cover of the upper storey (20%) results in favourable conditions for development of natural and artificial regeneration. Nonetheless, partially dense cover of *Athyrium distentifolium* disables the forest regeneration.

Table 4. Indices of spatial patterns of natural regeneration on PRP 7 – Bažinky 1

| Index | Value | | Bound | |
|---|---|---|---|---|
| | observed | expected | lower | upper |
| Hopkins-Skellam | 0.761 | 0.488 | 0.482 | 0.524 |
| Pielou-Mountford | 2.994 | 1.026 | 0.984 | 1.109 |
| Clark-Evans | 0.833 | 0.993 | 0.984 | 1.049 |

Mortality caused by rodents and game amounted in beech 82% and in sycamore maple 96%. Common birch was not planted within the PRP. Only 8 ind. originating from artificial regeneration (7 beeches, 1 sycamore maple; 32 ind. per ha) survived and develop on PRP 13, which is less than 1% from the total number of regeneration in the locality. The stand belongs to target management set 21 and air-pollution area B.

PRP 13 was established in 1976, the forest type is determined as slope-stony spruce stand with *Athyrium distentifolium* (8F1). Soil type is modal Podsol. The ground vegetation cover is high (95%) and is dominated by *Athyrium distentifolium* and *Calamagrostis villosa*. Competition of ground vegetation layer is very high. Thus, the natural regeneration predominantly occurs on elevations and decaying deadwood. The distribution of natural regeneration is influenced mainly by these soil surface types (preference of elevations) and the presence of ground vegetation cover (preference of mosses, *Avenella flexuosa* and *Vaccinium myrtillus*). Total number of trees in regeneration layer is high – 9,240 ind. per ha, only 72 ind. originate from artificial regeneration. Spruce forms 97%, rowan 3%, *Betula carpatica* is only individually admixed.

Height structure of the natural regeneration (ind. per ha) on transect of PRP 13 is shown in Fig. 6. The structural differentiation of the regeneration layer is rather low, but similarly to other plots still with continuously decreasing tree number in more advanced height classes. Clear exception is the height class 100.1–150.0 cm originating from the seed year 1993, which represents 22% from the total number of tree regeneration. Frequency of other height classes is for the most part between 120 and 880 ind. per ha, in the first and last height class the rate is distinctly lower 40 ind. per ha).

The diameter structure of natural regeneration on transect of PRP 13 is given in Table 5. Mostly represented are plants older than 1 year with dbh lower than 4.0 cm (99.5%; 9,200 ind. per ha). Least represented are seedlings (0.5%; 40 ind. per ha).

Fig. 7 shows the horizontal structure of natural regeneration on transect with mensurational and biological crown covers and the tree position of the parent stand. Mensurational crown cover amounted to 0.15; biological crown cover reached the value 0.22. The natural regeneration occurs mainly on elevations and in localities without completion of *Athyrium distentifolium*. The spatial pattern is clumped with clear preference of *Vaccinium myrtillus.* The height of the regeneration increases mainly in the lower part of the transect outside the crown projections of the parent stand. Admixed tree species occur in small groups together with spruce.

According to all three structural indices (Hopkins-Skellamov, Pielou-Mountford and Clark-Evans) the pattern of natural regeneration is clearly aggregated (Table 6). The Ripley's *K*-function gives similar results showing aggregation of regeneration on PRP 29.

Table 5. Diameter structure of lower tree storeys on the transect of PRP 13 – Strmá stráň C (ind. per ha)

| Diameter class (cm) | Tree species | | | Total |
|---|---|---|---|---|
| | spruce | rowan | birch | |
| Seedlings | 40 | – | – | 40 |
| ≤ 4.0 | 8,920 | 240 | 40 | 9,200 |
| Total | 8,960 | 240 | 40 | 9,240 |

**PRP 33 – Nad Benzínou 3**

Forest stand 306 B12 with PRP 33 – Nad Benzínou 3 is located on middle slope with SW exposition. The stand shows high spatial, age and species diversification with relatively opened canopy. Within the forest cycle the initial destruction stage is accompanied by regeneration phase. The stand is classified as phenotype category B with average age 124 years. The stand is dominated by mountain pine (78%). Spruce comprises 20%, rowan 1% and beech 1%. Middle height shows high variation according to species (mountain pine – 1 m, spruce – 7 m, rowan – 5 m, beech – 4 m). Favourable microclimate of the relatively warm SW slope and good soil conditions (mainly cryptopodzols with sporadic podzols) enable natural layering of beech (Fig. 8). The forest stand belongs to target management set 31.

