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RESEARCH ARTICLE

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Are clearcut borders an effective tool for Scots pine (*Pinus sylvestris* L.) natural regeneration?

Lukáš Bílek, Zdeněk Vacek, Stanislav Vacek, Daniel Bulušek, Rostislav Linda, and Jan Král
Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, 16951 Prague 6. Suchdol, Czech Republic.

Abstract

Aim of the study: To describe the effect of stand edge after clearcut on the process of Scots pine (*Pinus sylvestris* L.) natural regeneration along the edge-to-interior gradient. The density, height, horizontal structure and quality of natural regeneration was evaluated.

Area of the study: Kokořínsko Protected Landscape Area, Northern Bohemia (Czech Republic). The study sites naturally host Scots pine *Pinetum oligotrophicum* with cover of *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea L.* in the herbal storey.

Material and methods: Two 40 × 40 m permanent research plots were situated at the forest edge, two adjacent plots were established within the forest stand as control plots. Differences in regeneration characteristics were tested by analysis of variance (ANOVA) followed by the Tukey HSD test. Interactions between regeneration characteristics and the distance from the edge were evaluated by Pearson correlation. The relationship between the top storey and natural regeneration was depicted by pair-correlation function. Principal components analysis was carried out to assess overall data structure.

Main results: Generally, the further from the stand edge, the lower natural regeneration density ($r \leq -0.64$, $p<0.001$), mean height ($r \leq -0.54$, $p<0.001$) and the best-quality promising individuals ($r = -0.40$, $p<0.05$) were found, whereas significant influence on overall average pine quality was not observed. The highest regeneration density (15,250 pcs/ha) was reached at a distance of 5-10 m from the stand edge.

Research highlights: The forest edge interior can become favourable location for natural regeneration and can be implemented into traditional regeneration approaches in pine regions.

Additional keywords: pine silviculture; forest edge effect; stand quality; Central Europe.

Abbreviations used: dbh (diameter at breast height); PCA (principal components analysis); pcs (pieces); PRP (permanent research plot); PRPe (permanent research plot – forest edge); PRPc (permanent research plot – control).

Authors´ contributions: Conception and design of the experiment and manuscript drafting: LB, SV, ZV; data analysis and interpretation: ZV, SV, LB, RL; technical support, data collection and the manuscript revision: ZV, DB, JK, RL. Authors had total access to the data and are responsible for the integrity and accuracy of the analysis.

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Correspondence should be addressed to Lukáš Bílek: bilek@fld.czu.cz

Introduction

Scots pine (*Pinus sylvestris* L.) is the most widespread pine species and one of the most important tree species in Eurasia (Coban *et al.*, 2016) with a large ecological as well as economic impact (Oleksyn *et al.*, 2002; Grigoriadis *et al.*, 2014). However, in the context of global climate change with negative effects on forests (Loarie *et al.*, 2009) and due to its wide natural range, Scots pine faces a number of ecologically diverse conditions substantially different from its ecological optimum (Benavides *et al.*, 2013). In the Mediterranean, Scots pine is limited especially by summer droughts (Castro *et al.*, 2002). In Central and Northern Europe, Scots pine is hampered mostly by low temperatures (Ryyppö *et al.*, 1998). In the Czech Republic, natural pine forests occur on the poorest and driest soils, where extreme edaphic characteristics of these sites overshadow the macroclimatic conditions and limit competition of most woody species (Mikeska *et al.*, 2008).

Scots pine as a pioneer tree species has relatively high demands on light and its spontaneous natural regeneration under canopy closure is less common than *e.g.* in spruce. However, better light conditions in gaps or close to the forest edges can initiate the stand regeneration process (Burton, 2002; Bílek *et al.*, 2014). Furthermore, successful natural regeneration of pine depends on micro-habitat characteristics (Wittich, 1955) and the climatic conditions (temperature and precipitation) during seed germination and initial growth of seedlings (Puhlick *et al.*, 2012). For example, a thick layer of humus can slow down or even suppress the emergence of seedlings by preventing contact between the seed germ and mineral soil (Ibáñez & Schupp, 2002). Naturally occurring Scots pine saplings are normally suppressed by too dense canopy. However, Coban *et al.* (2016) showed that they are to a certain extent tolerant to shading and they can survive relatively long periods (10-12 years) with the ability to exploit subsequent opportunities should a canopy gap occur. The height and density of saplings correlate negatively with the proximity of parent trees (Siipilethto, 2006), because their competition prevents regeneration development (Montes & Canellas, 2007; Ruuska *et al.*, 2008). In this respect, parent trees root competition can be very limiting factor, especially in the conditions of dry and poor locations (Kuuluvainen & Ylläsjärvi, 2011; Axelsson *et al.*, 2014).

In the past, the main approach in Scots pine management were clearcuts and following artificial regeneration (Aleksandrowicz-Trzcińska *et al.*, 2014). At present, this regeneration method is on the decline as greater effort is made to exploit natural pine regeneration (Bílek *et al.*, 2016; Vacek *et al.*, 2016). However, even this management approach is often considered as a tool for homogenization of the stand structure (Uotila *et al.*, 2002), whereas regeneration in gaps can contribute to a more varied spatial and species structure of the stand and increase its naturalness (Beckage *et al.*, 2005). Depending on the size and shape of the gap, we observe an increase in light intensity within the gap directly affecting the growth of natural regeneration (McCarthy, 2001; Pasanen *et al.*, 2016). On the other hand, an increase in light intensity can favour ground vegetation which reduces success of the natural regeneration (Ruuska *et al.*, 2008). The existence of a dense herbal layer and unfavourable conditions of the forest floor are often the most important obstacles for the initiation of Scots pine natural regeneration and high seedling densities (Castro *et al.*, 2002; Grigoriadis *et al.*, 2014).

Currently, we have been observing the uptrend of small-scale close-to-nature management which uses canopy gaps (Kuuluvainen & Aakala, 2011; Halme *et al.*, 2013; Reynolds *et al.*, 2013) to stimulate the natural regeneration process. However, in the case of Scots pine as a pioneer and light demanding tree species, gap regeneration may be very challenging long-term process with uncertain outcome. In commercial forests, the secondary edge effect (defined here as a change of site and stand conditions along the edge-to-interior gradient after clearcut) can serve as an alternative or supplement both to conventional large-scale management and gap regeneration, whereas in forests with significant non-production functions it can be used to increase their structural variability and resistance (Similä & Junninen, 2012; Churchill *et al.*, 2013; Puettmann *et al.*, 2015).

In the past, research was focused primarily on the shade-tolerant tree species, while the Scots pine was given little attention. In this paper we evaluate the influence of the forest edge on growth, quantity, structure and quality of natural regeneration. The paper covers the following questions: (i) How does the distance from the forest edge affect the density of natural regeneration? (ii) How does the forest edge affect the height and spatial distribution of natural regeneration? (iii) How does the forest edge influence the quality of natural regeneration and how far from the forest edge can we expect high-quality Scots pine regeneration? Finally, (iv) can we consider forest edges as suitable places for Scots pine regeneration?

Material and methods

Characteristics of the area of interest

The area of interest lies in the Kokořínsko Protected Landscape Area (50°34'31" N, 14°40'34" E). The basic primary rock consists of Quaternary sandstones and the prevailing soil type is Arenic Podzol. Annual precipitation reaches 610 mm and the annual mean temperature is 8.1 °C. Vegetation periods last about 162 days with the mean vegetation-period temperature oscillating around 14.4 ºC and the mean vegetation-period precipitation rates of 375 mm. The study sites naturally host Scots pine *Pinetum oligotrophicum* with sparse cover of *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea L.* in the herbal storey.

Data collection

In total four 40×40 m permanent research plots (PRP) were established. Plot No. 1 was established 5 m from the forest edge (PRPe 1) created after a large-scale clearcut 30 years ago. A control plot (PRPc 4) was marked out as directly neighbouring to the first one (>45 m from the forest edge). The other two plots were established identically (PRPe 2 - stand edge and PRPc 3 - control plot). The stand edge of PRPe 1 has an east aspect; the edge of PRPe 2 has a south aspect. The overview of basic characteristics is presented in Table 1.

All trees (dbh>4 cm) and natural regeneration individuals (dbh<4 cm, h >150 cm) within each PRP were

Table 1. Overview of basic stand and site characteristics of permanent research plots.

