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The root system of pedunculate oak (*Quercus robur* L.) at the margins of regenerated stands

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Abstract

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The paper aims to contribute to the determination of reasons causing the irregular growth of young pedunculate oaks occurring at the margins of naturally and artificially regenerated plots neighbouring with adult stands on alluvial sites. It presents analyses of aboveground biometric parameters, mortality, root system architecture of young trees, root density in the soil profile, global solar radiation and soil moisture content in dependence on the location of oaks at the northern, southern, eastern or western margins of the regenerated area and on the distance from the stand margin. The highest impact of the neighbouring adult stand is always recorded on the margin of the regenerated plot while its effect is weakening towards the plot centre, and fading away ca. 7 m behind the crown projection of adult trees. Regardless of the oak location (northern, southern, eastern or western margin), the cause is a high root density of marginal trees of the adult stand, which induces the critical lack of water under their crown projections.

Keywords: forest regeneration; stand margin; edge effect; tree morphology; mortality; microclimate

The growth of seedlings from natural seeding and young plants from artificial regeneration is affected by ecological conditions of the site. In the case of regeneration by clear felling, these conditions are changing, among other things in dependence on the size and shape of the regenerated area, and they are further modified by the impact of margins of the cut stand (edge effect). The stand margin represents a specific ecological interface with a steep gradient of microsite elements. According to Petrík (1986), there are two causes of the specific microclimate forming at the stand margin. The first one is a combination of the stand microclimate with the microclimate of the open area due to which a temporary microclimate is formed. The second one consists in the occurrence of complementary climatic phenomena. The forest stand margin is sunlit or casts shadow onto the open area, intercepts rainwater, and entraps fog drops. If on the lee side, it shelters the open area and may either reduce or increase the amount of precipitation. Lateral screening secures favourable microclimate, reduces evapotranspiration and temporarily suppresses the growth of weeds. On the other hand, it creates a rain shadow and usually adversely affects the growth rate of advance regeneration and young plantations. Young trees growing in the immediate vicinity of adult stand margin exhibit impaired height growth and higher mortality. The seriousness of the impact of stand margins depends on the stand height, orientation to cardinal points,

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terrain gradient and slope exposure. Stand margins influence the height increment of young plants to a distance of approximately a half of the stand height.

Information about how the stand margin affects ecological conditions of the margin of the regenerated area can be obtained through monitoring the microclimate of the regeneration elements of clear-cut character (gaps) of different sizes. Authors dealing with such studies were for example Slavík et al. (1957), Krečmer (1960), Krečmer and Fojt (1966), Mosandl (1983 ex Poleno et al. 2009), Kern et al. (2013) or Čater et al. (2014).

According to Slavík et al. (1957), average precipitation in the gap is logically distributed with respect to the prevailing wind direction. Under the margin of crown canopy, there are zones of increased relative precipitation, surmounting 100% namely on the windward side. According to Krečmer (1960), the highest amount of precipitation falls onto the gap centre. Markedly poorer is the water supply at margins situated on the leeward side in respect to prevailing winds. Throughout the year, the lowest soil moisture is in the northern part of the gap and the highest soil moisture is in the eastern part and in the centre. Mosandl (1983 ex Poleno et al. 2009) found out that the precipitation amount in the centre of gaps with the diameter of 30 m was only slightly lower than in the open area while eastern margins of the gaps exhibited considerably higher precipitation amounts. On the strip felling in a pure pine stand, Krečmer and Fojt (1966, 1967) recorded the highest precipitation supply in the central part of the gap.

Maximum daily temperatures of air, soil surface and plants in the gap are higher than in the stand – only those measured on the insolated northern part of the gap reach values of the clear-cut area. Night air temperatures in the gap are lower than in the stand due to higher heat radiation (Slavík et al. 1957). Krečmer (1960) similarly found out that the northern part of the gap is warmest during the growing period while the southern part is coldest, this corresponding with the soil temperatures that are highest in the northern part of the gap and lowest in the southern part of the gap.

The reason for the adverse influence of the stand margin on the growth of planted or natural regenerated trees may be the more or less reduced intensity of solar radiation but also the time of exposure to sunlight (Slavík et al. 1957). According to Krečmer (1960), the longest total annual time of exposure to solar radiation is observed in the central part of the gap. One-day measurements showed that the northern margin and the southern margin of the gap receive the highest (64%) and the lowest (12%) amount of energy from solar radiation, respectively (the open area receives 100%). Minckler et al. (1973 ex Poleno et al. 2009) found out in the felled gaps of varying size in the US mixed broadleaved forests that the light supply increases at all margins of the stand gap with the exception of its southern margin on clear days. In small gaps sized 3/4 of tree height, the greatest light dose is enjoyed by the northern margin of the gap, which is followed by the gap centre, and further on by the western, eastern and southern margins. In larger gaps (with diameter larger than the mean tree height), the highest amount of light is received by the gap centre and then by the northern, western, eastern and southern margins. According to Mosandl (1983 ex Poleno et al. 2009), duration of solar radiation in the centre of a gap sized 30 m in diameter reaches 6–21% of the value measured in the open area. On the northern margins of the gaps (i.e. on the southern margins of stands), the time of exposure to solar radiation increases to 13–32%. When studying the microclimate of strip felling in a pure pine stand, Krečmer and Fojt (1966, 1967) observed the greatest (lowest) solar radiation from May to August in the middle (on the southern part) of the strip felling throughout the year. As compared with the open area, the solar radiation treat was reduced on average by 30% at places exposed to direct sunlight and by up to 75% on parts shaded by the stand on the southern part of the clear-cut.