PRP 33 was established in 1980, the forest type is determined as acidic dwarf pine-spruce stand with *Vaccinium myrtillus* and *Calamagrostis villosa* (9K2). Soil type is modal cryptopodsol with relatively favourable chemical and physical soil properties. Specific soil properties with

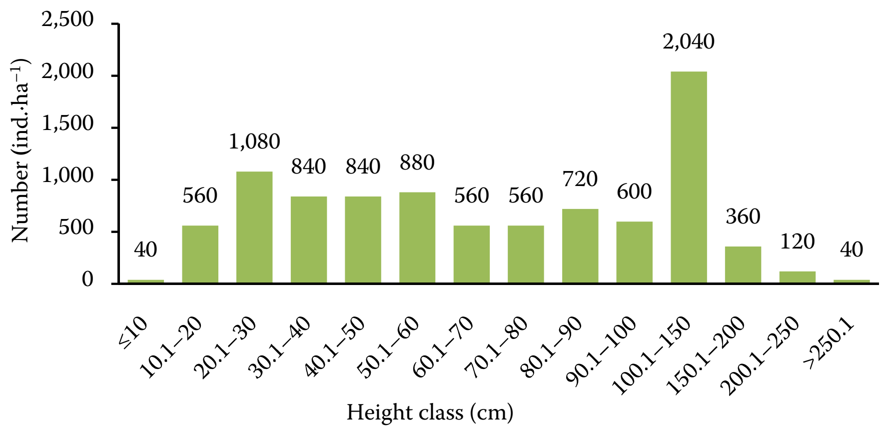


Fig. 6. Height structure of the natural regeneration on the transect of PRP 13 – Strmá stráň C (individuals per ha)

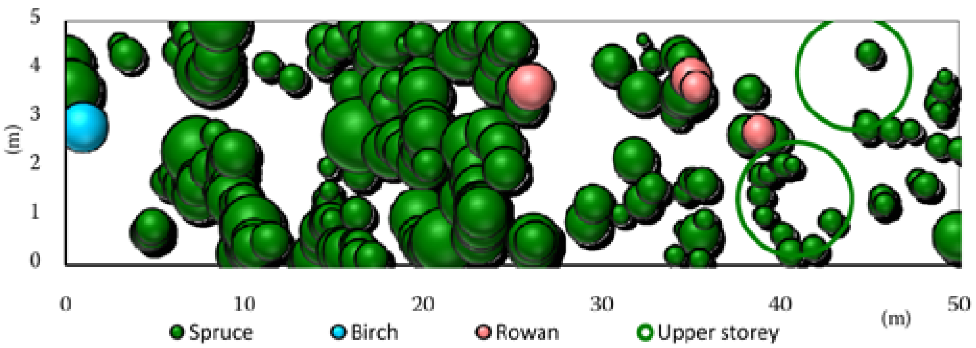


Fig. 7. Horizontal structure of natural regeneration on the transect of PRP 13 – Strmá stráň C

good moisture (low variation), soil aeration and favourable aboveground humus horizons create conditions for natural layering of beech branches that are during the period of snow cover pressed to the soul surface. The ground vegetation cover is medial (60%) and is dominated by *Calamagrostis villosa* and *Vaccinium myrtillus*. The number of root taking branches is influenced mainly by the developmental phase and vitality of beech biogroups, soil surface and aboveground humus characteristics and ground vegetation cover. Total number of root taking branches per ha is 434. The process of rooting is generally very slow lasting 12 to 26 years. Thus, the structure of natural regeneration within beech biogroups is highly heterogeneous with large differences in size and age of individuals. The layering occurs mainly on sun exposed branches oriented downwards the slope. The structure of forest stand with natural layering of beech is shown on Fig. 9. The vertical, horizontal and species structure is highly differentiated.