PRP	Position[1]	Slope (°)	Altitude (m)	Forest type[2]	Tree layer age (yr)	dbh (cm)	Height (m)	Canopy	Stocking	Stand volume (m^3/ha)
PRPe 1	Edge	0	268	0M3	129/10	27.4	21.1	0.73	0.61	257
PRPe 2	Edge	0	267	0M3	129/10	29.4	24.5	0.72	0.67	386
PRPc 3	Center	0	267	0M3	129/10	27.6	21.2	0.68	0.55	264
PRPc 4	Center	0	268	0M3	129/10	26.9	21.2	0.78	0.67	277

PRP: permanent research plot. dbh: diameter at breast height. [1] Location of plots within the forest stand. [2] 0M3: poor oak pine stands with blueberry (*Vaccinium myrtillus* L.).

mapped using FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.). Crown projections of trees were measured in at least four perpendicular directions to determine the canopy characteristics; dbh, height and crown height were measured in the tree layer. In natural regeneration, position, height and crown height of all individuals were measured; crown width and dbh was measured in 10% randomly selected individuals.

The quality of each regeneration individual was evaluated using 4-grade scale. Q1: High quality individual with straight trunk; Q2: Individual with slight defects of the trunk, *e.g.* slight, simple sweep, abrasion or fraying marks up to 1/3 of the trunk girth and 15 cm length of the damage; Q3: Individual with prominent simple or complex trunk sweep, seriously damaged by fraying or abrasion exceeding 1/3 of the trunk girth or 15 cm of damage length, or an individual with damaged terminal shoot substituted by a shoot forming an acute angle with the trunk axis, or a leaning individual; Q4: considerable deformed individuals with no silvicultural value.

Data analysis

In each PRP, growth parameters, production and canopy closure (crown projection area and canopy density) of the tree layer were evaluated. In regeneration individuals, vertical structure was evaluated using the Gini index (Gi) (Gini, 1921) and horizontal structure using the Hopkins-Skellam index (H&Si) (Hopkins & Skellam, 1954) and the Clark-Evans index (C&Ei) (Clark & Evans, 1954) computed in the PointPro software (© CULS, Daniel Zahradník). The chi-square test of homogeneity was performed to test for the differences of spatial placement of regeneration individuals from uniform distribution - null hypothesis was that number of regeneration individuals in each subplot is equal. For assessing aggregation of regeneration individuals on different scales, Ripley's L functions (Besag, 1977) were computed for each plot. The relationship between the top storey and natural regeneration was depicted by pair-correlation function. Spatial positions of trees and regeneration were randomly toroidally shifted before analyses in R package "splancs" (Rowlingson & Diggle, 2017).

Statistical analyses of the natural regeneration parameters (density, height, quality) were processed by the Statistica (© StatSoft). Further, the plots were divided into 64 squares of 5 × 5 m. Differences among transects (8 × 5 m) with different distance from the forest edge and among PRPs were tested by the analysis of variance (ANOVA) followed by the Tukey HSD test. Pearson correlation between quality, height and density of regeneration and the distance from the edge was evaluated for the transects.

Regeneration density was evaluated in relation to individual quality aggregated into two levels (Q1+Q2 quality grades and Q3+Q4 quality grades) via Wilcoxon rank-sum test as well as the relationship of regeneration individual height on described aggregated quality levels in R software (R Core Team, 2017). Data from the same PRP type (control, edge) were analysed together. The neighbouring regeneration density was computed as number of trees per square meter in a circle with radius of 2.5 m from each regeneration individual in ArcGIS 10.5 (© ESRI).

Principal components analysis (PCA) was carried out in CANOCO (© Microcomputer Power) to evaluate the relation between natural regeneration parameters (density, mean height, mean quality and individual quality degrees), the distance from the forest edge and canopy density. The data were log-transformed and standardized before analysis. Maps and canopy analysis were performed in ArcGIS 10.0 (© Esri).

Results

Regeneration density and height

Density of the natural regeneration on PRPe 1 and PRPe 2 reached 11,413 pcs/ha (PRPe 1) and 6,375 pcs/ha (PRPe 2). On the PRPc 3 and 4, there were 4,012 pcs/ha and 1,594 pcs/ha (Table 2). The distance from the stand edge significantly influenced natural regeneration on PRPe 1 (ANOVA; $F_{(7, 56)}$=8.3, p<0.001), PRPe 2 (ANOVA; $F_{(7, 55)}$=11.7, p<0.001) and PRPc 3 (ANOVA; $F_{(7, 50)}$=5.8, p<0.001). On PRPc 4, the relation was not confirmed (ANOVA; $F_{(7, 35)}$=1.1, p>0.05; Fig. 1).

Table 2. Basic stand and structure parameters of pine natural regeneration on permanent research plots.

PRP	Density (ind/ha)	Mean height (cm)	Mean dbh (mm)	Mean crown width (cm)	Mean crown base (cm)	Mean quality	Mean HDR	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)	G[1] (Gi)	R[2] (C&Ei)	A[3] (H&Si)
PRPe 1	11,413	258	18.5	50	100	2.44	192.6	8.1	46.3	38.2	7.2	0.635	0.831*	0.736*
PRPe 2	6,375	289	18.2	49	97	2.61	182.2	4.2	38.4	48.8	8.6	0.759	0.897*	0.664*
PRPc 3	4,012	212	12.1	44	89	2.44	256.1	6.7	46.2	41.5	5.6	0.388	0.777*	0.816*
PRPc 4	1,594	195	12.9	43	86	2.81	160.3	2.1	28.7	54.8	14.3	0.315	0.562*	0.903*

PRP: permanent research plot. dbh: diameter at breast height. HDR: height to diameter ratio. Q1-Q4: quality degree of the regeneration individuals. G: Gini index. R: Clark-Evans index. A: Hopkins-Skellam index. [1]Range 0-1, low G<0.3, medium G=0.3-0.5, high G=0.5-0.7, very high differentiation G>0.7. [2]Medium value R=1, clusterness R<1, regularity R>1. [3]Medium value A=0.5; clusterness α>0.5; regularity α<0.5. *Aggregation - statistically significant value for R, A indices (α=0.05).

According to the Pearson correlations, on the PRPe 1 and 2 natural regeneration density decreases considerably with an increasing distance from the forest edge ($r \leq -0.64$), the significance being $p<0.001$. On PRP 3 ($r = -0.43$, $p<0.01$) we registered a value of medium correlation while on PRPc 4 no such relation was confirmed ($r = -0.29$, $p>0.05$). On PRPe 1 with the highest density of regeneration in a distance of 5-10 m from the edge, the regeneration reached 19,000 pcs/ha; in a distance of 20-25 m it was 12,750 pcs/ha and only 5,400 pcs/ha in a distance of 40-45 m.

Mean height of natural regeneration differentiated according to the distance from the stand edge is depicted by Fig. 2. Contrary to plots established under the canopy, there were observed statistically significant differences in mean height of regeneration individuals at the plots on the forest edge.

Height and horizontal structure

Among the PRPs, statistically significant difference was observed in the mean height of regeneration individuals (ANOVA: $F_{(3, 3737)}=137.3$, $p<0.001$). The

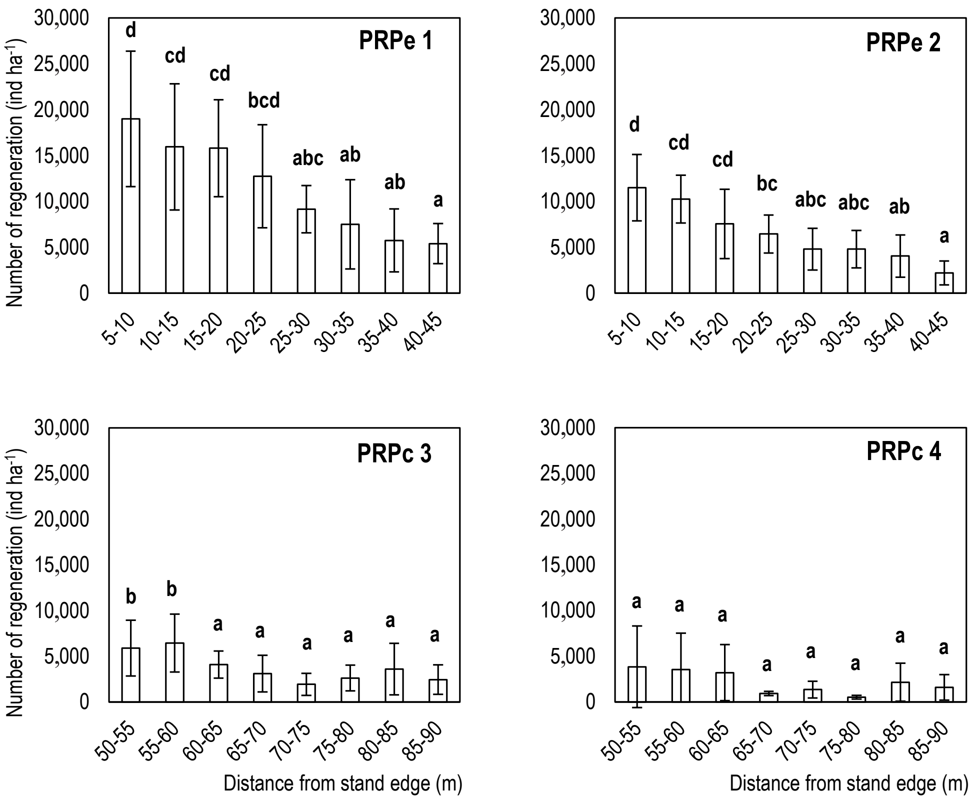

Figure 1. Number of individuals of pine natural regeneration differentiated according to the distance from the stand edge on PRP; statistically significant differences ($p<0.05$) are indicated by different letters. Error bars represent standard deviation (SD).

