Natural regeneration of sessile oak under different light conditions

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Abstract: Different variants of regeneration felling or different light conditions (total site factor 15–95%) and weed control were evaluated in relation to the 4-year development of individuals of regenerated sessile oak. The regeneration density is not dependent on light conditions. The highest mortality occurs on the open area of clear felling. For a certain time in youth, it is possible to consider oak as a shade-tolerating species. With the increasing light intensity the diameter and height growth of oak seedlings increases proportionally, being the highest at 100% light intensity. However, to support at least medium-fast growth, the species requires minimally 50% light intensity (smaller closed clear-felled areas). On the other hand, more extensive unprotected cleared areas appear to be quite unsuitable at the initial stages of regeneration. The positive effect of weed control on the success and growth of natural regeneration is questionable. We recommend developing the regenerated stand by means of a series of small-area (about ≤ 0.3 ha) two-stage felling with a medium-long regeneration period (15–20 years).

Keywords: sessile oak; natural regeneration; light conditions; close-to-nature forest management

At lower locations of the Czech Republic, oak is one of the most important commercial species. The natural proportion of oak within the CR is estimated to be about 19%, the present proportion ranges about 7%. A long-term silvicultural target is to maintain this proportion or to increase it slightly. In the CR, methods of artificial regeneration have been well managed from the aspect of both research and practice. However, principles of close-to-nature forestry force foresters more and more to change thinking and standard stereotypes. The basic building element of this conception and frequently also its pitfall is natural regeneration or the shelterwood system of management. It is interesting for forest practice if and under what conditions it is possible to take into account natural regeneration of oak.

Natural regeneration of oak is of considerable importance. At proper regulation, it provides the best biological results not requiring high costs (Vyskot 1958). Compared with pedunculate oak preferring higher locations and drier soils sessile oak is considered to be a semi-sciophyte in youth, at higher age a heliophilous species (e.g. Roloff 2001; Röhrig, Bartsch 2006 etc.). According to Peřina et al. (1964), oak advance growth is very sensitive to late frosts. If it is suddenly released, it suffers from sunstroke. In youth, it tolerates shading by a parent stand, which is very important from the aspect of its protection. According to Röhrig, Bartsch (2006), oak is able to survive at 15% relative radiation of an open area for several years. For sustainable growth, it needs at least 20%. Under these conditions, however, height increment

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and particularly diameter increment are reduced to a half as well as metabolism and the development of roots. Lüpke (1998) found natural regeneration already at values of relative radiation exceeding 10% (broken canopy), but certainly at values over 15–20% (gaps in canopy of a diameter of 17–25 m, about 0.05 ha). Height increment increased roughly up to 40% relative radiation being then constant. For the successful growth of oak, 30–60% relative radiation is necessary (open canopy, gaps up to 0.2 ha). Diaci et al. (2008) recommended the size of gaps to be 0.03–0.05 ha (diffusion radiation 8–18%) for the successful regeneration of pedunculate oak. Within particular gaps, they found the most suitable conditions for the oak advance growth to be in their centre and northern part. They recommended the creation of elliptic gaps with a longer northern part. After the first 4 years of the life of oak seedlings, the authors recommended to extend gaps to about 0.1 ha because of the quality development of regenerated individuals.

According to Košulič (2010), shaded oak trees show very good shape and fine branching. Weinreich (2000) found out that gaps with relative radiation exceeding 32% did not have any negative effects on the quality development of seedlings. Diaci et al. (2008) did not find any relationships between the quality of seedlings and light intensity. However, particular older oak trees growing in small gaps showed unfavourable slenderness ratio (h/d ratio) and grew outside the stem vertical axis. Relationships between the growth of oak and light intensity were summarized by Reif and Gärtner (2007) as follows: the height growth of oak is higher under conditions of stand shade than on the open area; in the first years, maximum height growth of the seedlings is achieved at the relative light intensity 20–40% or 25–50% in the second year of life. Light reduction results in higher height increment, larger leaf area and the higher content of chlorophyll, however, it also results in the insufficient development of a root system, lower metabolism, lower assimilatory capacity and generally lower growth performance.

However, the majority of the authors do not consider light to be a primary factor limiting the vitality of oak regeneration. Shütz (1991) (in Weinreich 2000) recommended the minimum area for oak regeneration from 0.25 to 0.3 ha because of snow damage and distortion. Similarly, Röhrig and Bartsch (2006) recommended rich light intensity to prevent stem distortion and forking the leading shoot. The appearance of forest weed, unlike other species, does not threaten young oaks. All authors consider competition with other species, e.g. shade trees (hornbeam, beech, lime), to be one of the main limiting factors of the natural regeneration of oak. Therefore, Röhrig and Bartsch (2006) recommended increasing particularly light intensity. Thus, oak can take growth advantages before these species. The failure of natural regeneration of oak can be then attributed particularly to browsing damage, insect (*Tortrix viridana*) damage, predation (birds, rodents), fungal attack and diseases (*Microsphaera alphitoides*), massive occurrence of forest weeds, late frosts (Reif, Gärtner 2007).

