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THE INFLUENCE OF REGENERATION FELLINGS ON THE DEVELOPMENT OF ARTIFICIALLY REGENERATED BEECH (*FAGUS SYLVATICA* L.) PLANTATIONS

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Abstract

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This paper analyses the development of beech plantations aged 7 to 18 years that were planted in gap cuts (0.1–0.25 ha; ISF 50%), clear cuts (0.5–1.0 ha; ISF 87%) and finally underplanted areas in shelterwood cuts in mature spruce stands (G = 22–26 m^2/ha; ISF 28%). The research consisted of the following analyses: height growth, diameter growth and beech quality development. We used standard statistical tools ($p < 0.05$) for evaluating height and diameter growth, which showed significant differences in both characteristics (total height and DBH) within 7-year-old and 13-year-old plantations grown in all three regeneration treatments. The tallest beech trees with greatest DBH at the age of 7 and 13 were found in clearings whereas shortest and thinnest trees grew in shelterwoods. However, at the age of 18, there was no significant different between gap cut and clear cut in both parameters. The best quality was observed in shelterwoods.

Keywords: European beech, regeneration felling, artificial regeneration, height, DBH – the diameter at breast-height, quality, ISF – Indirect Site Factor

INTRODUCTION

The Czech Republic is a country whose tree species composition of forests has dramatically changed (Kupka, 1999). Norway spruce (*Picea abies* L.) and Scotch pine (*Pinus sylvestris* L.) monocultures have been established since 18th and 19th centuries because of rapidly increasing wood consumption as a result of their use as a source of energy. Spruce and pine monocultures met the expectations and wood production increased by at least 50% (Poleno *et al.*, 1994). The system of uniform, even-aged coniferous monocultures managed through the age class approach would be typically economically advantageous and effective if it was not sensitive to disturbances and when it does not endanger the fertility and productivity of a forest site (Tesař *et al.*, 2004). At least 6–7 million ha of pure Norway spruce stands in Europe are located outside their natural range (Teuffel *et al.*, 2004), usually on sites that are naturally dominated by broad-leaved species or by mixtures of conifer and broadleaved species (Löf *et al.*, 2007). The proportion of natural broadleaved forests has been reduced from 66% to 33% of Europe's forest area (Kenk *et al.*, 2001). The increase of the share of broad-leaved tree species in our forests is becoming one of the most crucial tasks of contemporary forest management in both the Czech Republic and abroad. It is possible to achieve this through direct spruce monoculture conversions (Tesař *et al.*, 2004). However, the necessity of forest conversion will confront managers and researchers with major ecological, silvicultural and practical challenges (Malcolm *et al.*, 2001).

The vast majority of spruce monocultures located from the third to sixth altitudinal vegetation zones

(Plíva, 1987) are in a reversible stage. Increasing proportion of broadleaved tree species such as the European beech (*Fagus sylvatica* L.) can gradually return forests to biological balance and restore their productivity (Průša, 1999).

Under spruce monoculture conversion and also because of the rule that requires the planting of "soil-improving and mechanically stable tree species" (MZD) according to Czech forest law, beech is the most commonly planted species for this purpose. Its suitability mainly lies in its native origin from this zone, especially in *Fageta piceoso-abietina* and *Fageta abietina-piceosa* acidic sites, its ecological demands and its soil-improving properties (Průša, 1999). Forest conversion from conifers to broadleaves can be achieved through planting, direct seeding or natural regeneration of broadleaves following clear-cutting or regeneration beneath conifer shelterwoods (Lüpke *et al.*, 2004).

Concerning growth dynamic and strategy Löf *et al.* (2007) described beech as a shade-tolerant species; with respect to the ability to survive at low growth rates; he labelled beech as the most shade tolerant compared to 6 other tree species (including lime and Norway spruce). Welander *et al.* (1998) and Petritan *et al.* (2007) also characterize beech as a very shade-tolerant and heavy shade-casting species; Szwagrzyk *et al.* (2001) characterize it as strongly shade-tolerant. Kobe *et al.* (1997) discovered that shade-tolerance can vary within a tree species depending on site specific conditions and factors (e.g. soil moisture). Many researchers have examined the distinction between shade-tolerant and shade-intolerant tree species on the basis of trade-offs between the ability to survive at low light levels vs. the ability to achieve a high growth rate at high light levels (Kobe *et al.*, 1997; Collet *et al.*, 2001; Kunstler *et al.*, 2005; Löf *et al.*, 2007, etc.).