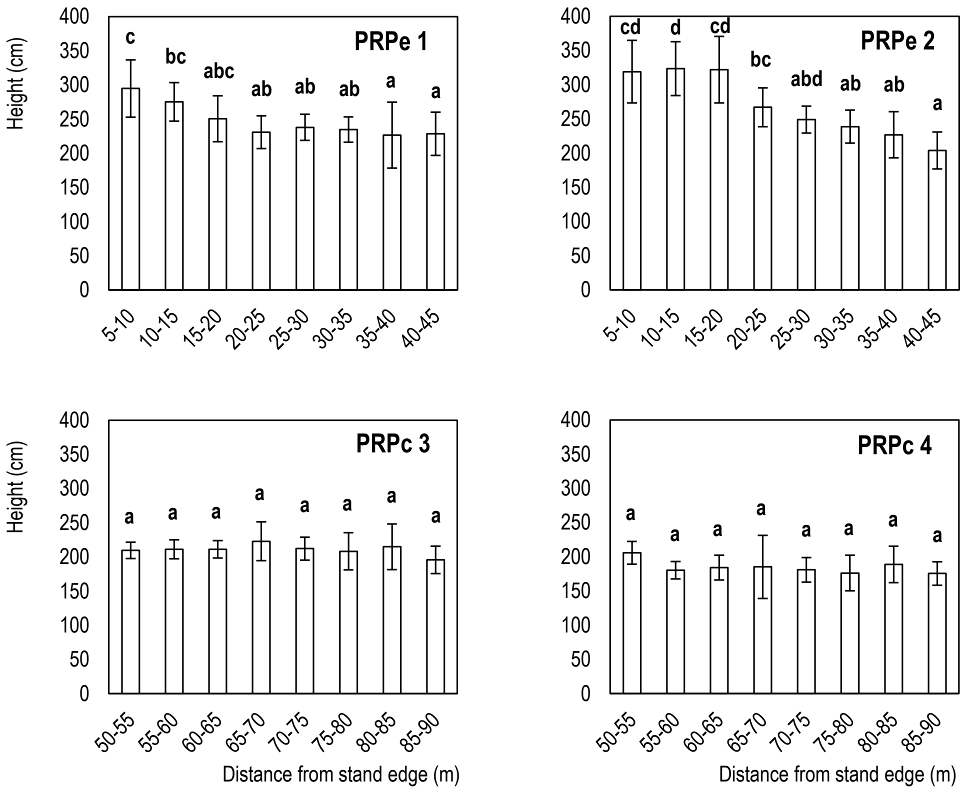

Figure 2. Mean height of natural regeneration differentiated according to the distance from the stand edge on PRP; statistically significant differences (p<0.05) are indicated by different letters. Error bars represent standard deviation (SD).

mean height of regeneration individuals was significantly higher on PRPe 1 (257.9 cm ± 87.5 SD) than on PRPc 4 (194.6 cm ± 46.5 SD). Similarly, on PRPe 2 (287.7 cm ± 110.9 SD) the mean height of regeneration individuals was significantly higher than on PRPc 3 (212.3 cm ± 53.7 SD) (Table 2). Statistically significant difference in the mean height of regeneration individuals among transects was observed on PRPe 1 (ANOVA: $F_{(7, 56)}$=4.8, p<0.001) and on PRPe 2 (ANOVA: $F_{(7, 55)}$=14.6, p<0.001). On PRPc 3 (ANOVA: $F_{(7, 52)}$=0.9, p>0.05) and on PRPc 4 (ANOVA: $F_{(7, 35)}$=1.4, p>0.05) statistically significant differences were not confirmed (Fig. 2). There was a negative correlation between distance from the edge and height on both PRPe 1 and PRPe 2 ($r \leq$-0.54, p<0.001). On the contrary, on PRPc 3 and PRPc 4, no statistically significant correlation between the distance from the stand edge and height of the regeneration ($r \leq$-0.14, p>0.05) was confirmed. According to the Gini index high to very high level of vertical differentiation in the regeneration layer was confirmed on both PRP close to the stand edge PRPe 1 (Gi=0.635) and PRPe 2 (Gi=0.759). The height differentiation was medium on both control plots PRPe 3 (Gi=0.388) and PRPe 4 (Gi=0.315).

Structural indices altogether with chi-squared test of homogeneity (p<0.001 in all PRPs) and L-functions indicates that natural regeneration on all PRP was significantly aggregated (Table 2, Figs. 3, 4). The further from the stand edge, the more prominent aggregation of natural regeneration occurs. The plots located further from the stand edge (PRPc 3 and PRPc 4) had more significantly aggregated horizontal structure (PRPc 3: R(C&Ei) = 0.777, A(H&Si) = 0.816; PRPc 4: R(C&Ei) = 0.562, A(H&Si) = 0.903) in comparison to PRPe 1 and 2 (PRPe 1: R(C&Ei) = 0.831, A(H&Si) = 0.736; PRPe 2: R(C&Ei) = 0.897, A(H&Si) = 0.664), esp. on PRPe 1 in a distance of 5-10 m (R(C&Ei) = 0.841, A(H&Si) = 0.691).

The distances between natural regeneration individuals and the nearest individual in tree layer were computed; on all PRPs, the most common distance from each regeneration individual to the nearest top storey individual was around 2 m. Confidence intervals for distances (t–distribution, 95%); PRPe 1 - 2.17 ± 0.05 m, PRPe 2 – 1.96 ± 0.06 m, PRPc 3 - 1.98 ± 0.08 m and PRPc 4 - 1.97 ± 0.1 m.

Overall relationship between regeneration individuals and to storey trees is depicted by pair-correlation function (Fig. 5).

Regeneration quality

In contrast to quantity and height, the difference in the mean quality of natural regeneration individuals