Healthy, respectively fully foliated beeches occur only in climatic most favourable years (in the last period 1996, 2007 and 2009). In most years prevail trees with moderate or average defoliation. Between 1981 and 1990 during the air-pollution disaster and in years with climatic extremes also dying branches or parts of polycorms occurred.

Table 6. Indices of spatial patterns of natural regeneration on PRP 13 – Strmá stráň C

| Index | Value | | Bound | |
|---|---|---|---|---|
| | observed | expected | lower | upper |
| Hopkins-Skellam | 0.824 | 0.499 | 0.436 | 0.567 |
| Pielou-Mountford | 2.862 | 1.123 | 0.933 | 1.370 |
| Clark-Evans | 0.669 | 1.048 | 0.970 | 1.124 |

Between 1980 and 2009 only two seed years of beech were observed. In 1992 the average seed fall reached 9 seeds per square meter (degree of fructification 1: 6–25 seeds per $m^2$), but with no full seeds. In 2007 the average seed fall amounted 116 seeds per $m^2$ (degree of fructification 3: 101–250 seeds per $m^2$), the ratio of full seeds reached 48%.

The vegetative reproduction is essential for successful beech regeneration in given extreme environmental conditions, where generative reproduction occurs only in the most favourable years with exceptional climatic data.

According to all three structural indices (Hopkins-Skellamov, Pielou-Mountford and Clark-Evansov) the pattern of natural vegetative beech regeneration is clearly aggregated (Table 7). The Ripley's *K*-function gives similar results showing aggregation of regeneration within distanece superior to 1 m. Within distance 1m (within the biogroups) the layers of beech are distributed randomly.

## Relict pine wood

Natural pine stands in Krkonoše Mountains are marked by low age heterogeneity (the oldest individuals 165 years), low standing volume variability and expressed small-scale texture – the finest of our azonal natural forests. Characteristic is mainly mosaic of bio-groups and free areas with sporadic regeneration. Thus, for these stands high textural heterogeneity is characteristic (cf. Vacek et al. 2009).

The natural occurrence of Scots pine is determined edaphically. In the Krkonoše Mts. these azonal associations (relict pine wood) occur only in the locality Chojnik in Poland, where they cover an area of 2.25 ha in the range of beech vegetation zone.

Fig. 8. The natural layering of beech in the ecotone of the upper forest limit in the Krkonoše Mts. (foto S. Vacek)

**PRP 37 – Chojnik – relict pine wood**

The forest stand 213j with PRP 37 – Chojnik is located on middle slop with NW exposition. The stand can be characterised as mature with locally abundant natural regeneration of beech, sessile oak, Scotch pine, silver birch and other tree species of different age and size. Within the forest cycle the