Since the oak is considered a light demander, foresters believe that its impaired growth results from insufficient light availability. Tolerance of pedunculate oak to reduced light treat under the influence of adult stand or neighbouring stand was studied especially in the natural regeneration. According to our previous study (Houšková 2006), oak trees from natural seeding die under the shelter of the parent stand; under the reduced shelter (stocking 0.5), their growth shows stagnation and impaired vitality. The retarded growth, impaired vitality or dieback of the natural regeneration that had not been released in time was reported also by Lust and Speleers (1990), von Lüpke (1998), Dobrowolska (2008) and other authors. The situation is somewhat different in the planted young sessile oak. Von Lüpke (1987) compared the growth of sessile oak 8 years after planting in the open area (0.7 ha), in the stand gap (0.2 ha) and in the sheltered area with about 11% of the open area illumination. According to the author, height growth in the open area (photosynthetically active radiation 100%) and in the stand gap (photosynthetically active radiation 45.5% of the open area) did not differ statistically. However, young trees growing under the stand shelter reached only 20% of the height of young trees growing at higher light intensities. The author maintains that the tolerance to shading is so high in the sessile oak that a light reduction to ca. half of the open area illumination does not suppress its height growth significantly. Impaired height growth and increased mortality were very noticeable only under a shelter which induced light reduction to 11%. Vor and von Lüpke (2004) also studied the influence of diverse relative illumination on the growth of sessile oak. They found out that compared with a plot with the diffuse radiation at 68.5% of the open area radiation, the transplants exhibited considerable mortality and impaired height and diameter growth at the diffuse radiation of 8.3%.

The above data indicate that the lack of light will not be a decisive factor for the reduced growth of planted young oaks. Moreover, tree species demanding light or shade respond identically if occurring near the adult stand margin, this phenomenon showing at all locations – northern, southern, eastern, western margins of the clear-cut regeneration element.

Since the growth of each tree is markedly affected by the development of its root system, main objectives of the paper were to find out how the root system of young oaks planted in the immediate vicinity of an adult stand margin develops, and what is the mutual relationship between the root system of young oaks from sowing and planting and the root system of marginal trees occurring on the stand margin, also in relation to cardinal points.

MATERIAL AND METHODS

All analyses were done in one year on alluvial sites (Fluvisols, non-flooded areas, forest type 1L1) in adult stands of pedunculate oak (hereinafter "stands" aged 100 years, with 85% oak, 15% ash, stocking 1.0 and tree height 32 m).

All regenerated plots were squares sized 0.8–1.0 ha with the axes oriented to the north-south and east-west. Plots analysed at the Židlochovice Forest Enterprise (Forests of the Czech Republic, State-owned Company) were 7 years after planting (Lanžhot) and 2 years after sowing (Židlochovice). Plots analysed at the Šternberk Forest Administration (Forests of the Czech Republic, State-owned Company) were aged 10 years (Litovel). All young plantations were established in the spring with 2-year bare-rooted seedlings. Complex analyses were done only at the Lanžhot site. Due to high labour consumption, only those analyses at the Litovel and Židlochovice sites were conducted that were to confirm or disprove conclusions from the Lanžhot site. The Židlochovice locality was to answer a question whether the oaks from planting and sowing would show the same reaction.

The analyses were performed at the northern (NM), southern (SM), eastern (EM) and western (WM) margins of regenerated plots (five replications of each margin), and directly in the neighbouring adult stands. Surveyed spots were marked as follows: P – stand (in the stand, 10 m from its margin); A – margin of the regenerated plot (in the middle between the stems of marginal trees); B – half of stand crown projections reaching into the regenerated plot; 1 – margin of stand crown projections reaching into the regenerated plot; 3 – at a distance of 3 m from the margin of crown projections towards the centre of the regenerated plot; 7 – at a distance of 7 m from the margin of crown projections towards the centre of the regenerated plot. These measuring points were chosen because the greatest impact of the stand margin shows on the margin of the regenerated plot, gradually decreasing and fading out ca. 3 m behind the crown projection of marginal trees in the stand. The crowns reached to a distance of 5–8 m from the stems.

Biometric parameters of the aboveground part – shoot length (distance from the soil surface to the tip of the terminal shoot) and root collar diameter (stem diameter at a distance of 10 cm above the soil surface) were measured at all times in 100 oak trees. Mortality was determined at measuring points on an area sized 2 × 40 m with the longer side parallel to the stand margin.

On each site and at each measuring point, average trees (in light of both shoot length and root collar diameter) were chosen for root system analyses. All root systems were lifted by hand using the archaeological method. Each root system was inspected to determine its type and possible malformations. Other ascertained parameters included the number and diameter of skeletal roots (diameter was measured 10 cm from the setting point; plagiotropically growing roots occurring on the taproot or on substitute taproots were classified as horizontal roots), the number and diameter of substitute taproots (diameter was measured 5 cm from the point of their setting), and the rooting depth (perpendicular distance from the soil surface to the deepest part of the root system). The obtained values were used to calculate the root area index (*Ip*) denoting the relation between the size of the entire root system and the shoot length as a ratio of the cross-sectional areas of all roots (in mm^2) at the measuring point to the tree length (in cm). The root area index defines how many mm^2 of roots fall per 1 cm of tree length. A similar calculation was used to obtain *Ip* of horizontal skeletal roots where the calculation included only the horizontal skeletal roots. Each root was cut lengthwise in order to determine the incidence of rots and possible infestation by biotic agents.