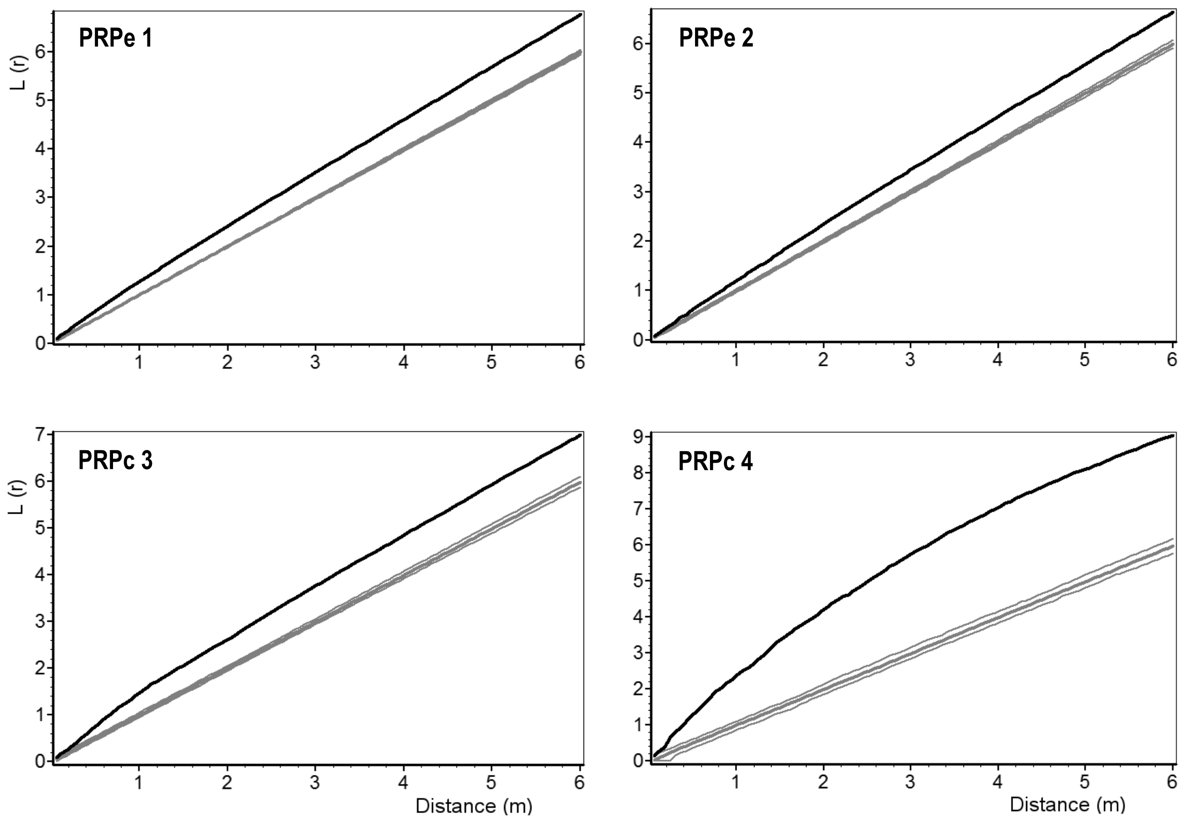

Figure 3. Horizontal structure of natural regeneration on PRP expressed by *L*-transformation of Ripley's *K* function. The black line represents the *L*- function for real distances of recruits on PRP, the thick grey line illustrates the random spatial distribution of recruits and two thinner central curves represent a 95% confidence interval. When the black line of recruits distribution on PRP is below this interval, it indicates a tendency of individuals toward regular distribution, and if it is above this interval, it shows a tendency toward aggregation on particular distance.

between particular transects was confirmed only on PRPe 2 (ANOVA; $F_{(7, 52)}$=2.6, p<0.05). No PRP showed any significant influence of the distance from the stand edge on the mean quality of regeneration individuals, nevertheless on PRPe 1 *post hoc* comparison of particular transects showed significant differences in favour of regeneration quality near the stand edge (p<0.05; Fig. 6).

According to the Pearson correlation relative occurrence of the best-quality Q1 individuals was significantly influenced in the negative sense (r=-0.40, p<0.05) with a different share among transects (ANOVA; $F_{(7, 56)}$=5.2, p<0,001) on PRPe 1. There were 1,044 pcs/ha (8.1%) of these Q1 individuals on the densest PRPe 1, while there were only 33 Q1 individuals (2.1%) on the least dense PRPc 4. There were reported differences in regeneration quality degree Q2 (ANOVA; $F_{(7, 56)}$=2.9, p<0.05) and Q3 (ANOVA; $F_{(7, 56)}$=3.8, p<0.01). The worst-quality individuals Q4 did not show any differences in occurrence (ANOVA; $F_{(7, 56)}$=0.9, p>0.05) on PRP 1. On PRP 2, differences were also spotted in Q1 (ANOVA; $F_{(7, 55)}$=2.3 p<0.05) and Q3 (ANOVA; $F_{(7, 55)}$=2.3, p<0.05). Also on PRP 2 the distance from the edge negatively correlated with best-quality Q1 individuals share (r=-0.32, p<0.01) and positively correlated with Q3 individuals (r=0.32, p<0.01). Share of particular quality degrees is shown in Fig. 7.

Testing for differences in neighbouring regeneration individuals density between aggregated quality levels showed significant results for both control and edge PRPs (Fig. 8). For control PRPs, the difference in regeneration density was 0.069 tree/m^2 (0.707 tree/m^2 for Q1+Q2 *vs* 0.638 tree/m^2 for Q3+Q4; Wilcoxon rank-sum test, p=0.005), for edge PRPs, the difference was 0.076 tree/m^2 (1.356 tree/m^2 for Q1+Q2 *vs* 1.280 tree/m^2 for Q3+Q4; Wilcoxon rank-sum test, p=0.003).

Significant results were obtained as well for regeneration tree height with respect to its quality (Fig. 9). Mean regeneration height showed higher values in for control and edge PRPs as well (Wilcoxon rank-sum test, p<0.001 in both cases). The difference was 17% for control PRPs (224.3 cm for Q1+Q2, 191.2 cm for Q3+Q4) and 26% for edge PRPs (229.1 cm for Q1+Q2, 237.5 for Q3+Q4).

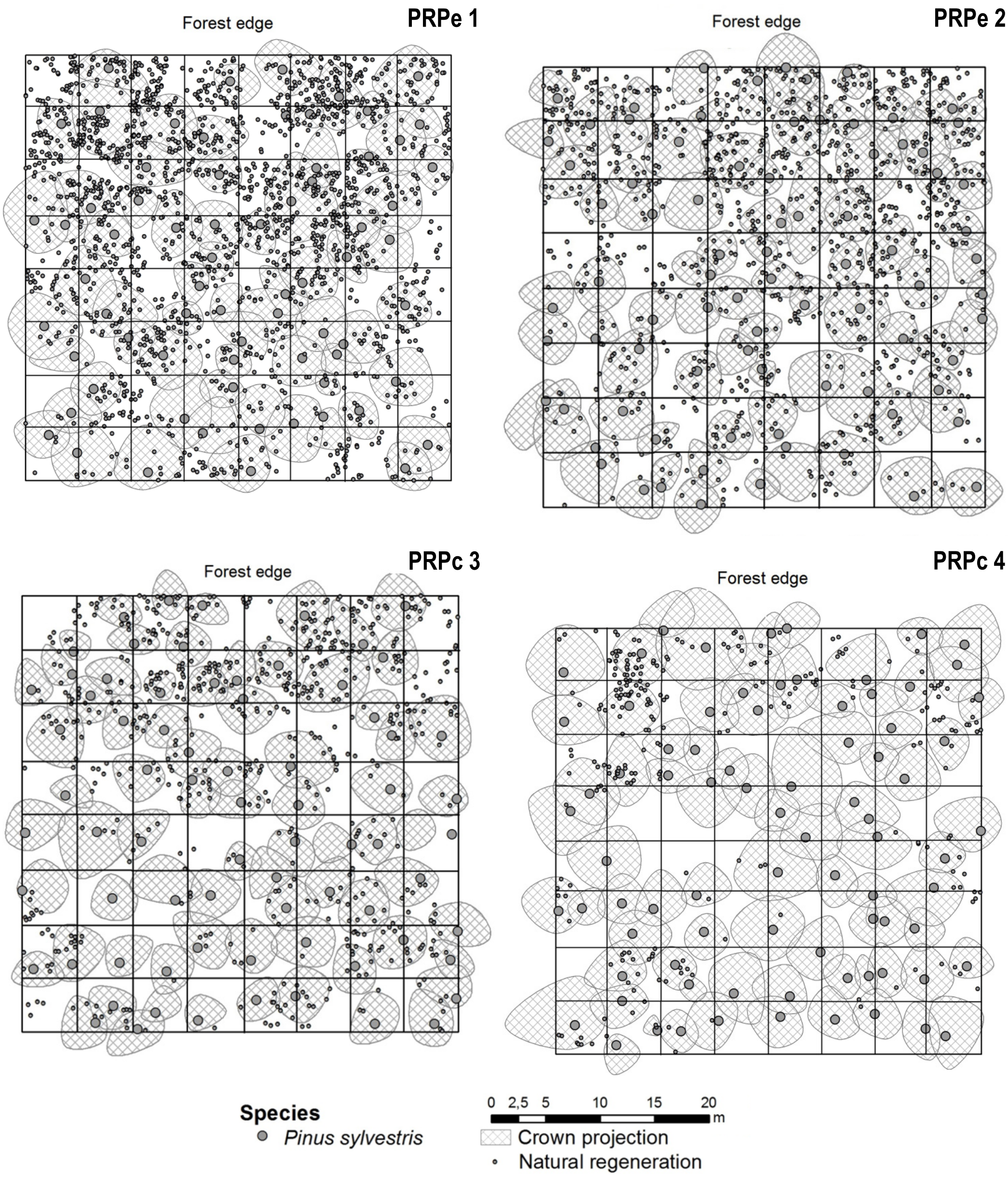

Figure 4. Horizontal structure of tree layer and natural regeneration on PRP divided to 5 m transects.