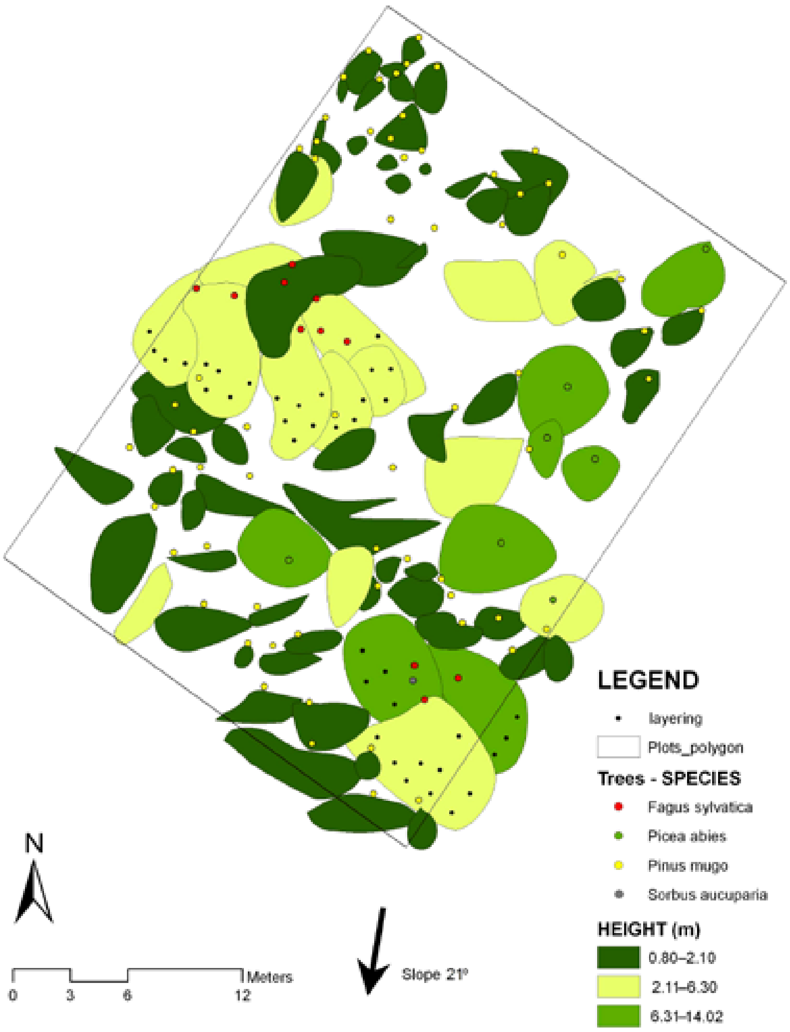


Fig. 9. Horizontal structure of PRP 33 – Nad Benzínou 3. In the explanatory note: tree species according to heights and layering of beech

Table 7. Indices of spatial patterns of natural regeneration on PRP 33 – Nad Benzínou 3

| Index | Value | | Bound | |
|---|---|---|---|---|
| | observed | expected | lower | upper |
| Hopkins-Skellam | 0.972 | 0.497 | 0.353 | 0.666 |
| Pielou-Mountford | 6.881 | 1.172 | 0.740 | 1.875 |
| Clark-Evans | 0.493 | 1.076 | 0.888 | 1.262 |

prevalent terminating optimal stage and beginning destruction stage are accompanied by regeneration phase. The stand is classified as phenotype category B. Within the two-storeyed stand the upper storey (age 191 years) is dominated by pine (90%) with admixed beech (10%). The understorey (age 22 and 11 years) is formed by beech (70%) and sycamore maple (age 22 and 11 years). The middle height of the overstorey is 20 m, stocking is 7. Thanks to crown cover reduction during the last year (70%) more favourable conditions for natural regeneration established. The stand belongs to target management set 13.

PRP 37 was established in 2004, according to Polish typology the forest site type is determined as dry pine wood (FT 0Z0). The plot is located in broken relief with numerous isolated granite rocks; soil type is Lithosol to Cambisol. The ground vegetation cover is relatively low (20%) and is dominated by *Vaccinium myrtillus*. Thus, competition of ground vegetation layer for resources is limited. The distribution of natural regeneration is influenced mainly by the canopy of the overstorey and soil surface characteristics, mainly its desiccation.

Total number of trees in regeneration layer is 12,080 ind. per ha. Beech forms 72%, sessile oak 15%, Scotch pine 7%, silver birch 3%, rowan 2%, spruce 1%, sycamore maple is represented only by few individuals

Height structure of the natural regeneration (ind. per ha) on transect of PRP 37 is shown in Fig. 10. The structural differentiation of the regeneration layer is very high with predominantly decreasing tree number in more advanced height classes. Individuals lower than 30.1 cm amount 83%. Mostly represented is regeneration inferior to 10.0 cm (49%; 5,960 ind. per ha), high number of individuals is also in height class 10.1–20.0 cm (26%; 3,200 ind. per ha). On the contrary the lowest number of tree regeneration is in height class 70.1–100.0 cm (1%; 80 ind. per ha each).