Root density was determined in soil pits (length 1.5 m, depth 1.2 m) dug out in all measuring points. Walls of each soil pit were inspected for the occurrence of the number and diameter (2.0–10.0 mm) of roots in the soil layers 0–40, 40–80, and 80–100 cm (length of the evaluated layer being at all times 100 cm). From the wall of all soil pits, ten soil cores were taken by using a sampler (diameter 5 cm) in the soil layers 30–40 and 70–80 cm. The soil cores were homogenized in the laboratory. Six analytical soil samples of 100 ml were taken from the homogenate. The samples were washed down and fine roots (< 2 mm) were separated from them. Their weight was determined after drying to constant mass. 300 soil pits were dug and 6,000 soil cores were taken overall.

Soil moisture content was determined using Virrib measuring apparatuses (AMET Co., Czech Republic) with measuring probes being installed vertically, i.e. soil moisture was measured at a depth of 15–40 cm. There were 60 points for soil moisture content measurement overall (3 points – P, 1, 7 at each location – NM, SM, WM, EM).

Global radiation was determined using the method of calculation in ArcGIS (Version 10, 2010) with the Spatial Analyst and its instruments Points Solar Radiation and Area Solar Radiation. These instruments calculate total global radiation based on the digital terrain model or digital surface model either on a whole-area scale in the landscape (Area Solar Radiation) with the output being a grid with the value of radiation changing according to the relief, or directly for given places with values being figured up and recorded in attributes for input sites. The methods are based on the principle of hemispheric visibility (Rich et al. 1994), and further modified into the form of instruments for ArcGIS (Fu, Rich 2002). Global radiation at various distances from the margins of neighbouring stands was calculated based on a simplified digital surface model. Since no sufficiently accurate terrain model or surface model was available for the Lanžhot site and the regenerated plot was of plain character, it was necessary to survey the location and altitude of all soil moisture measuring points by using the Trimble ProXH GPS instrument (Trimble Co., USA). Furthermore, linear surveys of stand margins were made from all cardinal points and the mean height of surrounding stands was measured. For higher accuracy, the GPS measurement data were elaborated using corrections from the CZEPOS network of reference stations. The mean altitude of the plot being chosen 181 m a.s.l. for calculating the global radiation, altitudes of the measured locations exhibited only minimum deviations. A simplified digital surface model was constructed subsequently based on increasing the cardinal altitude of the plot by the heights of stands on the margins. The digital surface model created in this way was subsequently applied the above-mentioned instruments for calculating the global radiation. In order to retain the sequence with the soil moisture content measurements, the same period (1 May–30 September 2011) was chosen for the calculation. The Points Solar Radiation tool directly yielded the value of global radiation for the selected period at the measuring points. In total, there were 12 points for global radiation detection (3 points – P, 1, 7 at each location – NM, SM, WM, EM at Lanžhot site).

The significance of differences was *t*-tested at a level of significance $\alpha = 95\%$ – MS Excel (Version 2010). Regarding the fact that the objective was to determine how the monitored parameters change in dependence on the distance from the stand margin towards the centre of the regenerated plot and how these parameters are affected by cardinal points, the statistical evaluation and brief comments of results are as follows:

(*i*) Trend and statistical significance of differences in results in dependence on the distance from the stand margin to the centre of regenerated plot on each cardinal point: the statistical evaluation aimed at the statistical significance of differences between the neighbouring points of measurement;

(*ii*) Trend and statistical significance of differences in results between cardinal points at the same measuring point: at the statistical evaluation, the aspect with the highest average value detected at the given measuring point was at all times chosen in the given parameter regardless of cardinal points (in tables of results denoted as K); all values detected at the remaining cardinal points were tested in relation to that value.

RESULTS

Biometric parameters of the aboveground part, root system architecture, mortality

The implemented studies show (Tables 1 and 2) that parameters significantly increasing nearly always at each cardinal point from the margin of the

Table 1. Mortality and parameters of aboveground part and root system of oaks after planting at Lanžhot and Litovel sites