In silvicultural considerations, it is necessary to start from a fact that sessile oak as a semi-sciophilous species is able to grow under various ecological conditions. In initial stages of natural regeneration, the oak regeneration requires protection provided through its parent stand, in next stages its demand on light increases. On the basis of these findings, it is possible to recommend using shelterwood felling. Thus, the area and time intensity of accretion cutting will be a controversial issue. Bergmann (2001) recommended both large-area and small-area (suitable particularly in larger tracts of oak stand where there is an interest in achieving various age structures) shelterwood felling. Röhrig et al. (2006) and similarly also Matić et al. (1999) (pedunculate oak) recommended to use rather large-area shelterwood felling with a short regeneration period. Lüpke (2008) also came to similar conclusions when he recommended clear felling with the use of seed trees based on the comparison of three variants of the regeneration of a mixed oak-beech stand (1st irregular shelterwood – 3 gaps of a diameter of 23 m, mean value of relative radiation 26%; 2nd group shelterwood – 2 gaps of a diameter of 30 m, relative radiation 35%; 3rd clear felling with reserved trees – clearcut with few remnants, relative radiation 70%), to carry out quickly clear felling leaving reserved trees. On the other hand, Diaci et al. (2008) emphasized ecological disadvantages of large-area shelterwood felling recommending rather small-area procedures. Zakopal (1969) (in Košulič 2010) reported the failure of natural regeneration at large-area shelterwood felling when weed infestation occurred due to ash. Even clearcut gaps were not suitable. Shelterwood gaps of an area of 0.015 ha appeared to be successful. Košulič (2010) regarded 0.01 ha shelterwood gaps as optimal for the regeneration of oak. According to Lüpke (2008), small-area close-to-nature management weakens competitive advantages of oak as against other tree species.

However, it is not quite proved by supporters of the often discussed conception of "natural oak

Table 1. Forest inventory (2003–2012) of examined stands

Stand	Area (ha)	Age (year)	Density (%)	Stock ($m^3 \cdot ha^{-1}$)	Composition (%)	RP
55B13b	4.1	126	90	312	oak 87, Douglas fir 5, pine 3, beech 3, larch 2	I
56B12a	15.5	119	90	368	oak 70, larch 18, spruce 4, pine 3, beech 3, Silver fir 2	II
21C13	0.8	130	50	179	oak 58, pine 33, larch 5, spruce 2, beech 2	III

regeneration with permanent canopy cover" (e.g. Lüpke 1998; Weinreich 2000; Diaci et al. 2008).

The aim of our paper is to compare the effects of different variants of regeneration felling on the successfulness and growth response of sessile oak regeneration at nutrient-rich sites of medium-altitude locations.

MATERIAL AND METHODS

In the area of the Training Forest Enterprise in Křtiny, Masaryk Forest, Mendel University in Brno (Vranov Forest District), three stands were selected (Table 1) in a regeneration stage with dominant sessile oak. The stands are situated at medium-altitude locations (altitude about 440 m a.s.l.) on slightly steep land at nutrient-rich sites – 2H, 3B (site type units of the Czech typological system).

In all cases, the parent rock consists of granodiorite to granite, the soil type is Luvic Cambisol. *Fagi-Querceta typica* are potential vegetation (maps of the Czech typological system). *Galium odoratum, Poa nemoralis, Melica nutans, Luzula luzuloides* and *Festuca altissima* dominate in the herb layer in the actual stand type.

In each of the stands, 1 research polygon (RP) was established in such a way that it would represent the variability of stand conditions. The actual natural regeneration of oak comes from the 2002 seed year. In 2003, 5 variants of regeneration were carried out within RP I, II (about 1.5 ha) – (a) no felling, (b) small-area shelterwood felling of various intensity (initial and seed stage), (c) cutting face (about 0.2–0.3 ha) – at one stand height with the lateral shading of a parent stand from two sides at least, (d) cutting face (about 0.5 ha) as the outer edge of border cutting (shading of a parent stand from one side) at 1.5 stand height, RP III (0.8 ha), (e) clear felling (0.8 ha). To evaluate light conditions, hemispherical photos were taken within RP I, II in a 10 × 10 m grid (Nikon Coolpix 4500 + Fish-Eye FC-E8). For the purpose of comparison (RP I vs RP II), weed control was carried out at RP I each year. The 3% concentration of Roundup Classic was applied with a knapsack sprayer onto the whole surface before budding once a year.