Many researchers have found that the optimal light condition for growth is directly related to large gaps that are occupied by particular species in virgin forests. For example, Zeibig *et al.* (2005) investigated the disturbance pattern of a European beech virgin forest in the Slovenian Dinaric Alps where the gap size varied from 6 to 833 m^2, with a mean value of 137 m^2 and where 90% of them were smaller than 300 m^2. Underplanting, especially with shade-tolerant European beech, has become common practice in Central Europe (Lüpke *et al.*, 2004). Little research has been done in support of planting under shelterwoods as a silvicultural tool, especially where tree species other than beech are concerned (Löf *et al.*, 2007).

The object of this paper is to evaluate the differences within height, thickness and quality development between three types of regeneration fellings (shelterwood cuts, gap cuts, clear cuts) that are commonly used for artificial regeneration of beech within spruce stand conversion.

MATERIAL AND METHODS

Study Area

The observations took place in the central part of the Czech Republic in the Czech – Moravian Highlands, especially in the Žďár nad Sázavou district in altitudes 600–800 m above sea level on acid cambisols. The research was conducted on a group of 5A3 *Fageta piceoso-abietina* geobiocenose types (less often 6A3 *Fageta abietina-piceosa*) (Plíva, 1987), which was inspired by the large proportion of these sites within secondary spruce monocultures (Průša, 1999).

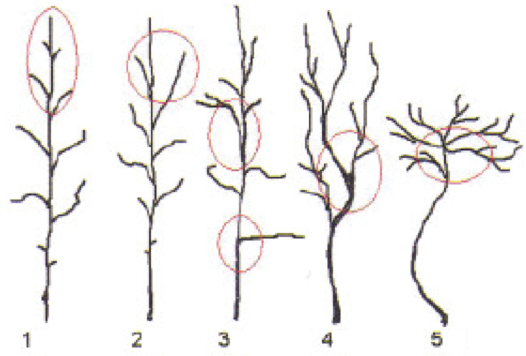
Acidic ecological series exist in the fifth altitudinal vegetation zone (5. LVS) as the second most frequent (37% of area) and these conditions are the most common (45% of area) in the sixth altitudinal vegetation zone (6. LVS). Acidic ecological series of the fifth and the sixth altitudinal vegetation zones occupy nearly 16% of our country's forested land (Zpráva, 2010). Groups of 5A3 and 6A3 geobiocenose types are typically representative in HS 53 ("management set of stands" 53), which is the second most represented management set in the Czech Republic. Spruce occupies 75% of the area of this management set of stands (Souček, Tesař, 2008).

Research Plot Design

We modified the scale of different regeneration cut areas from Coates (2000) using findings of the most common forest management practice in the Czech Republic described by Mauer, Truhlář (2005) and Pernegr (2008). It identifies a suitable scale of regeneration fellings and age classes of beech plantations for us to observe. Our scale distinguishes between regeneration cuts with an open area of 0.1–0.25 ha, which is representative of gap-cutting systems, and clearings with an open area from 0.5 to 1.0 ha, which is representative of clear-cutting systems. Finally, the last category consists of shelterwood cuts with beeches that were underplanted beneath the canopy of mature spruce stand overstorey with a basic area ranging from ca. 22–26 m^2/ha, which is representative silvicultural treatment of shelterwood systems. Three age classes of young beech plantations were chosen: those aged 7, 13 and 18 years. All research plots were comparable with respect to their establishment because all of them were planted by 10,000 bare-rooted plants of beech per hectare.

Methodology

Basic biometrical features were measured and the morphological quality within the studied beech plantations evaluated. The total height was measured by a telescopic rod with accuracy to centimetres and stem diameter at the breast-height (DBH) was measured with a calliper with accuracy to millimetres and average DBH was calculated using two mutually perpendicular



1: *An evaluation of beech individual quality and their classification on a scale of 5 quality classes according to the morphological parameters of the above-ground part of plant. The ovals show diagnostic defects that classify an individual into relevant class. The scale originated from Leonhardt, Wagner (2006) and was adapted by the authors.*

measurements. In order to calculate the average height increment, the initial height of planted bare-rooted plants was assumed to be 30 cm. The morphological quality was evaluated using a widely-used classification system that was first mentioned in a study by Gockel (1994). Only a small modification was made when the fifth (deeply branched and spreading individuals from above the flattened crown) and the sixth (deeply branched spreading individuals with an elliptic crown) were united. Therefore, the final five classes classification scale (Fig. 1) is identical with the scale used by Leonhardt, Wagner (2006) and Bartoš, Souček (2010).