Site	Location	Measuring point	No. of analysed trees	Aboveground part length (cm)	Root collar diameter (mm)	Mortality (%)	Root system type	Root system deformation (No. of trees)		Horizontal skeletal roots total		Substitute taproots		Rooting depth (cm)		*Ip* of all roots	*Ip* of horizontal skeletal roots
								none	L	number	diameter (mm)	number	diameter (mm)	average	maximal		
Lanžhot	NM	A	10	39.8 ± 6.1 –	10.1 ± 1.6 –	65		0	10	5.4 ± 1.6 K	2.67 ± 0.75 K	2.6 ± 0.9 K	8.1 ± 2.1 –	19.7 ± 6.1 –	25.8 ± 5.8 –	1.14 ± 0.47 –	0.42 ± 0.18 K
		1	5	+ 157.7 ± 14.5 –	+ 22.4 ± 4.2 –	21		1	4	+ 10.8 ± 2.7 –	+ 4.82 ± 1.36 –	+ 4.2 ± 1.4 K	+ 13.9 ± 3.3 –	+ 39.6 ± 5.2 K	+ 42.6 ± 2.7 –	+ 3.65 ± 0.48 –	+ 1.64 ± 0.36 –
		3	5	+ 205.6 ± 15.3 –	– 26.8 ± 5.4 –	12		5	0	– 12.6 ± 1.1 –	– 5.61 ± 1.47	– 4.7 ± 1.9 K	– 13.9 ± 3.4 –	+ 53.2 ± 5.2 –	+ 58.4 ± 5.1 –	– 3.48 ± 0.41 K	– 1.62 ± 0.51 K
		7	5	+ 277.4 ± 16.3 –	+ 38.1 ± 0.6 +	7		5	0	– 13.5 ± 0.6 –	– 6.54 ± 2.14 –	+ 6.9 ± 2.2 –	+ 15.9 ± 3.9 –	+ 79.6 ± 10.6–	+ 82.2 ± 11.4 –	+ 4.22 ± 0.51 –	+ 2.22 ± 0.29 +
	SM	A	10	40.8 ± 5.8 –	10.8 ± 1.7 K	71		1	9	5.5 ± 1.7 –	2.57 ± 1.10 –	1.7 ± 0.6 –	8.8 ± 2.2 –	24.2 ± 5.8 –	27.2 ± 5.6 –	1.28 ± 0.42 K	0.36 ± 0.17 –
		1	5	+ 167.4 ± 11.1 –	+ 26.4 ± 2.5 –	24	ST	3	2	+ 10.4 ± 1.1 –	+ 5.76 ± 2.08 K	+ 3.9 ± 1.1 –	+ 11.7 ± 1.9 –	+ 39.4 ± 9.5 –	+ 39.8 ± 8.6 –	+ 3.34 ± 0.84 –	+ 2.04 ± 0.57 K
		3	5	+ 207.2 ± 34.2 K	– 27.0 ± 6.2 –	13		5	0	– 13.3 ± 1.2 K	– 5.72 ± 1.55 K	– 4.1 ± 1.4 –	+ 14.1 ± 2.2 K	+ 55.0 ± 4.4 K	+ 57.3 ± 4.5 –	– 3.41 ± 0.35 –	– 1.58 ± 0.47 –
		7	5	+ 281.0 ± 39.7 –	+ 48.8 ± 5.3 K	6		5	0	– 14.6 ± 1.1 –	+ 7.72 ± 1.55 –	+ 7.3 ± 2.4 K	+ 17.0 ± 4.3 –	+ 71.2 ± 9.2 –	+ 75.6 ± 12.8 –	+ 5.44 ± 0.97	+ 2.82 ± 0.34 –
	EM	A	10	43.2 ± 6.4 –	9.9 ± 1.0 –	64		0	10	4.7 ± 1.0 –	2.10 ± 0.82 –	1.9 ± 1.1 –	8.5 ± 1.9 –	23.9 ± 4.9 –	28.1 ± 6.4 –	1.19 ± 0.41 –	0.42 ± 0.17 –
		1	5	+ 182.0 ± 12.5 K	+ 27.6 ± 2.9 K	23		3	2	+ 11.4 ± 2.4 –	+ 4.98 ± 1.48 –	+ 4.1 ± 1.9 –	+ 14.6 ± 3.6 K	+ 40.2 ± 5.8 –	+ 44.2 ± 2.1 K	+ 3.85 ± 0.54 K	+ 1.58 ± 0.35 –
		3	5	199.1 ± 11.9 –	– 27.8 ± 2.1 K	15		5	0	– 12.0 ± 1.5 K	– 4.88 ± 1.45 –	– 4.3 ± 1.6 –	– 13.3 ± 4.3 –	+ 53.1 ± 4.4 –	+ 55.4 ± 2.7 –	– 3.13 ± 0.51 –	– 1.47 ± 0.35 –
		7	5	+ 268.0 ± 9.1 –	+ 40.6 ± 4.8 –	7		5	0	– 14.8 ± 2.2 –	+ 7.48 ± 3.31 K	+ 6.7 ± 2.1 –	+ 17.7 ± 4.6 K	+ 72.4 ± 11.2–	+ 79.6 ± 6.2 –	+ 5.89 ± 0.89 K	+ 3.22 ± 0.51 K
	WM	A	10	45.2 ± 6.6 K	9.7 ± 1.1 –	68	S	2	8	4.1 ± 1.8 –	2.12 ± 0.50 –	1.1 ± 0.5 –	10.9 ± 3.8 K	24.7 ± 5.2 K	29.4 ± 6.1 K	1.23 ± 0.38 –	0.38 ± 0.13 –
		1	5	+ 129.6 ± 11.1 +	+ 19.6 ± 1.3 +	27		1	4	+ 8.0 ± 0.7 –	+ 3.80 ± 0.91 –	+ 2.3 ± 0.5 +	– 10.9 ± 3.8 –	+ 39.5 ± 7.9 –	+ 42.0 ± 7.0 –	+ 2.84 ± 1.11 –	+ 1.55 ± 0.19 –
		3	5	+ 176.6 ± 15.5 –	– 23.0 ± 1.8 –	17		4	1	+ 10.1 ± 1.1 –	– 4.20 ± 2.01 –	– 2.7 ± 1.7 +	+ 13.5 ± 3.1 –	+ 50.6 ± 5.2 –	+ 62.2 ± 7.3 K	– 2.80 ± 0.53 –	– 1.22 ± 0.25 –
		7	5	+ 289.0 ± 18.1 K	+ 37.3 ± 0.6 +	10	ST	5	0	+ 13.7 ± 0.6 –	+ 6.91 ± 2.81 –	+ 4.3 ± 1.9 +	+ 16.0 ± 4.6 –	+ 93.5 ± 10.2 K	+107.4 ± 12.6 K	+ 4.15 ± 0.44 +	+ 2.13 ± 0.28 +
Litovel	NM	1	6	259.2 ± 20.7 –	30.3 ± 2.8 –	25		3	3	10.3 ± 1.5 –	8.45 ± 1.37 –	2.7 ± 0.6 –	12.1 ± 3.4 K	56.8 ± 10.6 –	61.7 ± 8.9 –	2.02 ± 0.36 +	1.19 ± 0.38 +
	SM	1	6	260.6 ± 44.4 –	35.0 ± 9.9 –	28		3	3	13.2 ± 2.3 –	5.97 ± 2.13 –	2.6 ± 0.5 –	10.3 ± 2.2 –	55.4 ± 9.2 –	60.6 ± 10.5 –	2.64 ± 0.65 –	1.64 ± 0.55 –
	EM	1	6	286.0 ± 15.9 –	33.0 ± 5.6 –	19		0	6	15.3 ± 4.13K	5.98 ± 2.52 –	3.3 ± 0.8 K	11.9 ± 3.8 –	59.8 ± 12.4K	68.2 ± 10.4 K	3.05 ± 0.78 K	2.00 ± 0.96 –
	WM	A	6	75.6 ± 5.2	16.2 ± 0.5	79	ST	1	5	5.7 ± 1.2	5.26 ± 1.13	–	–	22.7 ± 0.9	22.7 ± 0.9	2.02 ± 0.92	2.02 ± 0.92
		1	6	+ 287.2 ± 34.3 K	+ 37.0 ± 6.2 K	21	S	2	4	+ 8.7 ± 3.2 +	– 6.22 ± 2.27 K	–	–	+ 47.5 ± 2.1 –	+ 57.5 ± 8.1 –	– 2.66 ± 0.49 +	– 2.66 ± 0.49 K
		3	6	+ 383.5 ± 22.4	+ 46.2 ± 2.6	13	ST	6	0	+ 22.0 ± 2.9	+ 8.18 ± 3.28	3.2 ± 1.7	13.7 ± 3.6	+ 64.6 ± 9.2	+ 69.7 ± 6.6	+ 4.19 ± 0.78	– 2.76 ± 0.93
		7	6	+ 429.2 ± 40.9	– 45.6 ± 5.8	5		6	0	+ 27.2 ± 4.6	– 7.15 ± 2.49	– 2.6 ± 0.5	+ 16.4 ± 2.8	+108.9 ± 10.3	+109.2 ± 11.5	– 4.41 ± 0.96	– 2.98 ± 0.86