Interaction between regeneration, tree layer and stand edge

The complex relationship between natural regeneration, canopy and distance from the forest edge is presented in a PCA analysis (ordination diagram) in Fig. 10. The first ordination axis explains 52.9%, the first two axes 76.1% and all four axes 92.0% of data variability. X-axis shows silviculture quality of Scots pine natural regeneration. The distance from the stand edge negatively correlated with the quantity and mean height of regeneration, even in the case of Q1 individuals' numbers. The denser canopy of parent stand, the lower mean stand quality (occurrence of Q1 and Q2 individuals) and, on the contrary, the higher share of poor-quality and deformed individuals (Q3 and Q4). Comparison shows high homogeneity of PRPs near the stand edge, while the inner plots are rather heterogeneous. The diagram also suggests that the smallest explaining variable was canopy density. The top left part of the diagram - two PRPe in the stand edge - shows the typical high mean heights and the density of regeneration individuals in contrast to both PRPc in the stand centre.

Discussion

Many researchers investigate population structures and factors influencing Scots pine regeneration in Europe (Kuuluvainen & Juntunen, 1998; Montes &

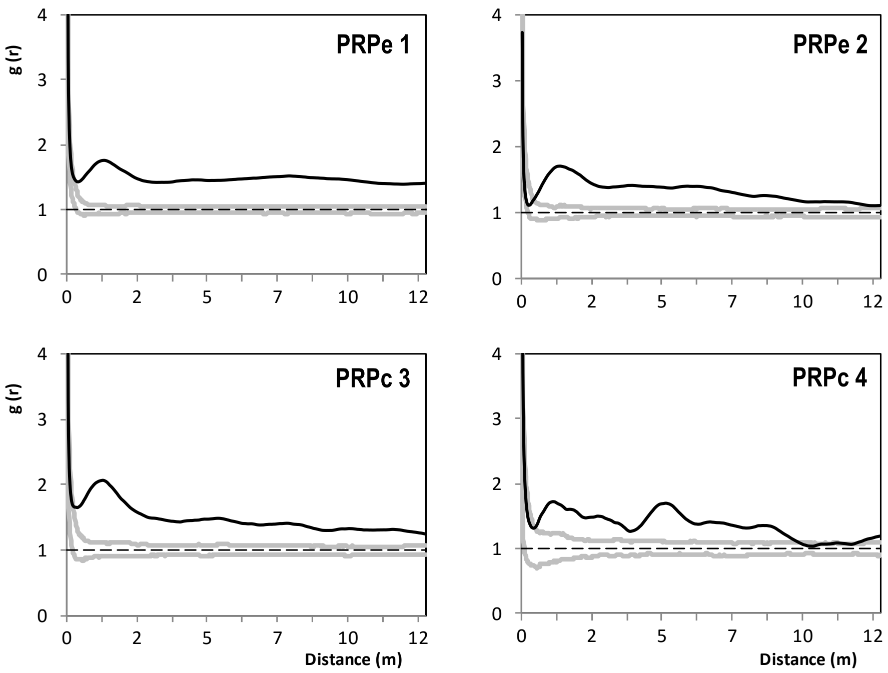

Figure 5. The relation between natural regeneration and the tree layer on particular permanent research plots; the bold black line represents the cross-type pair correlation function for real distances of individuals; the dashed black line on the level of g (r)=1 represents the mean course for random spatial distribution of trees and the two grey curves 95% confidence interval; when the observed value exceeds the upper limit of the simulation interval, it indicates significant aggregation - positive relationship between two tested groups, and if it is under this interval, it shows inhibition - negative relationship.

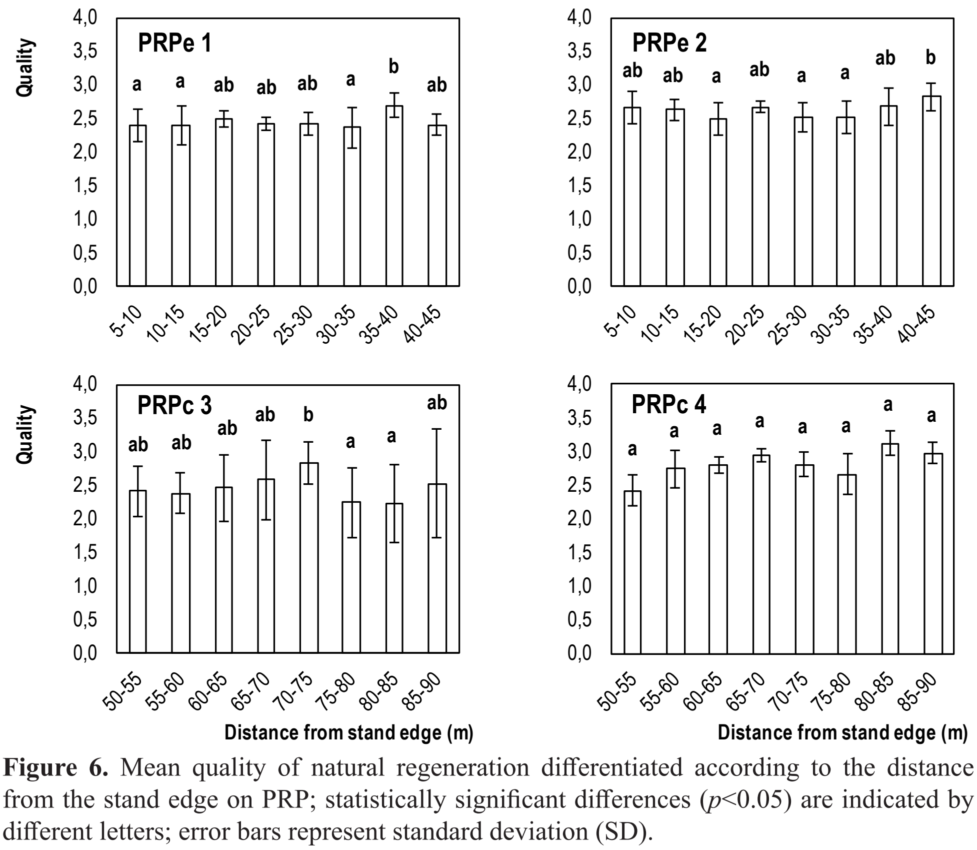

Figure 6. Mean quality of natural regeneration differentiated according to the distance from the stand edge on PRP; statistically significant differences (p<0.05) are indicated by different letters; error bars represent standard deviation (SD).

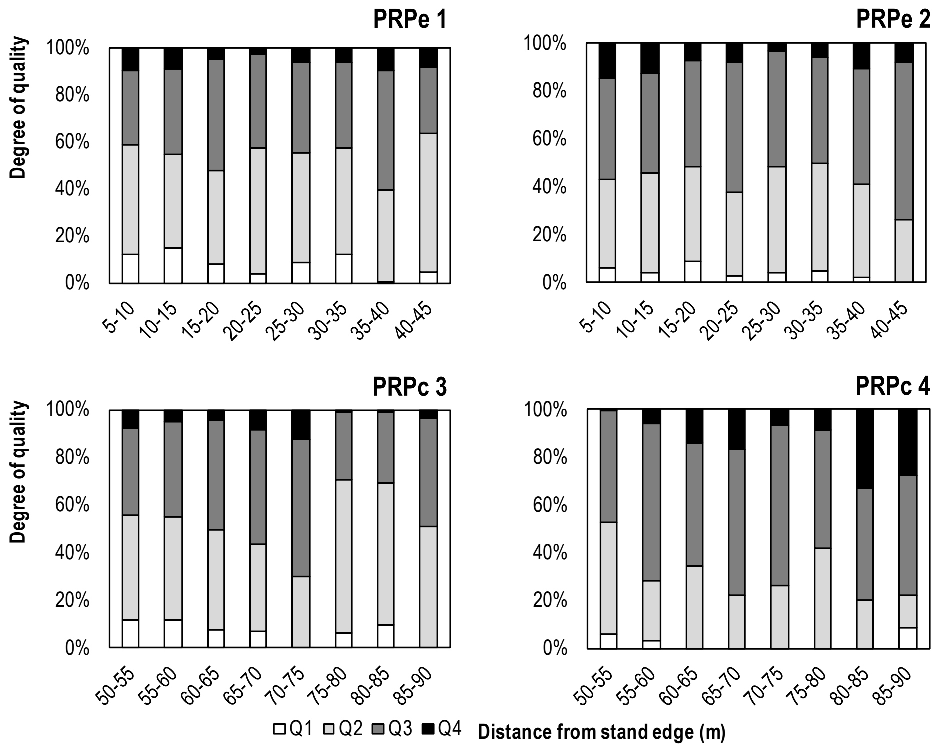

Figure 7. Percentage representation of silviculture quality degrees of natural regeneration on PRP differentiated according to the distance from the stand edge.