All three attributes (total height, DBH, morphological quality) were observed in the same individuals. The individuals were chosen in each of the plots using two diagonal transects. Within each of plots, from 52 to 87 individuals were measured. For each category defined by the age (7, 13, 18 years) and silvicultural system (gap-cutting, clear-cutting, shelterwood-cutting) two plots characterised by normal development (without huge effects like serious mortality after planting or damages) were identified. There were so covered eighteen plots together to the measurement.

We used an indirect method for measuring light – the fish-eye technique. We used hemispherical photos analysis to gain Indirect Site Factor (ISF; expressed as the percentage of above canopy light) as a characteristic of the light input into plots and after that we compared the light environment within the plots to each other. In the issue of the fish-eye technique accuracy as an indirect method of light measurement there are enough papers comparing this method with direct methods of light measurement, including Rich *et al.* (1993), Čater *et al.* (2013), etc. We took hemispherical images in upper layers of particular beech plantation during overcast sky conditions using a self-levelling platform. The hemispherical photo evaluation was performed using WinSCANOPY (Pro 2012a) software. The zenith angle for the analysis process was appointed at 120° as the most exact and suitable value recommended by Bequet (2011) and Čater *et al.* (2013). The ascertained values of ISF added by the data pertaining to the basic area within shelterwood cuts and total area of fellings without overstorey in case of gap cuts and clear cuts are shown in Tab. I. We found out the light environment of gap cuts and shelterwood cuts as approximately one third and one half of light environment of clear cuts respectively.

We used of Statistica 8.0 (Statsoft, Inc., Tusla, Oklahoma, 2007) software tools for performing statistical tests and analyses. Firstly, descriptive statistics were calculated. After that the null hypothesis that data were normally distributed was tested by normal probability plot (Shapiro-Wilk test). The data did not show normal distribution so non-parametrical Kruskal-Wallis test was afterwards used to find existence of significant differentness.

I: *The basic characteristics of regeneration fellings and of indirect site factor (ISF) values*

Type of regeneration felling	Area of felling (ha)	Basic area (G; m²/ha)	ISF (%) range	ISF (%) average/median
clear cut	0.5–1	-	53–100	87/94
gap cut	0.1–0.25	-	34–63	50/52
shelterwood cut	-	22–26	19–37	28/28

II: *The values of total height and average annual height increment within all regeneration cuts and age categories*

Type of regeneration felling	Total height (cm) Mean value			Annual height increment[1)] (cm/year);Mean value			Annual height increment within period[2)] (cm/year)	
	7 years	13 years	18 years	7 years	13 years	18 years	7–13 years	13–18 years
clear cut	290 ± 57	572 ± 65	775 ± 117	37 ± 8.1	41 ± 5.0	41 ± 6.5	47	41
gap cut	251 ± 70	384 ± 128	693 ± 121	32 ± 10.5	27 ± 9.8	36 ± 6.7	22	62
shelterwood cut	207 ± 61	299 ± 63	511 ± 98	25 ± 8.7	21 ± 4.8	27 ± 5.4	15	42

1) The average height increment within each of the periods – 0–7, 0–13 and 0–18 years – was calculated using the initial height of planted bare-rooted seedling that were 30 cm tall

2) The value was calculated from the total height mean values of particular age categories of felling

Dunn test was finally used how to determinate particular significant differences.

RESULTS AND DISCUSSION

Height growth

Significant differences in height growth ($p < 0.05$) were found within 7 and 13-year-old plantations in all regeneration treatments (one another), and within 18-year-old beeches we found significant differences in height growth ($p < 0.05$) between shelterwood cuts and gap cuts and also between shelterwood cuts and clear cuts (Tab. III).