parameters expressed as arithmetic means ± standard deviations, NM – northern margin, SM – southern margin, EM – eastern margin, WM – western margin, A – margin of the regenerated plot, 1 – margin of stand crown projections reaching into the plot, 3 – at a distance of 3 m, 7 – at a distance of 7 m from the margin of crown projections towards the centre of the plot, significance of differences in results in dependence on the distance from the stand margin to the centre of the regenerated plot at each location denoted in front of the arithmetic mean: significant (+), non-significant (–), significance of differences in results between the locations at the same measuring point denoted behind the standard deviation: significant (+), non-significant (–), K – aspect with the highest average value detected at the given measuring point regardless of cardinal points, all values detected at the remaining cardinal points tested in relation to this value, ST – substitute taproots, S – superficial, L – root system development into the letter "L" shape, i.e. L malformation, *Ip* – root area index

Table 2. Mortality and parameters of aboveground part and root system of oaks after sowing at Židlochovice site (western margin)

	Measuring point							
	A		B		1		3	
	taproot	substitute taproots	taproot	substitute taproots	taproot	substitute taproots	taproot	substitute taproots
Aboveground part length (cm)	0.0 ± 0.0	9.7 ± 4.5	18.6 ± 1.5	+ 20.0 ± 3.2	+ 50.6 ± 3.7	+ 52.0 ± 7.8	+ 81.7 ± 2.3	+ 78.7 ± 9.9
Root collar diameter (mm)	0.0 ± 0.0	3.8 ± 1.2	5.6 ± 0.57	– 5.0 ± 1.1	+ 8.4 ± 1.1	+	+ 11.7 ± 1.4	+ 10.5 ± 1.3
Mortality (%)	88		46		18		5	
Root system type (number of trees)	0	10	3	7	5	3	6	4
Root system deformation (number of trees)								
No deformation	0	1	1	2	1	0	6	4
Deformation into L	0	9	2	5	4	3	0	0
Tangle	0	0	0	0	0	0	0	0
Number of horizontal skeletal roots (pc)	0.0 ± 0.0	7.6 ± 4.2	9.6 ± 2.5	– 10.0 ± 1.5	+ 16.2 ± 2.5	+ 15.3 ± 1.5	+ 28.1 ± 2.7	+ 30.3 ± 2.8
Diameter of horizontal skeletal roots (mm)	0.0 ± 0.0	0.81 ± 0.47	2.24 ± 0.51	+ 2.56 ± 1.02	– 2.90 ± 1.50	– 3.30 ± 1.79	– 2.75 ± 0.96	– 3.01 ± 1.41
Number of substitute taproots	0.0 ± 0.0	2.4 ± 0.5	0.0 ± 0.0	– 2.4 ± 0.6	0.0 ± 0.0	– 2.9 ± 0.7	0.0 ± 0.0	– 2.5 ± 0.6
Diameter of substitute taproots (mm)	0.0 ± 0.0	1.5 ± 1.1	0.0 ± 0.0	+ 3.6 ± 0.6	0.0 ± 0.0	+ 6.6 ± 2.1	0.0 ± 0.0	+ 6.8 ± 1.4
Taproot diameter (mm)	0.0 ± 0.0	0.0 ± 0.0	5.3 ± 0.6	0.0 ± 0.0	+ 8.4 ± 0.5	0.0 ± 0.0	+ 12.0 ± 1.4	0.0 ± 0.0
Rooting depth (cm)	0.0 ± 0.0	11.2 ± 4.3	18.1 ± 6.9	– 16.7 ± 7.1	– 19.2 ± 8.8	– 16.3 ± 6.5	– 55.9 ± 5.7	– 53.7 ± 4.2
Ip of all roots	0.0 ± 0.0	1.96 ± 0.84	3.54 ± 1.30	+ 5.50 ± 1.32	– 3.79 ± 2.05	– 6.14 ± 1.68	– 3.63 ± 0.61	– 5.51 ± 0.65
Ip of main skeletal roots	0.0 ± 0.0	1.96 ± 0.84	2.89 ± 1.25	+ 3.79 ± 1.06	– 3.31 ± 1.51	– 3.80 ± 0.32	– 3.02 ± 0.61	– 4.09 ± 0.43