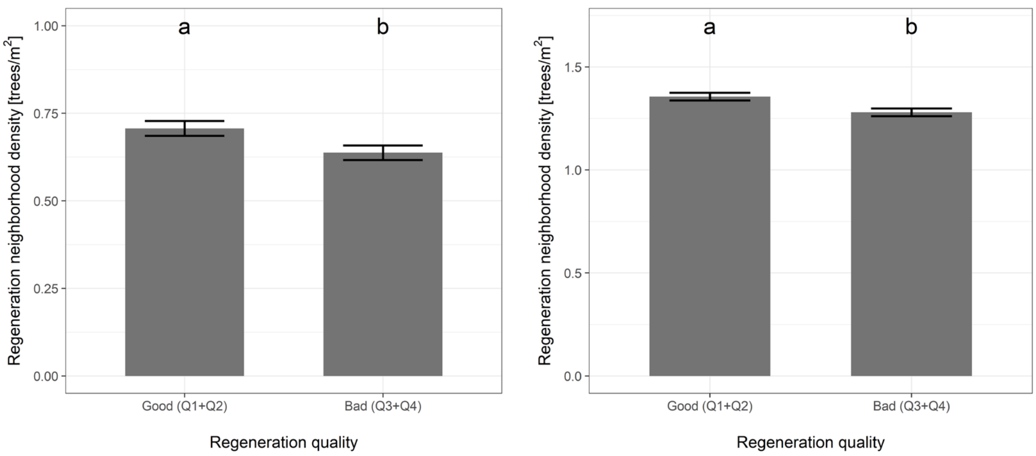

Figure 8. Regeneration neighbourhood density in circle with radius 2.5 m from each individual. Wilcoxon rank-sum test was used for testing for significant differences between aggregated regeneration quality levels (Q1+Q2 and Q3+Q4). Error bars depict mean value ± standard error. Plot for control PRPs is on the left, for edge PRPs on the right. Different indices above bars depict statistically significant differences.

Canellas, 2007; Pasanen *et al.*, 2016), but studies describing the stand edge effect on regeneration and stand development are rather scarce or consider only edge-to-exterior gradient (Ruuska *et al.*, 2008).

The first part of our research addressed the effect of forest edge on seedling and sapling density as the basic prerequisite for obtaining high quality regeneration. Natural regeneration density differed significantly on particular plots. In the studied pure pine stands, the numbers of natural regeneration individuals ranged from 1,594 pcs/ha (PRPc 4) to 11,413 pcs/ha (PRPe 1). For example, on PRPe 1 (with the highest density of regeneration) 5-10 m from the stand edge, numbers of regeneration reached 19,000 pcs/ha, whereas only 5,400 pcs/ha at distance 40-45 m were observed. Further from the edge, no differences in regeneration numbers on

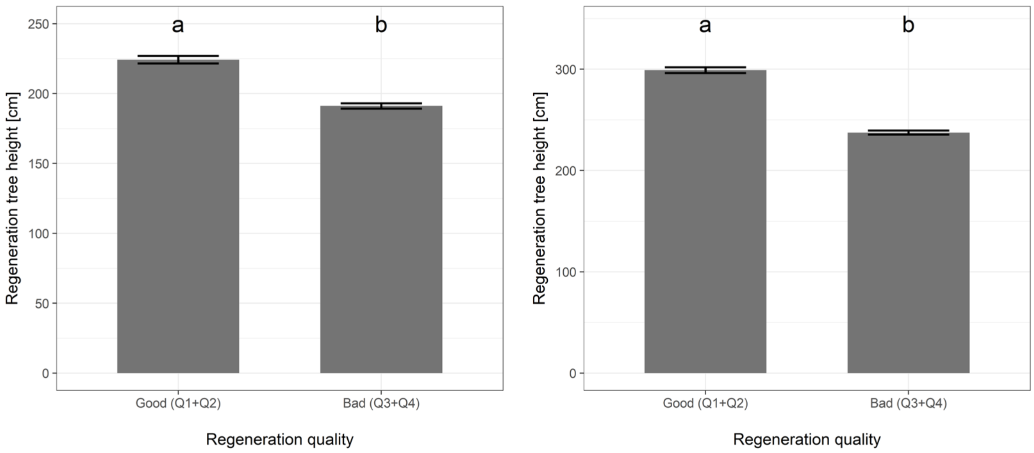

Figure 9. Comparison of regeneration height between aggregated tree quality levels (Q1+Q2 and Q3+Q4). Plot for control PRPs is on the left, for edge PRPs on the right. Wilcoxon rank-sum test was used for testing for significant differences. Error bars depict mean value ± standard error. Different indices above bars depict statistically significant differences.

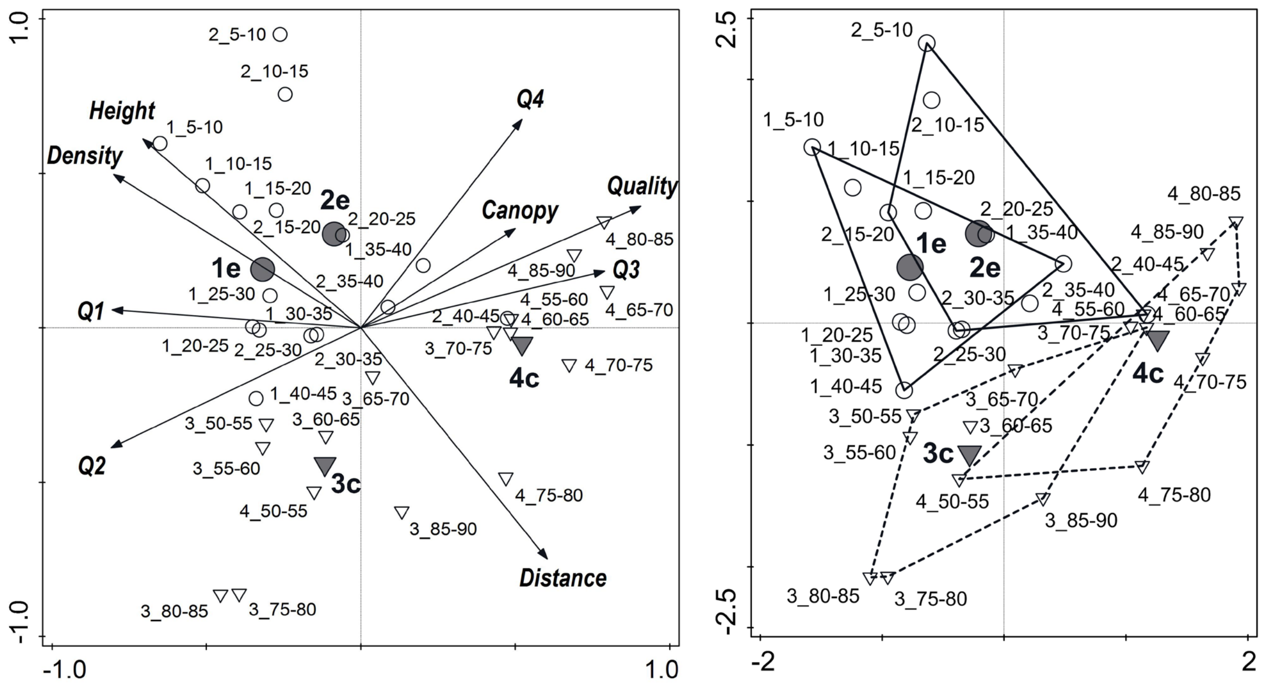

Figure 10. Ordination diagram of PCA of relationships among parameters of natural regeneration (density, mean height, mean quality and individual quality degrees - Q1 the best, Q4 the worst), stand canopy of mature stand and distance from the stand edge on the left side and classified sample diagram differentiated according to plots on the right side; marks indicate PRP in the stand edge (● 1e, 2e) and in the stand centre (▼ 3c, 4c) with numbers of transects (5 m) from the stand edge.

control plots were stated. Generally, distinctly lower natural regeneration densities were found in the stand interior. These were comparable to values from other regions in the Czech Republic (344-4,940 pcs/ha, Vacek *et al.*, 2016; and 244-1,348 pcs/ha, Vacek *et al.*, 2017). On the contrary, plots along the forest edge were superior to the control plots with 1.5 to 7 times higher regeneration densities. Similarly, in pine stands from the Mediterranean region or Fennoscandinavia, a decreasing trend in regeneration numbers related to increasing lack of light is reported by Kuuluvainen & Juntunen (1998) and Montes & Canellas (2007). A positive influence of side light close to forest edges was proven also for other tree species (Burton, 2002; Šálek *et al.*, 2013).