The tallest beeches were grown in clearings, followed by individuals in gap cuts (Tab. II). However, at the age of 18, there was no significant difference in the total height between gap cuts and clearings (Tab. III). The shortest were underplanted beeches in shelterwood cuts, significantly. This trend was constant in all examined age categories. However, even though the greatest increment in trees aged 7–13 years was observed in clear cuts (47 cm/year), the increment in shelterwood cuts and gap cuts rose more rapidly between the 13th–18th years of age (42 and 62 cm/year, respectively) compared to clearings. The height increase of clearings (41 cm/year) decreased slightly in this period (see part *Annual height increment within each period* in Tab. II). So, the average annual height increment within period 13–18 years was the highest in the gaps, whereas underplanted beeches showed slightly greater annual increment compared to individuals grown in clearings. However, average annual height increment up to 7, 13 and 18 years (the initial height of planted bare-rooted seedling was calculated as 30 cm) is the highest in clearings in all of three age categories (see part *Annual height increment* in Tab. II).

The influence of light environment (expressed by ISF value) to beech height growth is clear. The shape of simple polynomical model curves (made from the mean values) are mostly concave (the 13-years-old model apart) with a positive relationship between total height and ISF value up to approximately 60% ISF (Fig. 2). Also with Petritan *et al.* (2007), total height (and average height increment) increased only slightly above 60% ISF; the curve of the function moves only 0.082° towards axis *x* (Petritan *et al.*, 2007). Similar models of total height in proportion to ISF were proven by Pacala *et al.* (1994). He examined shade-tolerant tree species and observed similar shapes of the model curve as seen in our findings (Fig. 2). It was especially true in our study for the total height dependence on ISF by beeches aged 18 years, as well as for the common model regardless of age (Fig. 2). However, our research included only development above 17.1% ISF so, about findings of Petritan *et al.* (2009) our research was put above the inflection point.

Löf *et al.* (2007) found the total height ranging from 68 to 130 cm at the age of 3, sequentially increasing with higher light intensity (from dense shelterwood cuts to gap cuts). With an assumed initial height of 30 cm when the plantation was established, the average height increment within the observed period was approximately 13–33 cm/year (we identified an average increment of 25, 32 and 37 cm/year during the first 7 years). He found significantly taller individuals in the dense (G = 26 m^2/ha; ISF 14%), sparse (G = 16 m^2/ha; ISF 38%) and gap (G = 0 m^2/ha; ISF 90%) treatments than in the control plots (G = 35 m^2/ha; ISF 6%). He observed a positive relationship between total

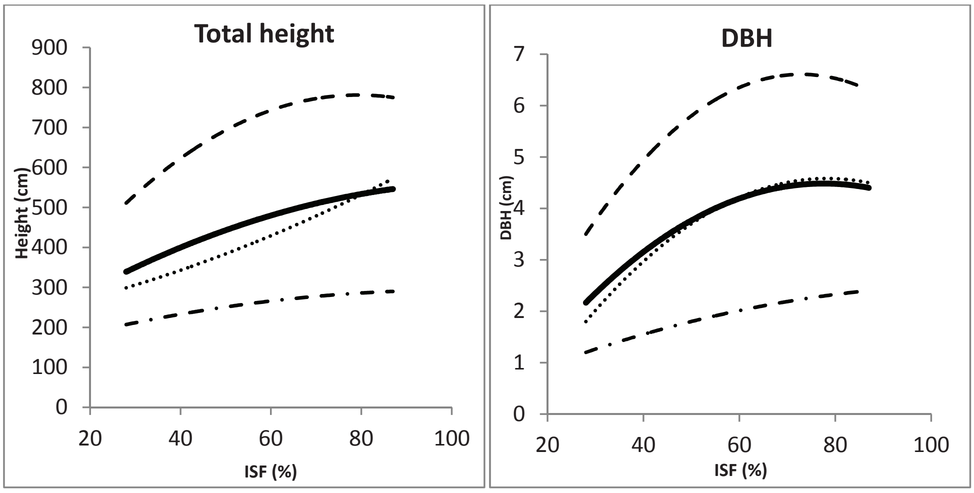
III: *Total height and DBH test criterions from non-parametrical statistical analyses*

	Total height – Test criterion DBH – Test criterion								
	7 years			13 years			18 years		
Type of regeneration felling	**clearings**	**gaps**	**shelter-woods**	**clearings**	**gaps**	**shelter-woods**	**clearings**	**gaps**	**shelter-woods**
clearings		0.001224 0.000132	0.000022 0.000000		0.000000 0.005942	0.000000 0.000000		0.072267 1.000000	0.000000 0.000000
gaps	0.001224 0.000132		0.000040 0.000318	0.000000 0.005942		0.000101 0.000000	0.072267 1.000000		0.000000 0.000000
shelterwoods	0.000022 0.000000	0.000040 0.000318		0.000000 0.000000	0.000101 0.000000		0.000000 0.000000	0.000000 0.000000	