Monitoring of the natural regeneration of sessile oak was carried out from 2007 to 2010. Across RP, five transects were laid out to characterize various degrees of shading. Transects consisted of the series of plots 2 × 2 m in size (in total 476 plots). On each plot, the following parameters of oak regeneration were determined each year: density – N or mortality – M (as of 2010 compared to 2007), height – h in 2007, height increment – h_i (separately Lammas shoot and spring increment) and diameter at the root collar – d.r.c. in 3 successive years.

To evaluate relationships between variants of regeneration or light conditions and parameters of oak natural regeneration it was necessary to derive degrees of light intensity. Hemispherical photos were analysed using the WinsCanopy programme. For the purpose of this paper parameters of relative total radiation were used, namely total site factor – TSF and canopy openness. Based on the relationship of both variables (Fig. 1), 4 degrees of significantly different light intensity (Table 2) were

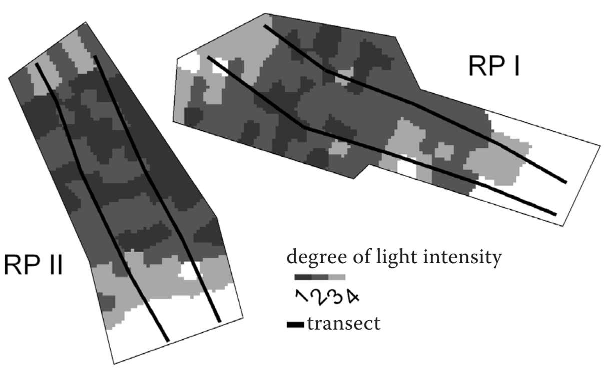

Fig. 2. A map of degrees of light intensity (RP I, II) and canopy openness

derived for RP I and II when about a 20% increase in TSF meant a 10% increase of canopy openness. In the open area (RP III), the TSF value of 100% was supposed (degree 5).

In the ArcMap 10 application, a virtual light map has been created where degrees of light intensity for RP I, II and the position of transects are displayed (Fig. 2). The spatial division of degrees of light intensity corresponds to the distribution of regeneration variants: (1) = full or slightly broken canopy, (2) = broken canopy (with small gaps), (3) and (4) = clear-felling element with various light conditions. Effects of factors – light intensity (at all RP) and chemical control (only at RP I, II) were tested using non-parametric ANOVA.

RESULTS

Development of oak regeneration density (mortality)

The total mean density of oak seedlings, which was about 80 thousand/ha (min 5–max 682.5 thousand), decreased in the course of the 4-year development to a half, i.e. 40 thousand individuals per ha (min 0–max 275 thousand) as follows: in 2008 the decline was by 20 thousand and every other year by 10 thousand. Effects of the degree of light intensity are not quite significant in that case. The significantly lowest number of seedlings at the beginning and at the end of the monitored period was found