parameters expressed as arithmetic means ± standard deviations, L – root system development into the letter "L" shape, i.e. L malformation, *Ip* – root area index, A – margin of the regenerated plot, B – half of stand crown projections reaching into the regenerated plot, significance of differences in results in dependence on the distance from the stand margin to the centre of the regenerated plot at each cardinal point is denoted in front of the arithmetic mean: significant (+), non-significant (–), 1 – margin of stand crown projections reaching into the plot, 3 – at a distance of 3 m regenerated plot (measuring point A) up to its part where the young oaks do not exhibit any signs of stagnation (measuring point 3) are: aboveground part length, root collar diameter, number and diameter of horizontal skeletal roots, number and diameter of substitute taproots and rooting depth. Differences in the size of these parameters between the individual cardinal points are statistically non-significant. The conclusions apply to all studied sites (Lanžhot, Litovel, Židlochovice), i.e. for young oaks originating both from sowing and planting.

Mortality considerably decreased from the margin of the regenerated plot (A) to a distance of 7 m from the margin of crown projections (7).

On a majority of measuring points and studied locations (NM, SM, EM, WM) of Lanžhot and Litovel sites, the young oaks developed a root system with substitute taproots. Exceptionally, they developed a superficial root system – at all times on the margin of the regenerated plot (A) and at the half of crown projection (B). Young oaks from sowing (Židlochovice site) occurring on the margin of the regenerated plot (A) developed only a superficial root system while young oaks occurring at other locations within the plot developed a system with the taproot or substitute taproots.

At all studied sites and locations (NM, SM, EM, WM), nearly all young oaks occurring on the margin of the regenerated plot (A) and on the margin of crown projections of the stand (1) featured root system malformations into L (the root system development into the letter "L" shape). The root system malformations did not occur at distances of 3 m (3) and 7 m (7) from the margin of crown projections.

At the Lanžhot and Litovel sites, the *Ip* value of all roots as well as the *Ip* value of horizontal skeletal roots increased on all locations (NM, SM, EM, WM) with the increasing distance from the margin of the regenerated plot towards its centre. With the exception of differences between measuring points 1 (margin of crown projections) and 3 (3 m from the margin of crown projections), the differences were significant. Differences between the locations (NM, SM, EM, WM) were non-significant. A similar trend was observed also in young oaks from sowing (Židlochovice site) although the difference between the measuring points B and the centre of the regenerated plot was non-significant.

Neither root rots nor root system infestation by biotic agents was found by analysing the root systems.

Root density in the soil

Density of roots (diameter 2.0–10.0 mm) in the soil layers 0–40 and 40–80 cm was studied only at the Lanžhot site (Table 3). Regardless of locations (NM, SM, EM, WM), the number of roots in the two soil layers at the margin of crown projections of the stand (1) was significantly higher than in the stand (P). A particularly great difference was observed in the layer 40–80 cm. At the distance of 3 m from the margin of crown projections (3), the numbers of roots became equal as compared with the measuring point in the stand (P) and at the distance of 7 m from the margin of crown projections (7), they were significantly lower. As compared with the number of roots, differences in average diameters of these roots were considerably smaller at all measuring points and in some cases even statistically non-significant. Unlike at the measuring point P (stand), roots were recorded even in the layer 80–100 cm on the margin of crown projections (1).

Biomass of fine roots markedly increased at all monitored sites and on all locations (NM, SM, EM, WM) in the soil layer 30–40 cm on the margin of the regenerated plot (A) as compared with the stand (P). The differences became mostly non-significant on the margin of crown projections (1), and at the distance of 7 m from the margin of crown projections, the biomass of these roots was minimal as compared with the stand (P). Even greater differences were observed in the soil layer 70–80 cm. As compared with the stand (P), all studied sites and all locations (NM, SM, EM, WM) showed a multiple significant increase of the biomass of fine roots on the margin of the regenerated plot (A) as well as on the margin of crown projections of the stand (1). As compared with the stand (P), the biomass of fine roots at the distance of 7 m from the margin of crowns was significantly lower.

Soil moisture

Although some small differences in the course of soil moisture content were recorded during the studied period (Fig. 1), one feature was common to all locations (NM, SM, EM, WM). It was the highest soil moisture content which was found in the stand (P), a somewhat lower soil moisture content observed at the distance of 7 m from the margin of crown projections (7), and the lowest soil moisture content on the margin of crown projections (1) where it was decreasing below 20% at all locations (NM, SM, EM, WM).