IV: *Total DBH and average stem diameter increment within all regeneration cuts and age categories*

Type of regeneration felling	DBH (cm) Mean value			Annual increment of DBH within period[1)] (mm/year)	
	7 years	13 years	18 years	7–13 years	13–18 years
clear cut	2.4 ± 0.77	4.5 ± 1.11	6.3 ± 1.95	3.5	3.6
gap cut	1.8 ± 0.84	3.7 ± 1.94	5.8 ± 1.54	3.2	4.2
shelterwood cut	1.2 ± 0.58	1.8 ± 0.64	3.5 ± 1.12	1.0	3.4

1) The value was calculated from the total height mean values of particular age categories of felling



2: Total height and DBH dependence on indirect site factors (ISF) using the polynomical intersperse. Models were creating just from the mean values. The dashed line represents 18-year-old plantations; the dotted line represents 13-year-old plantations; the dot-dash line represents 7-year-old plantations; the bold line represents the general model calculated from average values of all three previous models, so regardless of age. The equations for total height are: $y = -0.016x^2 + 3.2506x + 128.55$ *(7-years-old model);* $y = 0.0206x^2 + 2.2541x + 219.71$ *(13-years-old model);* $y = -0.1027x^2 + 16.28x + 135.65$ *(18-years-old model);* $y = -0.0329x^2 + 7.2966x + 160.52$ *(general model). The equations for DBH are:* $y = -0.0002x^2 + 0.0419x + 0.0174$ *(7-years-old model);* $y = -0.0011x^2 + 0.172x - 2.1544$ *(13-years-old model);* $y = -0.0015x^2 + 0.2249x - 1.5874$ *(18-years-old model);* $y = -0.0009x^2 + 0.1462x - 1.1893$ *(general model).*

height and continually increasing light from control plots to sparse shelterwood cuts. However, this trend did not continue into the gap cuts, where the total height was similar to sparse shelterwood cuts (Löf *et al.*, 2007). Ammer *et al.* (2007) found an average total height 183 and 175 cm under 7 and 15% ISF respectively (with the greater value corresponding to the lower light benefit), which is a little less than our values of 207 cm for the same aged beeches grown under a light intensity of 19–37% ISF. He identified an average annual height increment of 21 and 20 cm/year compared to our 25 cm/year. Szwagrzyk *et al.* (2001) and Collet *et al.* (2001) both found a very short average height increment of beech seedlings (0.5 and 1.2 cm/year) under 4% and 5% ISF respectively.

Kunstler *et al.*, 2004 and Petritan *et al.*, (2007 and 2009) stated that ISF 30–40% was the optimal value for height growth. Petritan *et al.* (2007) compared beech to maple (*Acer pseudoplatanus* L.) and ash (*Fraxinus excelsior* L.), where beech showed the significantly lowest height increment dependent on increasing light. However, beech proved to have the lowest mortality under low light intensities. This was also confirmed by Kunstler *et al.* (2005), who compared beech and downy oak (*Quercus pubescens* Willd.).

Petritan *et al.* (2007) found an average increment of beech (0.4–8 m height) under 20% ISF 40 cm/year (we observed 27 cm/year within whole period to 18 years growing under 28% ISF) and under 50% ISF 51 cm/year (in the same conditions we found 36 cm/year as an average over 18 years); Jakobsen *et al.* (2000) presented an average total height of 90–110 cm for 5-year-old beech plantations under 18–28% ISF (equating to an average annual increment of 12–16 cm/year compared to our observed 25 cm/year for seven-year-old beeches under 19–37% ISF); by contrast, Collet *et al.* (2001) observed a greater annual height increment of 42 and 38 cm/year respectively under light intensities of 28 and 33% ISF. Linnert (2009) published an annual increment of 48 cm/year under a light intensity of 50–60% ISF (for individuals 182–555 cm tall). Rumpf, Petersen (2008) found for 16-year-old beeches grown under 72, 56 and 46% ISF total height 615, 646 and 628 cm (ranking from the highest ISF to the lowest). This equates to an average annual increment of 36, 39 and 37 cm/year. These values are almost the same as in our gaps in which we found an average increment of 36 cm/year within 18-year-old plantations grown under 50% ISF.