Similarly, mean height of natural regeneration was significantly higher on PRPe 1 and 2 near the stand edge, in comparison with the control plots (PRPc).

The results correspond with Pukkala *et al.* (1993) from eastern Finland. Shade intolerance of pine is highlighted by other authors as well (Mason *et al.*, 2004; Ewald, 2007). Density as well as height showed significant negative correlation with the distance from the edge. Furthermore, on PRPs close to the forest edge pronounced gradient of light conditions resulted to generally very high vertical differentiation of regeneration layer, whereas on the control PRPs only medium differentiation was confirmed. Higher regeneration densities are leading to higher regeneration quality, at the same time, individuals of higher quality grades (Q1+Q2) are usually higher than individuals of lower quality grades (Q3+Q4). This was truth for edge as well as control plots.

With the exception of individual sanitary felling, the tree layer and regeneration layer have not been treated during the last 20 years. On the one hand, the stand structures and regeneration characteristics have not been influenced by silvicultural treatments and we were able to evaluate the regeneration development without these secondary effects. On the other hand, the lack of silvicultural treatments resulted in height to diameter ratios by far exceeding critical values for the stability of pine forest stands (Table 2). If applied in production forest, special attention must be paid to the stability of future forest stands with proper and timely canopy regulation.

In contrast to quantity and height, the mean quality of regeneration was not dependent on the distance from the stand edge. There were 1,044 pcs/ha (8.1%) of the most promising Q1 individuals, forming the core of the future stand. The number corresponds with the upper range of tree numbers in commercial forests in the Czech Republic (476-1,072 pcs/ha; Bílek *et al.*, 2016) as well as in Spain (678-1,092 pcs/ha; Marcos *et al.*, 2007).

Studied spatial distribution of natural regeneration individuals on PRPs was significantly aggregated, which corresponds with the study of Vacek *et al.* (2016) from pine forests in the Czech Republic, or with Tuten *et al.* (2015) investigating pine stands in North America. We confirmed more distinctive aggregation of regeneration inside the stand, in comparison with the stand edge. Barbeito *et al.* (2009) showed the opposite in a managed Mediterranean mountain forest, where in the even-aged stands the pattern of regeneration was highly influenced by the gaps created by harvesting. In this context, apart from further verification on other sites, it is advisable to study micro-habitat conditions and factors leading to substantial aggregation of the regeneration and parent trees, even under limit conditions of natural Scots pine habitats.

PCA analysis confirmed negative correlation of the distance from the stand edge with the density and height of the regeneration, even with the numbers of the best individuals. On the other hand, positive or non-significant influence of the distance from the stand edge on the relative occurrence of the lower-quality individuals was observed. It is apparent from the diagram that the stand canopy significantly influences natural regeneration density and its height, as well, which corresponds with the results of Vacek *et al.* (2016) and Montes *et al.* (2008). Other authors claim natural regeneration, in some cases, can survive better under moderately dense canopy than in an open area (Nilsson *et al.*, 2006; Wagner *et al.*, 2011), especially in arid localities where moderate canopy shading prevents the upper soil layers from drying out (Greene *et al.*, 1999).

In our study we did not consider the edge effect neither on mature trees, nor on individual stem quality or biodiversity, since the forest edges in our study are only temporal features with relatively short persistence. Nevertheless, there are numerous articles describing the positive effect of forest edges after harvest operation on *e.g.* plant communities (Euskirchen *et al.*, 2001), bryophytes (Dynesius *et al.*, 2008), bird communities (Brazaitis *et al.*, 2004) and forest stand and tree characteristics (Burton, 2002; Šálek *et al.*, 2013). Based on these findings forest edges must be also considered as valuable landscape components with numerous positive effects on ecosystem stability and biodiversity.

This study confirmed an overall positive edge effect on natural regeneration up to the distance of ½ of the stand height. In the case of 1 ha clearcut, the edge effect can contribute to regeneration of at least 0.2 more hectares of forest stands (considering only the east and south edges) if other requirements are met. Firstly, suitable germination bed or soil preparation is required, secondly the management goals and stand stability must be considered in a broader context. Thus, appropriate temporal and spatial felling policy should take into account the secondary effect of clearcut borders for natural regeneration of pine.

Conclusion

Our study confirmed statistically significant impact of the forest edge after clearcut on the growth and quality of Scots pine natural regeneration. The closer to the stand edge, the higher density of natural regeneration, mean height and share of best-quality promising individuals. Thus, in production forests, the interior of the forest edge created after conventional clearcut can become favourable location for natural regeneration and can be implemented into traditional management approaches in pine regions.

References

Aleksandrowicz-Trzcińska M, Drozdowski S, Brzeziecki B, Rutkowska P, Jabłońska B, 2014. Effects of different methods of site preparation on natural regeneration of *Pinus sylvestris* in Eastern Poland. Dendrobiology 71: 73-81.

Axelsson EP, Lundmark T, Högberg P, Nordin A, 2014. Belowground competition directs spatial patterns of seedling growth in Boreal forests in Fennoscandia. Forests 5 (9): 2106-2121. https://doi.org/10.3390/f5092106

Barbeito I, Fortin MJ, Montes F, Cañellas I, 2009. Response of pine natural regeneration to small-scale spatial variation in a managed Mediterranean mountain forest. Appl Veg Sci 12 (4): 488-503. https://doi.org/10.1111/j.1654-109X.2009.01043.x

Beckage B, Lavine M, Clark JS, 2005. Survival of tree seedlings across space and time: estimates from long-term count data. J Ecol 93 (6): 1177-1184. https://doi.org/10.1111/j.1365-2745.2005.01053.x

Benavides R, Rabasa SG, Granda E, Escudero A, Hódar JA, Martínez-Vilalta J, Rincón AM, Zamora R, Valladares F, 2013. Direct and indirect effects of climate on demography and early growth of *Pinus sylvestris* at the rear edge: changing roles of biotic and abiotic factors. PLoS One 8 (3): e59824. https://doi.org/10.1371/journal.pone.0059824

Besag J, 1977. Comments on Ripley's paper. J Roy Stat Soc A B39: 193-195.

Bílek L, Remeš J, Podrázský V, Rozenbergar D, Diaci J, Zahradník D, 2014. Gap regeneration in near-natural European beech forest stands in Central Bohemia-the role of heterogeneity and micro-habitat factors. Dendrobiology 71: 59-71.

Bílek L, Vacek S, Vacek Z, Remeš J, Král J, Bulušek D, Gallo J, 2016. How close to nature is close-to-nature pine silviculture? J For Sci 62 (1): 24-34. https://doi.org/10.17221/98/2015-JFS

Brazaitis G, Angelstam P, 2004. Influence of edges between old deciduous forest and clearcuts on the abundance of passerine hole-nesting birds in Lithuania. Ecol Bull 51: 209-217.

Burton PJ, 2002. Effects of clearcut edges on trees in the sub-boreal spruce zone of Northwest-Central British Columbia. Silva Fenn 36 (1): 329-352. https://doi.org/10.14214/sf.566

Castro J, Zamora R, Hódar JA, 2002. Mechanisms blocking *Pinus sylvestis* colonization of Mediterranean mountain meadows. J Veg Sci 13 (5): 725-731.

Churchill DJ, Larson AJ, Dahlgreen MC, Franklin JF, Hessburg PF, Lutz JA, 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. For Ecol Manage 291: 442-457.

Clark PJ, Evans FC, 1954. Distance to nearest neighbour as a measure of spatial relationship in populations. Ecology 35: 445-453. https://doi.org/10.2307/1931034

Coban S, Colak AH, Rotherham ID 2016. Interactions between canopy cover density and regeneration cores of older saplings in Scots pine (*Pinus sylvestris* L.) stands. Forest Syst 25 (3): e073. https://doi.org/10.5424/fs/2016253-08429

Dynesius M, Åström M, Nilsson C, 2008. Microclimatic buffering by logging residues and forest edges reduces clear-cutting impacts on forest bryophytes. Appl Veg Sci 11: 345-354. https://doi.org/10.3170/2008-7-18457

Euskirchen ES, Chen J, Runcheng B, 2001. Effects on edge on plant communities in a managed landscape in northern Wisconsin. For Ecol Manage 148: 93-108.

Ewald J, 2007. Ein Pflanzensoziologisches Modell der Schattentoleranz von Baumarten in den Bayerischen Alpen A Phytosociological Model of Shade Tolerance of Tree Species in the Bavarian Alps. Forum Geobotanicum 3: 11-19.