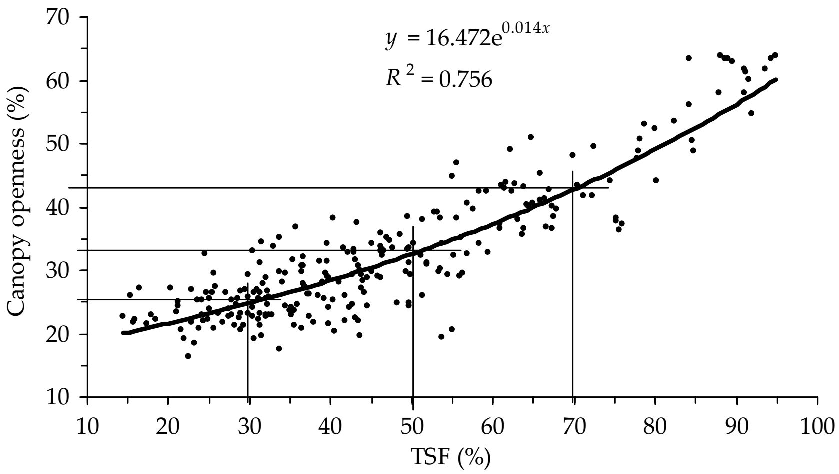

Fig. 1. Degrees of light intensity according to TSF

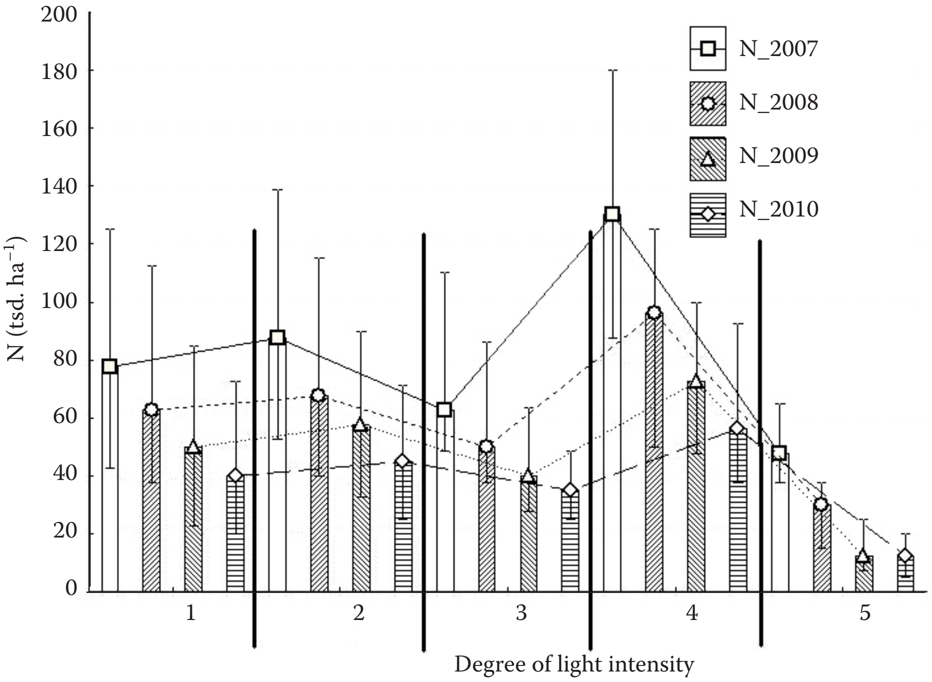

Fig. 3. The development of regeneration density (N) at particular degrees of light intensity

Table 2. Characteristics of particular degrees of light intensity

	Degree of light intensity (TSF %)				
	1 (15–30)	2 (30–50)	3 (50–70)	4 (70–95)	5 (100)
Area (%)	22	42	19	17	
TSF (%) (Median, min–max)	25.3 14.4–31.7	41.6 28.8–55.9	62.2 49.4–75.9	88.1 69.8–94.9	100
Canopy openness (%) (Median, min–max)	23.2 16.3–32.5	28.9 17.6–38.6	39.6 29.4–50.9	61.2 36.4–64.0	
Significance	***	***	***	***	

TSF – total site factor

Table 3. The development of regeneration density and mortality according to degrees of light intensity and chemical control (grey colour = significant, $P < 0.05$)

		Degree										
		1		2		3		4		5	1-4	
Weed control		yes	no	yes	no	yes	no	yes	no	no	yes	no
Year	2007	87.50	65.00	87.50	90.00	70.00	57.50	137.50	97.50	47.50	95.00	80.00
	2008	65.00	62.50	57.50	85.00	60.00	50.00	100.00	85.00	30.00	63.75	67.50
	2009	42.50	57.50	45.00	67.50	45.00	40.00	75.00	70.00	12.50	50.00	60.00
	2010	27.50	48.75	32.50	55.00	35.00	37.50	55.00	57.50	12.50	38.75	50.00
Mortality (%)		58	27	59	30	60	45	57	40	74	59	31

at degree 5. The highest number of seedlings was determined at degree 4 as compared to degrees 1, 3 and 5 (Fig. 3). The absolute values of regeneration density could be affected at degree 5 (RP III) by low stocking of the original stand (Table 1), i.e. by the lower number of parent trees; assessing the relative mortality was exact. The total mortality of seedlings (as of 2010) was significantly highest at degree 5. Otherwise, it did not differ within particular degrees (the mean value was lowest at degree 1) (Fig. 4).

The factor of weed control is statistically significant, however, the positive effects have not been proved (Table 3). While at the beginning of the monitored period there was a significantly higher number of seedlings on the plot with protection, in the next year the number of seedlings did not differ. Surprisingly, in the other years the density of seedlings was significantly higher on the plot without protection. The total mortality of seedlings was also significantly lower on the plot free of protection (by a half). It was evident particularly with the decreasing degree of light intensity.

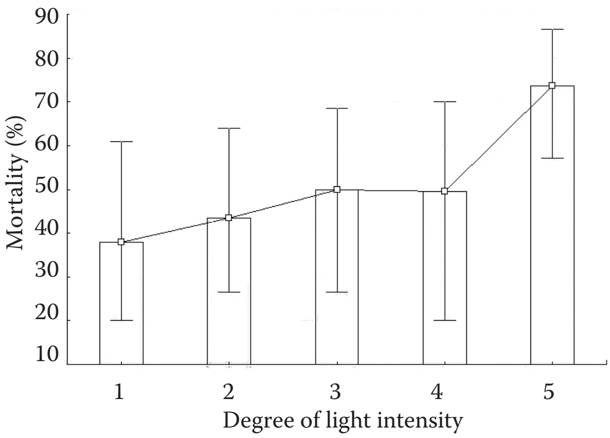

Fig. 4. The development of regeneration mortality at particular degrees of light intensity