The diameter structure of natural regeneration on transect is given in Table 8. Mostly represented are plants older than 1 year with dbh lower than 4.0 cm (87%; 10,600 ind. per ha). Considerably lower represented are seedlings (12%; 1,440 ind. per ha), representation of higher dbh classes is negligible.

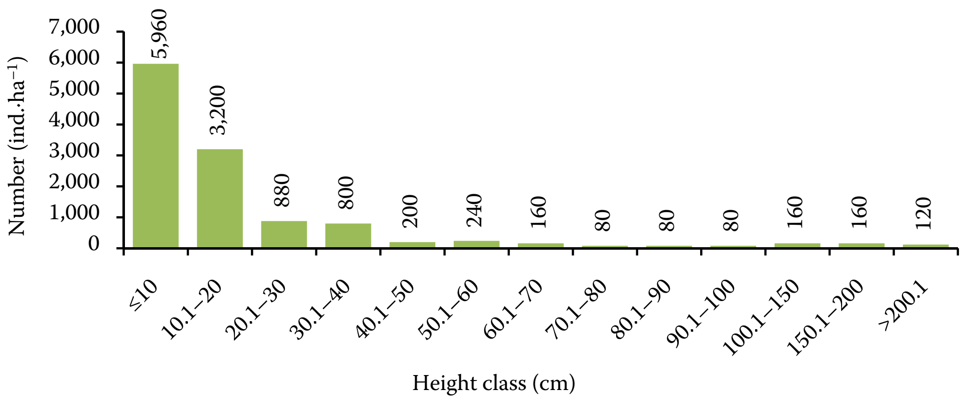


Fig. 10. Height structure of the natural regeneration on the transect of PRP 37 – Chojnik (individual per ha)

Table 8. Diameter structure of lower tree storeys on the transect of PRP 37 – Chojnik (individual per ha)

| Diameter class (cm) | Tree species | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | beech | pine | birch | oak | rowan | maple | spruce | |
| Seedlings | 520 | 440 | 80 | 280 | – | – | 120 | 1,440 |
| ≤ 4.0 | 8,200 | 360 | 280 | 1,520 | 200 | 40 | – | 10,600 |
| 4.1–8.0 | 80 | – | 40 | – | – | – | – | 120 |
| Total | 8,800 | 800 | 400 | 1,800 | 200 | 40 | 120 | 12,160 |

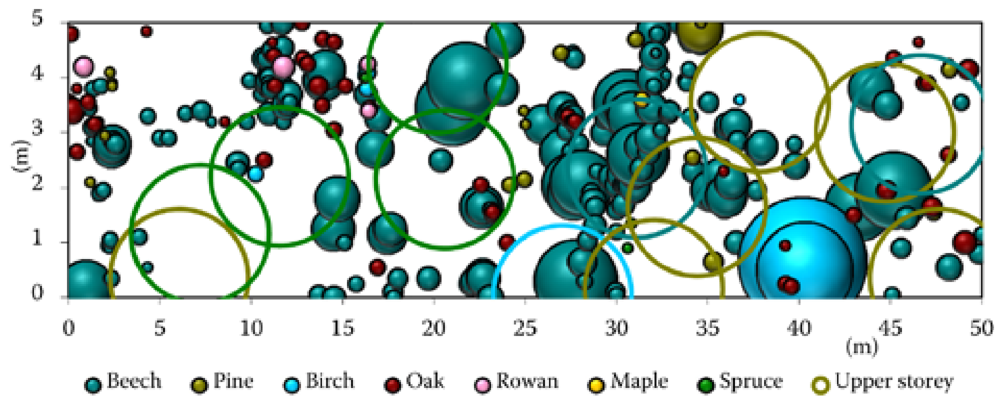


Fig. 11. Horizontal structure of natural regeneration on the transect PRP 37 – Chojnik