Table 3. Root density in the soil at Lanžhot, Litovel, Židlochovice sites

Site	Location	Measuring point	Density of roots of 2.0–10.0 mm in diameter						Biomass of fine roots (g in 100 ml of soil)	
			soil layer						soil layer	
			0–40 cm		40–80 cm		80–100 cm		30–40 cm	70–80 cm
			number	diameter (mm)	number	diameter (mm)	number	diameter (mm)		
Lanžhot	NM	P	18.7 ± 2.3	6.9 ± 2.9	8.2 ± 1.2	3.8 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	0.0250 ± 0.0024	0.0041 ± 0.0004
		A	not determined						+ 0.0373 ± 0.0042 K	+ 0.0510 ± 0.0056 –
		1	+ 26.2 ± 3.9 –	– 5.9 ± 3.1 –	+ 24.7 ± 2.7 K	+ 5.1 ± 2.7 –	9.3 ± 1.6 –	6.1 ± 2.8 K	– 0.0217 ± 0.0012 –	+ 0.0409 ± 0.0029 –
		3	+ 22.8 ± 2.5 K	– 4.5 ± 2.1 –	– 12.9 ± 2.1 K	– 5.8 ± 3.7 K	0.0 ± 0.0	0.0 ± 0.0	+ 0.0039 ± 0.0006 –	+ 0.0002 ± 0.0001 +
		7	+ 6.2 ± 1.1 K	+ 4.2 ± 0.4 K	+ 4.7 ± 0.7 K	– 3.4 ± 0.9 +	0.0 ± 0.0	0.0 ± 0.0	not determined	
	SM	A	not determined						+ 0.0411 ± 0.0028 –	+ 0.0580 ± 0.0037 K
		1	+ 29.2 ± 2.4 –	– 8.1 ± 3.4 –	+ 10.6 ± 2.7 –	+ 6.2 ± 2.1 K	6.1 ± 1.3 +	5.0 ± 1.1 –	– 0.0246 ± 0.0022 K	+ 0.0412 ± 0.0042 K
		3	+ 13.8 ± 1.9 +	– 6.6 ± 2.2 K	– 7.8 ± 1.9 +	– 5.4 ± 1.7 –	0.0 ± 0.0	0.0 ± 0.0	+ 0.0042 ± 0.0011 –	+ 0.0002 ± 0.0001 +
		7	+ 4.9 ± 0.7 –	– 4.0 ± 1.1 –	+ 2.2 ± 0.3 +	– 3.7 ± 1.1 +	0.0 ± 0.0	0.0 ± 0.0	not determined	
	EM	A	not determined						+ 0.0403 ± 0.0040 –	+ 0.0512 ± 0.0064 –
		1	+ 29.3 ± 2.2 –	– 7.6 ± 3.3 –	+ 12.7 ± 2.1 –	+ 6.1 ± 2.2 –	6.6 ± 0.8 +	4.6 ± 1.2 +	– 0.0220 ± 0.0016 –	+ 0.0368 ± 0.0024 –
		3	– 15.6 ± 2.2 +	– 5.7 ± 1.9 –	– 8.7 ± 1.1 +	– 5.4 ± 1.6 –	0.0 ± 0.0	0.0 ± 0.0	+ 0.0047 ± 0.0017 K	+ 0.0007 ± 0.0001 K
		7	+ 7.1 ± 0.8 –	+ 3.8 ± 0.8 –	+ 3.3 ± 0.9 –	– 4.3 ± 0.5 –	0.0 ± 0.0	0.0 ± 0.0	not determined	
	WM	A	not determined						+ 0.0382 ± 0.0037 –	+ 0.0490 ± 0.0062 –
		1	+ 29.5 ± 2.0 K	– 8.8 ± 3.2 K	+ 18.9 ± 1.2 +	+ 6.2 ± 2.2 –	10.7 ± 1.1 K	4.9 ± 0.7 +	+ 0.0151 ± 0.0012 +	+ 0.0319 ± 0.0019 +
		3	– 20.3 ± 1.5 –	– 4.9 ± 2.4 –	– 10.8 ± 1.7 –	– 4.9 ± 1.9 –	0.0 ± 0.0	0.0 ± 0.0	+ 0.0019 ± 0.0002 +	+ 0.0005 ± 0.0001 –
		7	+ 5.3 ± 0.5 –	+ 3.0 ± 1.2 –	+ 1.3 ± 0.5 +	– 5.3 ± 0.6 K	0.0 ± 0.0	0.0 ± 0.0	not determined	
Litovel	WM	P	not determined						0.0250 ± 0.0023	0.0141 ± 0.0024
		A	not determined						+ 0.0420 ± 0.0029	+ 0.0572 ± 0.0031
		1	not determined						+ 0.0327 ± 0.0012	+ 0.0373 ± 0.0018
Židlochovice	WM	P	not determined						0.0238 ± 0.0034	0.0130 ± 0.0011
		A	not determined						+ 0.0407 ± 0.0039	+ 0.0523 ± 0.0039
		1	not determined						– 0.0220 ± 0.0016	+ 0.0368 ± 0.0024

parameters expressed as arithmetic means ± standard deviations, NM – northern margin, SM – southern margin, EM – eastern margin, WM – western margin, P – stand, A – margin of the regenerated plot, 1 – margin of stand crown projections reaching into the plot, 3 – at a distance of 3 m, 7 – at a distance of 7 m from the margin of crown projections towards the centre of the plot, significance of differences in results in dependence on the distance from the stand margin to the centre of the regenerated plot at each cardinal point is denoted in front of the arithmetic mean: significant (+), non-significant (–), significance of differences in results between the cardinal points at the same measuring point is denoted behind the standard deviation: significant (+), non-significant (–), K – aspect with the highest average value detected at the given measuring point regardless of cardinal points, all values detected at the remaining cardinal points tested in relation to this value