Stem Diameter Growth

Significant differences ($p < 0.05$) were found in the same cases as with height growth analyses (Tab. III). Hence, significant differences exist in age categories 7 and 13 years within all three regeneration treatments (one another). There are also significant differences between shelterwood cuts and gap cuts and also between shelterwood cuts and clear cuts in the 18-year-old beeches (Tab. III).

The greatest DBH were found in beeches grown in clearings, followed by individuals from gaps (Tab. IV). However, at the age of 18, there was no significant difference in the total height between clearings and gap cuts (Tab. III). Significantly lowest DBH was found in shelterwood cuts within all of three age categories. At the age of 7 and more manifestly at the age of 13, DBH of underplanted beeches lagged behind two other regeneration fellings (DBH was 1.2 and 1.8 cm respectively and the average annual increment of DBH within period from 7 to 13 years was only 1.0 mm/year compared to 3.2 and 3.5 mm/year in gaps and clearings). However, beeches grown in shelterwood cuts increased fairly progressively in the 13–18 years period (3.4 mm/year compared to 4.2 and 3.6 mm/year in gaps and clearings respectively). So, the distinct thickness growth of underplanted beeches initiated later compared to another two regeneration fellings (see part *Annual increment of DBH within period* in table IV).

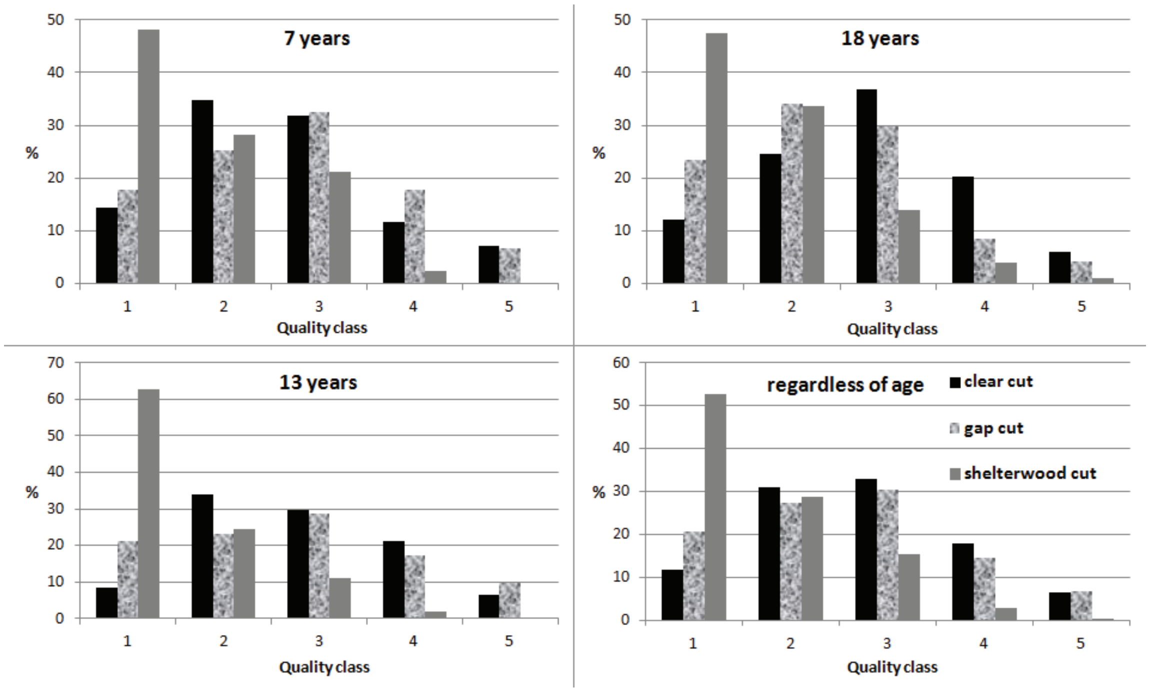
The influence of light input within observed types of regeneration fellings to thickness growth of beeches is manifest even more then in case of the height growth. The shape of simple polynomical model curves (made from the mean values) are fairly steep up to approximately 60–70% (it is more evident in 13-years-old, 18-years-old and general model) and after that the increase is gentle (Fig. 2). The increase of DBH corresponding to higher ISF is not so strong with 7-year-old beeches. Petritan *et al.* (2009) also discovered that the shape of the curve from 60% ISF showed only a gentle inclination (0.0007°) towards axis *x*.