Table 9. Indices of spatial patterns of natural regeneration on PRP 37 – Chojnik

| Index | Observed value | Expected value | Lower bound | Upper bound |
|---|---|---|---|---|
| Hopkins-Skellam | 0.810 | 0.499 | 0.445 | 0.554 |
| Pielou-Mountford | 3.174 | 1.107 | 0.960 | 1.292 |
| Clark-Evans | 0.710 | 1.040 | 0.976 | 1.110 |

Fig. 11 shows the horizontal structure of natural regeneration on transect with mensurational and biological crown covers and the tree position of the parent stand. Mensurational crown cover amounted to 0.06; biological crown cover reached the value 0.08. The natural regeneration of beech occurs mainly in small groups on microsites with favourable soil conditions. Oak regeneration also forms clumped structures, other tree species are distributed individually on microsites corresponding to their ecological requirements.

According to all three structural indices (Hopkins-Skellamov, Pielou-Mountford and Clark-Evansov) the pattern of natural regeneration is clearly aggregated (Table 9). The Ripley's *K*-function gives identical results showing aggregation of regeneration on PRP 37.

## CONCLUSIONS

The presented results confirm high potential of natural regeneration on permanent research plots. On the majority of plots in lower elevations (to 7$^{th}$ vegetation zone) we stated high density of natural regeneration of beech, spruce and admixed tree species. In suitable stand conditions (lower stand density of parent stand) the regeneration shows successful development. On several plots the regeneration occurs only sporadically, in these cases appropriate conditions for forest regeneration were yet not created (high stand density). It is also shown that by means of natural regeneration complete change in tree species composition can be reached; only few admixed individuals (especially in the case of beech) in parent stand can by good fructification outweigh otherwise dominating spruce. The pattern of natural regeneration strongly depends on the crown cover of the parent stand, soil surface characteristics, ground vegetation and moss cover. The horizontal structure of natural and combined regeneration is mostly aggregated; artificial regeneration shows random to regular distribution. Mensurational cover of regeneration layer is between 0.06 and 0.69, biological cover between 0.08 and 1.37. The highest values were reached in mixed spruce-beech stands, the lowest in relict pine wood. Total number of individuals per ha reached values from 12,000 to 335,000. On the other site, numbers of vegetatively reproduced individuals of beech and spruce in the ecotone of the upper forest limit are by far lower and reach values between 68 and 434 ind. per ha.

On the majority of permanent research plots with artificial regeneration originating from past management, this regeneration almost disappeared and till today only few percent of initial plant numbers remain in the stands. The reasons for the failure of artificial regeneration can be several: harsh mountain climate, extreme air-pollution, game damage, poor quality of nursery stock and insufficient care for plantations. Mainly low quality of outplanting that did not respect specific microsite conditions in the 7$^{th}$ and 8$^{th}$ vegetation zone significantly increased losses of reforestation (increase of losses by 23% and 38% respectively).

## References


Allen, C.D., Macalady A.K.,Chenchouni H., Bachelet D., McDowell N., Vennetier M., Kizberger T., Rigling A., Breshears D.D., Hogg E.H., Gonzalez P., Fensham R., Zhang Z., Castro J., Demidova N., Lim J.H., Allard G., Running S.W., Semerci A., Cobb N. (2010): A global overview of drought and heat-induced tree mortality revers emerging climate change risks for forests. Forest Ecology and Management, ***259***: 660–684.

Bugmann H. (2001): A review of forest gap models. Climatic Chang*e*, ***51***: 259–305.

Canham C.D., Denslow J.S., Platt W.J., Runkle J.R., Spies T.A., White P.S. (1990): Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Canadian Journal of Forest Research, ***20***: 620–631.

Chazdon R.L., Pearcy R.W. (1991): The importance of sunflecks for understory plants. Oecologia, ***69***: 524–531.

Coates K.D. (2002): Tree recruitment in gaps of various size, clearcuts and undisturbed mixed forests of interior BC. Forest Ecology and Management, ***127***: 249–269.