Gini C, 1921. Measurement of inequality on income. Econ J 31: 22-43. https://doi.org/10.2307/2223319

Greene DF, Zasada JC, Sirois L, Kneeshaw D, Morin H, Charron I, Simard MJ, 1999. A review of the regeneration dynamics of North American boreal forest tree species. Can J For Res 29: 824-839. https://doi.org/10.1139/x98-112

Grigoriadis N, Spyroglou G, Grigoriadis S, Klapanis P, 2014. Effect of soil scarification on natural regeneration of mature scots pine (*Pinus sylvestris*) stand in Greece. Global NEST J 16 (4): 732-742. https://doi.org/10.30955/gnj.001320

Halme P, Allen KA, Auniņš A, Bradshaw RHW, Brūmelis G, Čada V, Clear JL, Eriksson AM, Hannon G, Hyvärinen E, *et al.*, 2013. Challenges of ecological restoration: Lessons from forests in northern Europe. Biol Conserv 167: 248-256. https://doi.org/10.1016/j.biocon.2013.08.029

Hopkins B. Skellam JG, 1954. A new method of determining the type of distribution of plant individuals. Ann Bot 18: 213-227. https://doi.org/10.1093/oxfordjournals.aob.a083391

Ibáñez I, Schupp EW, 2002. Effects of litter, soil surface conditions, and microhabitat on Cerocarpus ledifolius Nutt. seedling emergence and establishment. J Arid Environ 52 (2): 209-221. https://doi.org/10.1006/jare.2002.0988

Kuuluvainen T, Juntunen P, 1998. Seedling establishment in relation to microhabitat variation in a windthrow gap in a boreal Pinus sylvestris forest. J Veg Sci 9 (4): 551-562. https://doi.org/10.2307/3237271

Kuuluvainen T, Aakala T, 2011. Natural forest dynamics in boreal Fennoscandia: a review and classification. Silva Fenn 45 (5): 823-841. https://doi.org/10.14214/sf.73

Kuuluvainen T, Ylläsjärvi I, 2011. On the natural regeneration of dry heath forests in Finnish Lapland: a review of V. T. Aaltonen (1919). J For Res 26 (S10): 34-44. https://doi.org/10.1080/02827581.2011.517951

Loarie RS, Duffy PhB, Hamilton H, Asner GP, Field ChB, Ackerly DD, 2009. The velocity of climate chase. Nature 462: 1052-1055. https://doi.org/10.1038/nature08649

Marcos JA, Marcos E, Taboada A, Tárrega R, 2007. Comparison of community structure and soil characteristics in different aged *Pinus sylvestris* plantations and a natural pine forest. For Ecol Manage 247: 35-42.

Mason WL, Edwards C, Hale SE, 2004. Survival and early seedling growth of conifers with different shade tolerance in a Sitka spruce spacing trial and relationship to understorey light climate. Silva Fenn 38 (4): 357-370. https://doi.org/10.14214/sf.404

McCarthy J, 2001. Gap dynamics of forest trees: a review with particular attention to boreal forests. Environ Rev 9 (1): 1-59. https://doi.org/10.1139/a00-012

Mikeska M, Vacek S, Prausová R, Simon J, Minx T, Podrázský V, Malík V, Kobliha J, Anděl P, Matějka K, 2008. Typologické vymezení, struktura a management přirozených borů a borových doubrav v ČR. Lesnická práce, Kostelec nad Černými lesy, Czech Republic. 450 pp.

Montes F, Canellas I, 2007. The spatial relationships between post-crop remaining trees and the establishment of saplings in *Pinus sylvestris* stands in Spain. Appl Veg Sci 10 (2): 151-160. https://doi.org/10.1111/j.1654-109X.2007.tb00513.x

Montes F, Rubio A, Barbeito I, Cañellas I, 2008. Characterization of the spatial structure of the canopy in *Pinus silvestris* L. stands in Central Spain from hemispherical photographs. For Ecol Manage 255: 580-590.

Nilsson U, Örlander G, Karlsson M, 2006. Establishing mixed forests in Sweden by combining planting and natural regeneration—Effects of shelterwoods and scarification. For Ecol Manage 237 (1): 301-311.

Oleksyn J, Reich PB, Zytkowiak R, Karolewski P, Tjoelker MG, 2002. Needle nutrients in geographically diverse *Pinus sylvestris* L. populations. Ann For Sci 59 (1): 1-18. https://doi.org/10.1051/forest:2001001

Pasanen H, Rouvinen S, Kouki J, 2016. Artificial canopy gaps in the restoration of boreal conservation areas: long-term effects on tree seedling establishment in pine-dominated forests. Eur J Forest Res 135 (4): 697-706. https://doi.org/10.1007/s10342-016-0965-8

Puettmann KJ, Wilson SMG, Baker SC, Donoso PJ, Drössler L, Amente G, Harvey BD, Knoke T, Yuanchang L, Nocentini S, Putz FE, Yoshida T, Bauhus J, 2015. Silvicultural alternatives to conventional even-aged forest management-what limits global adoption? For Ecosyst 2 (1): 8.

Puhlick JJ, Laughlin DC, Moor MM, 2012. Factors influencing ponderosa pine regeneration in the southwestern USA. For Ecol Manage 264: 10-19.

Pukkala T, Kuuluvainen T, Stenberg P, 1993. Below-Canopy distribution of photosynthetically active radiation and its relation to seedling growth in a boreal Pinus sylvestris stand: A simulation approach. Scand J Forest Res 8 (1-4): 313-325. https://doi.org/10.1080/02827589309382780

R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reynolds RT, Sánchez Meador AJ, Youtz JA, Nicolet T, Matonis MS, Jackson PL, De Lorenzo DG, Graves AD, 2013. Restoring composition and structure in southwestern frequent-fire forests: a science-based framework for improving ecosystem resiliency. United States Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA. 76 pp.

Rowlingson B, Diggle P, 2017. Splancs: Spatial and Space-Time Point Pattern Analysis. R package version 2.01-40. https://CRAN.R-project.org/package=splancs

Ruuska J, Siipilehto J, Valkonen, S, 2008. Effect of edge stands on the development of young *Pinus sylvestris* stands in southern Finland. Scand J Forest Res 23 (3): 214-226. https://doi.org/10.1080/02827580802098127

Ryyppö A, Iivonen S, Rikala R, Sutinen ML, Vapaavuori E, 1998. Responses of Scots pine seedlings to low root zone temperature in spring. Physiologia Plantarum 102 (4): 503-512. https://doi.org/10.1034/j.1399-3054.1998.1020404.x

Šálek L, Zahradník D, Marušák R, Jeřábková L, Merganič J. 2013. Forest edges in managed riparian forests in the eastern part of the Czech Republic. For Ecol Manage 305: 1-10.

Siipilethto J, 2006. Height distributions of Scots pine sapling stands affected by retained tree and edge stand competition. Silva Fenn 40 (3): 473-486.

Similä M, Junninen K (eds), 2012. Ecological restoration and management in Boreal forests: best practices from Finland. Metsähallitus, Natural Heritage Services, Vantaa, Finland. 54 pp.

Tuten MC, Sánchez Meador A, Fulé PZ, 2015. Ecological restoration and fine-scale forest structure regulation in southwestern ponderosa pine forests. For Ecol Manage 348: 57-67.

Uotila A, Kouki J, Kontkanen H, Pulkkinen P, 2002. Assessing the naturalness of boreal forests in eastern Fennoscandia. For Ecol Manage 161 (1): 257-277.

Vacek S, Vacek Z, Bílek L, Simon J, Remeš J, Hůnová I, Král J, Putalová T, Mikeska M, 2016. Structure, regeneration and growth of Scots pine (*Pinus sylvestris* L.) stands with respect to changing climate and environmental pollution. Silva Fenn 50 (4): 1564. https://doi.org/10.14214/sf.1564

Vacek S, Vacek Z, Remeš J, Bílek L, Hůnová I, Bulušek D, Putalová T, Král J, Simon J, 2017. Sensitivity of unmanaged relict pine forest in the Czech Republic to climate change and air pollution. Trees-Struct Funct 30 (5): 1599-1617. https://doi.org/10.1007/s00468-017-1572-0

Wagner S, Fischer H, Huth F, 2011. Canopy effects on vegetation caused by harvesting and regeneration treatments. Eur J Forest Res 130 (1): 17-40. https://doi.org/10.1007/s10342-010-0378-z

Wittich W, 1955. Standörtliche Bedingungen für die natürliche Verjüngung der Kiefer und für ihre Erziehung unter Schirm. Allg Forts Jagdtztg 109-177.