Rumpf, Petersen (2008) proved the correlation between increasing DBH and greater ISF with 16-year-old beeches that were underplanted and grown under 72, 58 and 46% ISF. They observed an average DBH of 4.0, 3.9 and 3.7 cm (ordered from highest ISF to lowest). By comparison, we found an average DBH of 5.8 cm in gaps under 50% ISF within plantations aged 18 years. Petritan *et al.* (2009) observed an average annual increment of nearly 2.5 mm/year under 33% ISF (for individuals 1–8 m tall) against our average annual increment of 1.0 mm/year (within 7–13 years) and 3.4 mm/year (within 13–18 years), both under a light intensity of 28% ISF. Löf *et al.* (2007) and Pichler *et al.* (2001) both found a significant influence of light to thickness increment. Also Ammer *et al.* (2007) examined beech plantations (7-year-old) grown under 7 and 15% ISF and he found the average annual increment 2.0 and 2.4 mm/year respectively (measured 3 cm above ground). We observed an annual increment of 1.0 mm/year measured in DBH under 28% ISF for the 7–13 years group. Collet *et al.* (2000) identified an annual increment of only 0.21 mm/year and 0.49 mm/year respectively for naturally regenerated beeches aged 5–15 years and grown under 5–15% ISF in a gap under 27–52% ISF. These values are substantially lower than our findings of 1.0 and 3.2 mm/year respectively in our plantations aged 7–13 years. By contrast, Linnert (2009) did not find any significant influence of light on DBH. However, Curt *et al.* (2005) found essentially the same results as we and many above-cited researchers proved a significant influence of light to diameter increment.

Quality Development

There was evident the highest quality of underplanted beech individuals grown in shelterwood cuts. Nearly 82% of beeches from shelterwoods (regardless the age) were classified as quality class 1 or 2, compared to 48 and 43% within gap cuts and clearings respectively (Fig. 3). At the age of 7 and 13, the quality of beeches in gaps and clearings was fairly similar, when quality classes 1 and 2 represented 43 and 49% within 7 years-old beeches and 44 and 43% at the age of 13 in gap cuts and clearings respectively. In addition, the worst quality classes 4 and 5 represented 24 and 19% within 7 years-old beeches and 27 and 28% within 13-years-old beeches in gap cuts and clear cuts respectively. However, at the age of 18, the morphological quality of beeches grown in clear cuts slightly fell behind beeches in gaps and, of course, greatly fell behind underplanted beeches. This was mainly because of the low proportion of high-quality individuals showing upright growth and preserving apical dominance of the leader with beeches aged 18 and grown in clearings (12% of quality cl. 1 and 25% of class 2 compared to gap cuts with 23% and 34% respectively) on the one hand. On the other hand, it is evident that there was high percentage of individuals showing fork branching without apical dominance and without the only main leader (quality cl. 3–accounting for 37% of individuals) or beeches strongly un-formable and spreading (combined, 27% of quality cl. 4 and 5) in clearings at the age of 18 (compared to 10% in gap cuts). From Fig. 3, it is strongly apparent that there was a qualitative dominance of beeches grown in shelterwood cuts compared to both other regeneration feelings. The graph shows that regardless of beech age (Fig. 3), it is possible to see only 3 % inferior individuals (quality cl. 4 and 5) and 18% fork-branched and un-formable beeches (quality cl. 3, 4 and 5 combined).

Our finding of gradually decreasing quality with increasing light corresponds with observations by Ammer *et al.* (2007), who examined changes of the ratio of branch biomass indexed by stem biomass (BSR – branch-shoot-ratio). That is because with a higher increment of branch biomass, a risk of un-formable and undesirable branching may form. Ammer *et al.* (2007) also found a huge different between sown and planted individuals (within all examined age ranges), so BSR was influenced by intraspecific competition (competition for the space). If a different BSR can be created by the competition of neighbouring individuals for space (meaning a competition for light) it might also be possible to influence BSR with a lower light intensity caused by the light conditions of a particular felling. This hypothesis was proved by Leonhardt, Wagner (2006), who found that a plantation's lower density due to a smaller number of planted individuals within a specific area can be substituted by a more closed canopy of overstorey



3: *The percentage of quality classes (the qualitative parameters of each quality class are shown in figure 1) of beech individuals aged 7, 13 and 18 years and regardless of age growing under different conditions of three observed types of regeneration felling*

(which means a lower ISF). The lower light benefit (created either by intraspecific competition in dense plantations or by closed canopy of mature stand overstorey) positively influenced the quality of beeches and both factors can more or less stand for the other one.