Diaci J., Pisek R., Bonina A. (2005): Regeneration in experimental gaps of subalpine *Picea abies* forest in the Slovenian Alps. European Journal of Forest Research, ***124***: 29–36.

Grassi G., Bagnaresi U. (2001): Foliar morphological and physiological plasticity in *Picea abies* and *Abies alba* saplings along natural light gradient. Tree Physiology, ***21***: 959–967.

Grassi G., Minotta G., Tonon G., Bagnaresi U. (2004): Dynamics of Norway spruce and Silver fir natural regeneration in mixed stands under uneven-aged management. Canadian Journal of Forest Research, ***34***: 141–149.

Gubka K. (2006): Effects of the altitude change on the structure of the soil protective and anti-erosive function. In: Jurásek A., Novák J., Slodičák M. (eds): Stabilization of Forest Functions in Biotopes Disturbed by Anthropogenic Activity. Proceedings of Conference in Opočno. Opočno, 5.–6. September 2006. Opočno, Forestry and Game Management Institute: 537–544.

Hanssen K.H. (2002): Effects of seedbed substrates on regeneration of *Picea abies* from seeds. Scandinavian Journal of Forest Research, ***17***: 511–521.

Hanssen K.H. (2003): Natural regeneration of *Picea abies* on small clear-cuts in SE Norway. Forest Ecology and Management, ***180***: 199–213.

Hofmeister Š., Svoboda M., Souček J., Vacek S. (2008): Spatial pattern of Norway spruce and silver fir natural regeneration in uneven-aged mixed forests of northeastern Bohemia. Journal of Forest Science, ***54***: 92–101.

Jonášová M., Prach K. (2004): Central-European mountain spruce (*Picea abies* [L.] Karst.) forests: regeneration of tree species after a bark beetle outbreak. Ecological Engineering, ***23***: 15–27.

Kaufmann M.R., Linder S. (1996): Tree physiology research in a changing world. Tree Physiology, ***16***: 1–4.

Korpeľ Š. (1991): Silviculture. Bratislava, Príroda, 475. (in Slovak)

Korpeľ Š. (1991): Primeval Forests of Slovakia. Bratislava, Príroda: 475. (in Slovak)

Kozlowski T.T. (2002): Physiological ecology of natural regeneration of harvested and disturbed forest stands: implications for forest management. Forest Ecology and Management, ***158***: 195–221.

Lepš J. (1996): Biostatistics. Jihočeská univerzita, České Budějovice: 166. (in Czech)

Matějka K., Vacek S., Podrázský V. (2010): Development of forest soils in the Krkonoše Mts. in the period 1980–2009. Journal of Forest Science, ***56***: 485–504.

Ripley B.D. (1981): Spatial Statistics. New York, John Wiley & Sons: 252.

Šerá B., Falta V., Cudlín P., Chmelíková E. (2000): Contribution to knowledge of natural growth and development of mountain Norway spruce seedlings. Ekológia, ***19***: 420–434.

Štícha J., Kupka I., Zahradník D., Vacek S. (2010): Influence of micro-relief and weed competition on natutral regenertion of mountain forests in the Šumava Mountains. Journal of Forest Science, ***56***: 218–224.

Ulbrichová I., Remeš J., Zahradník D. (2006): Development of the spruce natural regeneration on mountain sites in the Šumava Mts. Journal of Forest Science, ***52***: 446–456.

Vacek S. (1981): Chances of successful natural regeneration in the Krkonoše protective mountain forests. Lesnická práce, ***60***: 118–124. (in Czech)

Vacek S. (1990): Analysis of autochthonous Norway spruce populations at Strmá stráň locality in the Krkonoše Mts. Opera Corcontica, ***27***: 59–103. (in Czech)

Vacek S. (2000) Structure, development and management of forest ecosystems in Krkonoše Mts. [DrSc. Thesis.] Opočno, Prague, Forestry and Game Management Research Institute, Czech University of Life Sciences Prague: 684. (in Czech)

Vacek S., Lepš J. (1996): Spatial dynamics of forest decline: the role of neighbouring trees. Journal of Vegetation Science, ***7***: 789–798.