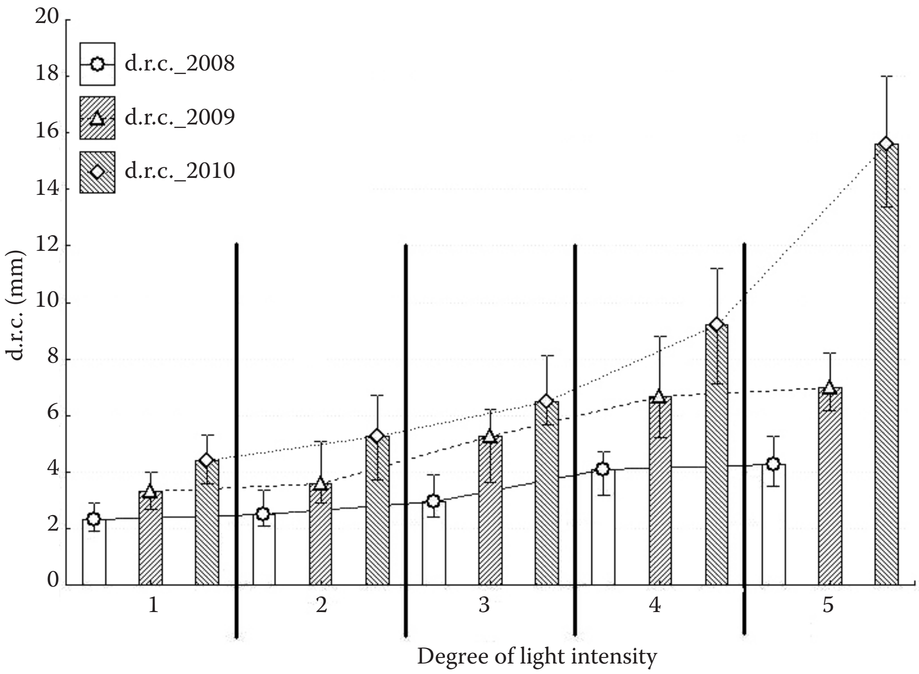

Fig. 5. The development of regeneration diameter increment at particular degrees of light intensity

d.r.c. – diameter at the root collar

Table 4. The development of diameter growth and the total diameter increment according to degrees of light intensity and chemical control (grey colour = significant, $P < 0.05$)

		Degree										
		1		2		3		4		5	1–4	
Weed control		yes	no	yes	no	yes	no	yes	no	no	yes	no
Year	2008	2.5	2.1	3.0	2.2	3.2	2.7	3.8	4.3	4.3	3.1	2.4
	2009	3.7	2.9	4.7	2.9	5.6	4.2	6.8	6.5	7.0	5.0	3.2
	2010	4.9	3.9	6.4	3.8	7.0	5.9	9.1	9.9	15.6	6.5	4.2
d.r.c. increment (mm)		2.4	1.7	3.1	1.7	3.8	3.3	4.7	5.6	11.1	3.2	1.9

d.r.c. – diameter at the root collar

The development of diameter and height growth of oak regeneration

The mean diameter of the root collar of oak seedlings, which was about 2.8 mm (min 1.2–max 9.0 mm) in 2008, increased to 6.1 mm during two years (min 2.5–max 23 mm). The mean height increment of oak seedlings, which started from the mean height of 16.7 cm (min 5–max 59.6 cm) in 2007, amounted to 9.1 cm (min 1.8–max 33.1 cm.) in 2008, increasing in the next years: 2009 – 15.2 cm (min 1.8–max 44.3 cm), 2010 – 16.5 cm (min 2–max 65.3 cm).

In both parameters, the degree of light intensity is an important factor when the mean values of di-

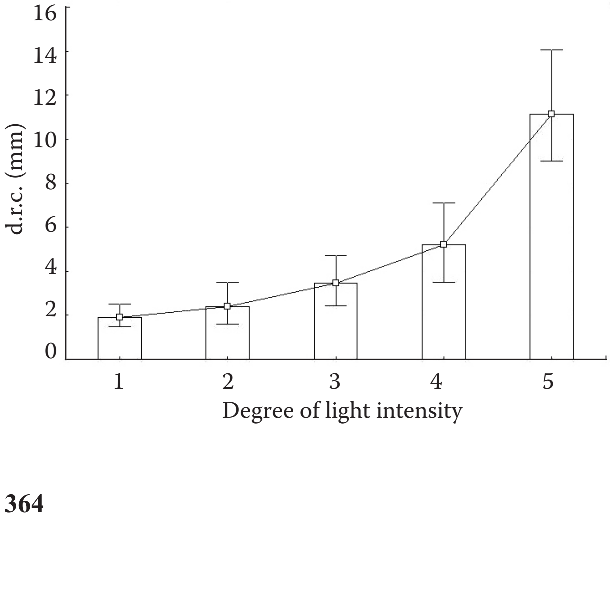

Fig. 6. The total increase in regeneration diameter increment at particular degrees of light intensity