Kint *et al.* (2010) proved that branch diameter and branch length are the most important factors for the self-pruning process. Long and thick branches are eliminated by self-pruning less that short and thin. He also found that with increasing ISF, beech individuals have more branches (less self-pruning) and the branches have greater dimensions. Kint *et al.* (2010) also observed that individuals in competition (overtopped trees) are thin and slender and have fewer branches. The competition induces a decrease of resources available for entire tree, resulting in a lower net primary production and allocation shifts towards the tree top where light foraging is likely more favourable (Kint *et al.*, 2010). Thus, these individuals (whose growth under competition results in thinner branches) are characterized by a greater ability to self-pruning. This set of findings agrees with our observations that underplanted beeches (in fact overtopped individuals under competition) show significantly lower values of total height and DBH during all examined period, but they also have the best quality.

Curt *et al.* (2005) observed a significant influence of ISF on net primary production (on a tree's annual increment and annual increment of branches), so it is possible to state in harmony with the findings of Kint *et al.* (2010). Petritan *et al.* (2009) found there to be a significant influence of increasing ISF to increasing crown length and diameter length. Her findings confirmed Bartelink (1997). The described morphological development agrees with our findings of overall decreasing beech quality with increasing light benefit

Reiniger (2000) observed the share of fork-branched individuals in clear cuts (without a description of its area or light intensity) at 59%. We found 57% fork-branched and un-formable beeches (quality cl. 3, 4 and 5 combined) in clearings regardless of their age (51, 57 and 63% in 7, 13 and 18-year-old trees, respectively).

CONCLUSIONS

Based on the comparison of young beech plantations grown in the same site under different silvicultural treatments creating different light conditions, it is possible to formulate the following conclusions:

- DBH and total height of beeches increased with the light benefit in the following order of regeneration fellings: shelterwood cut – gap cut – clear cut. At the ages of 7 and 13, these differences were significant throughout all of the treatments. At the age of 18, the order is the same, however there is no significant difference between clear cut and gap cut. DBH and total height are closely positively related to ISF up to approximately 60% ISF.
- The best quality was seen in beeches grown in the shelterwood cuts. Regardless of the age categories, 82% of the individuals were classified

as high-quality (labelled by a quality class of 1 or 2) there. The lowest quality was observed in clear cuts, however the quality in gap cuts was similar to clearings at age of 7 and 13.

SUMMARY

The topic of artificial regeneration of European beech is important because there is a need to convert the tree species composition of secondary conifer forests that cover more than 6 million hectares in Europe. We examined the growth dynamic and quality development of young artificially regenerated beech plantations grown within different regeneration fellings and under different light conditions. We measured the light conditions via the fish-eye technique using a self-levelling platform to take hemispherical images in the upper layer of plantations. We used the ISF value to characterize light conditions. The objective of our research was to compare the development of planted beech plantations (aged 7–18 years) from the quantitative and qualitative points of view. The research was focused on the main types of regeneration fellings: gap cuts (0.1–0.25 ha; ISF 50%), clear cuts (0.5–1.0 ha; ISF 87%) and shelterwood cuts in mature Norway spruce stands (G = 22–26 m^2/ha; ISF 28%). The investigation of individual beeches consisted of the following analyses: height growth, diameter growth and beech quality development. Suitable plots were found in altitudes 600–800 m above sea level on acid cambisols. We discovered significant differences ($p < 0.05$) in both quantitative parameters between all three regeneration treatments in 7-year-old and also 13-year-old plantations. The tallest height and maximum DBH significantly showed beeches planted in clearings, followed by beeches grown in gaps and finally underplanted beeches. At the age of 18 there was observed significant different between shelterwood cut vs. gap cut and shelterwood cut vs. clear cut, as well, in both of quantitative parameters. However, downward order from clearings over gap cuts to shelterwood cuts in terms of their average height and DBH was preserved despite non-significant difference between clearings and gaps. The best quality showed beeches grown within shelterwood cuts. Their best quality was evidently presented through all observed period (7–18 years). Gaps and clearings were qualitatively similar at the age of 7 and 13, however at the age of 18 the quality in gaps is better compared to clearings.

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