Vacek S., Podrázský V. (2003): Forest ecosystems of the Šumava Mts. and their management. Journal of Forest Science, ***49***: 291–301.

Vacek S., Souček J. (2001): Natural regeneration in the mountains of Sudety. In: Slodičák M., Novák J. (eds): Contemporary questions of mountain forest silviculture. In: Proceedings of conference 3rd Czech-Slovakian scientific symposium. Opočno, 13. 9.–14. 9. 2001. Jíloviště-Strnady, VÚLHM: 239–248. (in Czech)

Vacek S., Mareš V., Vašina V. (1987): Analysis of autochthonous spruce stands in NNR V Bažinkách. Opera Corcontica, ***24***: 95–132. (in Czech)

Vacek S., Vašina V., Balcar Z. (1988): Analysis of autochthonous spruce stands in NNR Rýchory and Boberská stráň. Opera Corcontica, ***25***: 13–55. (in Czech)

Vacek S., Lokvenc T., Souček J. (1995): Natural regeneration of forest stands. Methodology for implementation of research results into agricultural practice. Praha, MZe ČR, No. 20: 1–46. (in Czech)

Vacek S., Podrázský V., Mikeska M., Simon J. (2006): Forests and Ecosystems on the Tree Line in the National Parks of the Giant Mts. Kostelec nad Černými lesy, Lesnická práce: 112. (in Czech)

Vacek S., Matějka K., Simon J., Malík V., Schwarz O., Podrázský V., Minx T., Tesař V., Anděl P., Jankovský L., Mikeska M. (2007): Health status and dynamics of forest ecosystems under air pollution stress in the Giant Mts. Kostelec nad Černými lesy, Lesnická práce: 216. (in Czech)

Vacek S., Vacek Z., Schwarz O., Raj A., Nosková I., Balcar Z., Bulušek D., Bartošík Z., Rolínková V., Hirschová E., Zahradník D., Mikeska M., Hynek V., Baláš M., Bílek L., Malík V., Šolc R., Bednařík J. (2009a): Regeneration of Forest Stands on Research Plots in the Krkonoše National Parks. Kostelec nad Černými lesy, Lesnická práce: 288. (in Czech)

Vacek S., Matějka K., Remeš J., Ulbrichová I., Simon J., Turčáni M., Viewegh J., Bednařík J., Malík K., Malík V., Bílek L., Štícha V., Semelová V., Ešnerová J., Baláš M. (2009b): Forest Ecosystems of the Bohemian Forest National Park. Kostelec nad Černými lesy, Lesnická práce: 512. (in Czech)

Vacek S., Vacek Z., Schwarz O., Raj A., Bílek L., Nosková I., Balcar Z., Zahradník D., Baláš M., Bednařík J., Mikeska M., Simon J., Minx T., Matějka K. (2010a): Structure and Development of Forest Stands on Research Plots in the Krkonoše National Parks. Kostelec nad Černými lesy, Lesnická práce: 568. (in Czech)

Vacek S., Vacek Z., Bílek L., Nosková I., Schwarz O. (2010b): Structure and development of forest stands on research plots in the Krkonoše Mts. Journal of Forest Science, ***56***: 518–530

Yaussy D.A. (2000): Comparison of an Empirical Forest Growth and Yield Simulator and a Forest Gap Simulator Using Actual 30-Year Growth from Two Even-Aged Forests in Kentucky', Forest Ecology and Management, ***126***: 385–398.

Zukrigl K. (1991): Succession and regeneration in the natural forests in Central Europe. Geobios, ***18***: 5–6: 202–208.

Received for publication April 14, 2010
Accepted after corrections July 10, 2010

*Corresponding author:*

Prof. RNDr. Stanislav Vacek, DrSc., Česká zemědělská univerzita, Fakulta lesnická a dřevařská,
Kamýcká 129, 165 21 Praha 6-Suchdol, Česká republika
tel.: + 420 224 382 870, fax: + 420 234 381 860, e-mail: vacekstanislav@fld.czu.cz