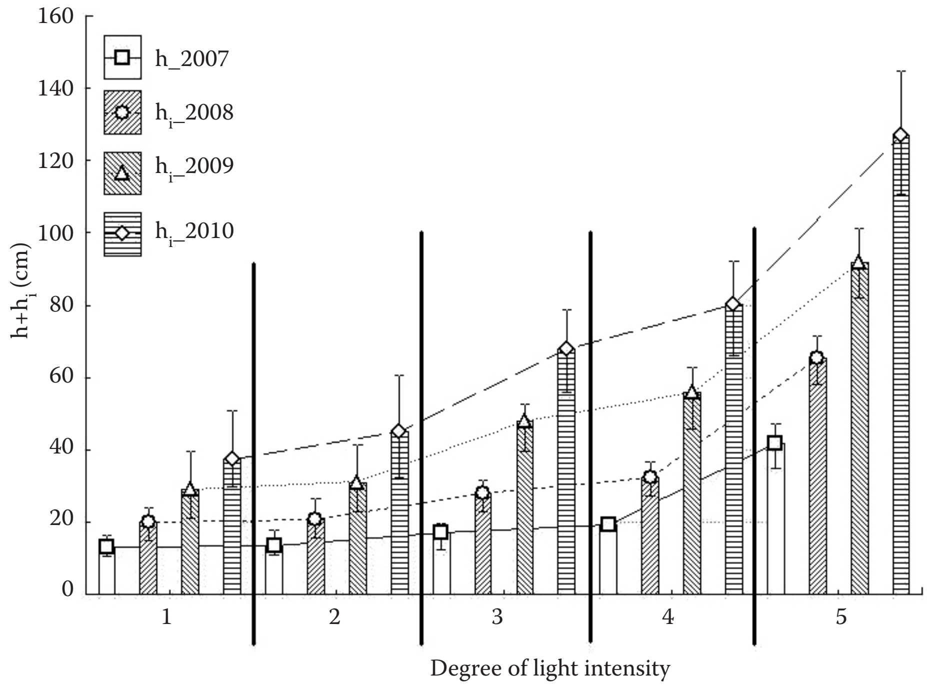

Fig. 7. The development of regeneration height increment at particular degrees of light intensity

h – height

h_i – height increment

Table 5. The development of height growth and the total height increment according to degrees of light intensity and chemical control (grey colour = significant, $P < 0.05$)

		Degree										
		1		2		3		4		5	1–4	
Weed control		yes	no	yes	no	yes	no	yes	no	no	yes	no
Year	h_2007	15.0	11.0	17.0	11.2	18.6	13.2	19.4	19.4	41.9	17.5	12.2
	h_i_2008	10.5	5.7	8.4	5.9	9.9	13.4	14.1	13.7	22.4	9.9	6.7
	h_i_2009	15.3	7.2	15.8	6.8	18.1	20.2	21.4	23.8	26.8	16.4	8.5
	h_i_2010	14.8	8.5	17.4	7.9	18.2	20.7	19.8	33.4	36.0	17.9	9.6
h_i sum (cm)		39.0	20.1	43.0	19.4	48.9	58.0	55.5	67.3	84.5	45.6	22.9

h – height; h_i – height increment

ameter and height increment increase with the increasing degree of light intensity (Fig. 5).

At the beginning of the monitored period (2008 to 2010), the diameter of root collar was also quite balanced being significantly lower at degrees 1, 2 and 3 as compared to degrees 4 and 5. These differences steadily increased and so, in 2009, the diameter was smaller at degrees 1 and 2 as compared to degrees 3, 4 and 5 and in 2010, the values of diameters differed at all degrees. The total increase in the root collar diameter in the monitored period was different at all degrees except degrees 1 and 2 (Fig. 6).

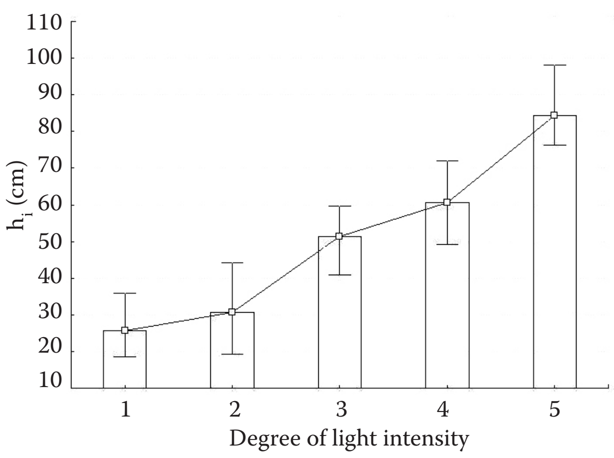

Fig. 8. The total increase in regeneration height increment (h_i) at particular degrees of light intensity

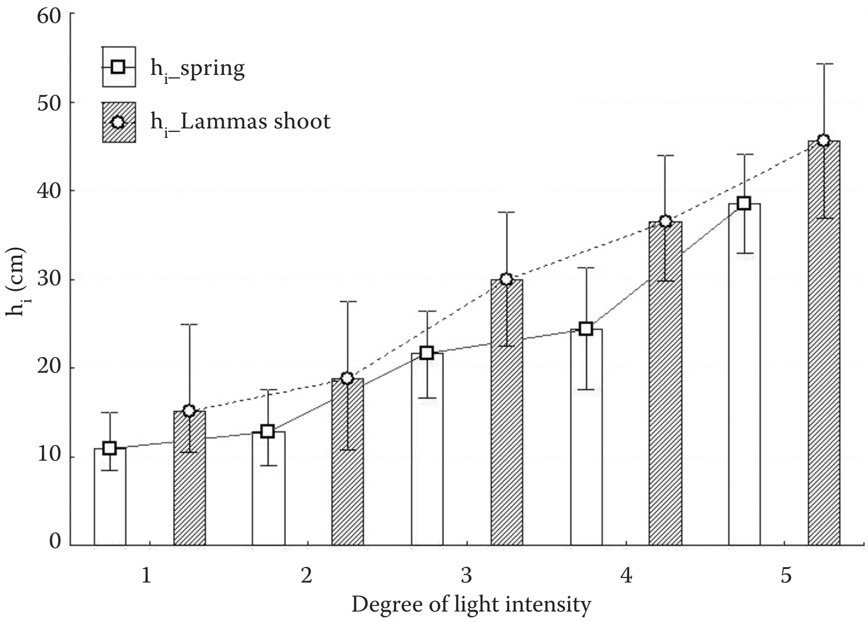

Fig. 9. Comparison of total height increments (h_i) of spring and Lammas shoots

Table 6. Spearman correlation of the regeneration growth parameters with light conditions

	N_2007	N_2008	N_2009	N_2010	Mortality	d.r.c. increment	h_i sum
Canopy openness (%)	0.19	0.02	-0.02	-0.08	0.36	0.55	0.60
TSF (%)	0.18	0.09	0.10	0.07	0.13	0.57	0.53

TSF – total site factor; d.c.r. – diameter at the root collar; h_i – height increment

In 2007, the height of seedlings was quite balanced being significantly the highest at degrees 4 and 5. In 2008, the height increment could be divided into 3 groups (Fig. 7): significantly lowest at degrees 1 and 2, followed by degrees 3 and 4 and the highest increment was at degree 5. This trend continued until the end of the period of monitoring; it was also evident at the evaluation of development of the total height increment of seedlings (Fig. 8). The Lammas shoot increment was significantly higher compared to the spring increment at all degrees of light intensity (Fig. 9). The factor of weed control was statistically significant; however, it was not possible to unambiguously demonstrate any positive effects even there (Tables 4 and 5). The mean root collar diameter and height increment were significantly higher on the plot with chemical control than on the plot without protection in all years (degrees 1–4). However, it applied particularly to the degrees of low light intensities, namely 1 and 2. At degrees 3 and 4, the root collar diameter was equal (insignificant) for both variants in the particular years (except at degree 3 in 2009). The height growth was balanced at degrees 3 and 4, or in some cases, the height growth was higher on plots without chemical control.

DISCUSSION

Our research has proved general findings of many authors, namely that oak behaves as a shade-tolerating species in youth being able to survive under less favourable light conditions for a certain time.

In our case, 8-year seedlings occurred in quite an abundant number (about 40 thousand individuals per ha) independently of the degree of light intensity (Table 6), namely even at minimum values of total radiation circa 15%, i.e. in a fully-closed stand. Thus, we cannot confirm the conclusions of Radkov (1948) (in Vyskot 1958) that self-seeding dies at stocking 0.8–0.9 after 6–7 years. The period of survival was longer. The mortality of individuals of regeneration did not decrease with increasing light intensity but rather on the contrary, it increased and the fast release on a larger clear-felled area (see degree 5) caused the absence of regeneration individuals (12.5 thousand seedlings per ha) and irregular coverage of the area.

After the application of large-area two- to three-stage shelterwood felling, Matić et al. (1999) considered natural regeneration of pedunculate oak to be successful if it reached the density of about 40 thousand seedlings per ha. According to Vyskot (1958), numerous studies proved that the number of oak seedlings which originated under the old stand decreased on older clear-felled areas. Some older papers (e.g. Vyskot 1958; Peřina et al. 1964) reported the danger of late frosts and sun scorch in suddenly released seedlings as the most frequent cause of this event. May late frosts, which occur particularly at locations with the limited outflow of cold air mainly at the high density of grass vegetation (heat removal), are especially dangerous (Reif, Gärtner, 2007).

Another situation occurs when taking into account the actual growth of seedlings. We confirm here a generally known finding that the growth performance of oak seedlings increases with increasing light intensity (Table 6). It was of interest that even at the lowest degree of light intensity, i.e. in a fully closed stand, height and diameter increments of oak seedlings increased. In detail it is possible to differentiate 4 types of growth in this trend: (1) slow (light intensity below 50%), (2) medium fast (light intensity 50–70%), (3) fast (light intensity 70–95%), (4) very fast (light intensity 100%). Thereat Lammas shoot increment is higher than spring increment, which was acknowledged e.g. by Roloff (2001).

We cannot confirm the statement of some authors (e.g. Reif, Gärtner 2007; Lüpke 1998 etc.) that the maximum height increment culminates at values of relative light intensity 30–50%, i.e. under the canopy of a parent stand. In our case, the values of diameter and height increments increased proportionally to light intensity, the highest values being on the open area with relative light intensity 100%. This fact was partly confirmed also by Lüpke (2008). By the comparison of 3 types of regeneration felling (mixed beech-oak stands), the author found the highest values of height on the open area with left reserved trees as compared with the other variants (group shelterwood felling). According to the author, the cause consists in the uneven age of seedlings, different degree of light intensity and competition with beech.

The expected effect of weed control on the success and growth of natural regeneration has not been proved, being rather questionable. Nevertheless, many authors (e.g. Röhrig, Bartsch 2006; Reif, Gärtner 2007) did not see a fundamental problem in weed competition in oak (unlike other tree species). According to findings of forest practice, however, chemical protection can be important for the creation of mixed stands, particularly for the natural regeneration of larch, pine, cherry and other tree species in mixtures with oak. Under given conditions, the mechanical preparation of soil was not necessary.

The parameters of natural regeneration analysed here do not show evidence of the quality of individuals of regeneration, which cannot be ignored in silvicultural considerations and decision-making. In our research, we would like to verify the findings of Weinreich (2000) that gaps with relative light intensity exceeding 32% do not affect fundamentally the quality of oak. It would also be of interest to assess the ratio of the sizes of the root system of seedlings and their aboveground parts, which will undoubtedly show a substantial effect on the stability and quality of a subsequent stand.

CONCLUSIONS AND RECOMMENDATIONS FOR FOREST PRACTICE

Research initiated by forest practice of the Křtiny Training Forest Enterprise, Masaryk Forest, Mendel University in Brno, is aimed at optimizing silvicultural procedures for the natural regeneration of sessile oak at nutrient-rich sites of medium-altitude locations within the conception of close-to-nature forest management. The aim of the study was to determine the growth response of natural regeneration of oak (mast year in 2002) at different variants of regeneration felling (in 2004) during four-year monitoring (2007–2010).

Our research has confirmed general findings on the ecology of the natural regeneration of sessile oak. For a certain time in youth, it is possible to consider oak to be a shade-tolerant species, however, to support at least the medium rate of growth, the species requires minimally 50% light radiation (smaller closed clear-felled areas). On the other hand, more extensive unprotected clear-felled areas subject to unfavourable climatic conditions appear to be quite unsuitable at initial stages of regeneration.

From the aspect of silvicultural practice, traditional border and gap felling and its modifications (e.g. various shelterwood forms or seed/reserved tree management) are therefore advantageous. We recommend developing the regenerated stand by means of a series of small-area (up to about 0.3 ha) two-stage shelterwood felling (strips) of a medium-term regeneration period (up to 15–20 years, i.e. 2–3 seed crops). Roughly 8-year oak seedlings growing at present at sufficient density in fully-closed parts of stands show the slowest but steady diameter and height increment. Thus, we cannot exclude the use of group shelterwood felling with a longer regeneration period or other management systems (such as "natural oak regeneration with permanent canopy cover").

It will be of interest to trace the further development of regeneration. At studied sites, forest weed is not a limiting factor for the success of natural regeneration of oak, thus chemical protection (weed control) is not a prerequisite. Only after the evaluation of other characteristics of regeneration, we will be able to provide more detailed silvicultural recommendations. Based on literature retrieval and results obtained, scientific research aimed at close-to-nature oak regeneration is always opened being very desirable for forest practice.

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