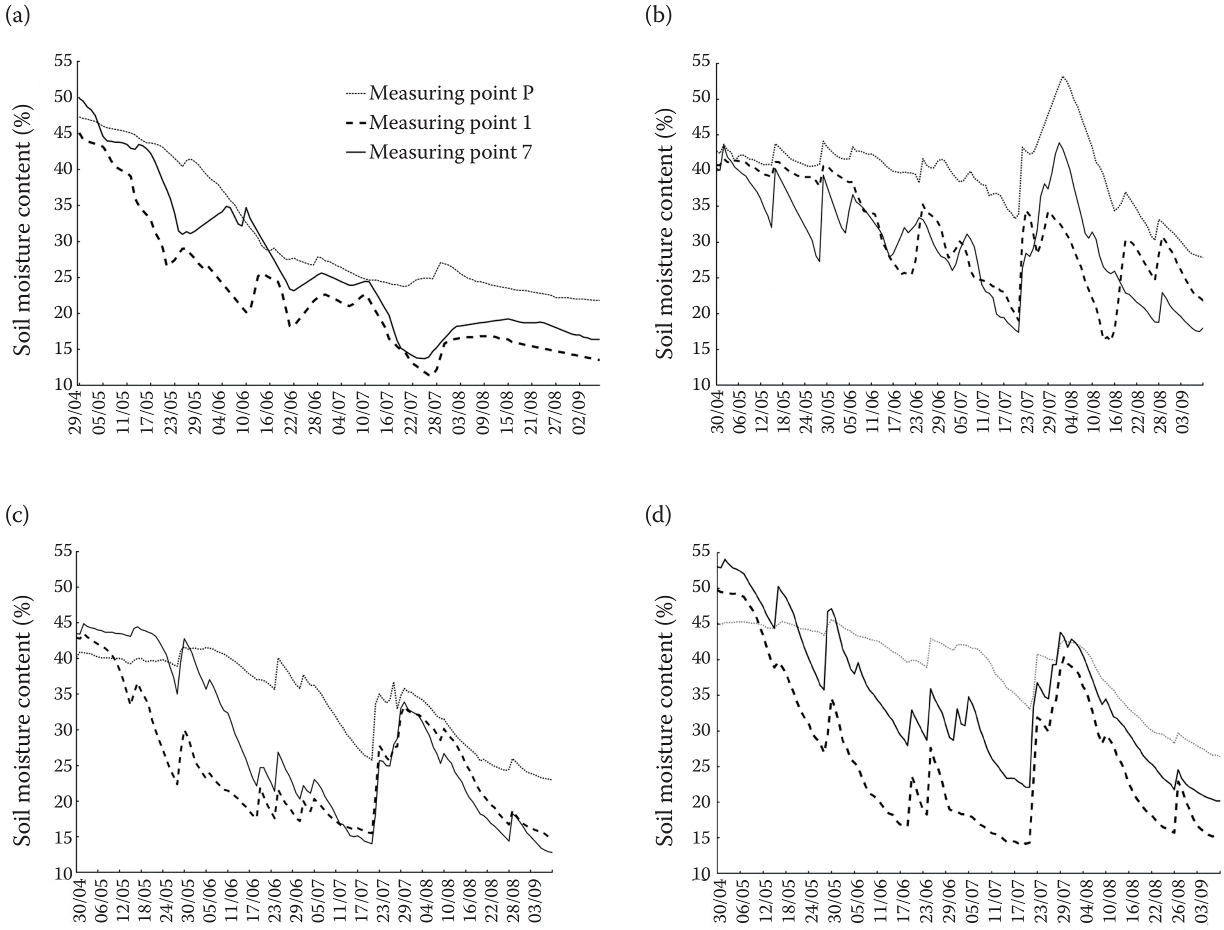

Fig. 1. Soil moisture content at the northern (a), southern (b), eastern (c), western (d) margin of regenerated plot at the Lanžhot site during the studied period

P – stand, 1 – margin of stand crown projections reaching into the plot, 7 – at a distance of 7 m from the margin of crown projections towards the centre of the plot

Global solar radiation

Approximately the same radiation was measured on the margins of crown projections (1) and at the distance of 7 m from the margin of crown projections (7) at the eastern and western margins (Table 4). The radiation measured on the same points at the northern margin was by up to 20% lower and the lowest radiation (ca. by 50%) was recorded at the southern margin.

DISCUSSION

The results of our research showed that young oaks exhibiting the worst growth were those occurring on the margin of the regenerated plot in the immediate vicinity of the adult stand margin. The adverse influence was decreasing with the increasing distance from the stand margin towards the centre of the regenerated area and fading out at a distance of ca. 7 m from the crown projections of marginal trees. In general, mortality was decreasing while the shoot length, root collar diameter, root system size and the depth of skeletal roots were increasing from the stand margin towards the centre of the regenerated plot. Root system form and rooting depth are parameters of the analysed marginal young oak trees that differed most from the normally growing oak trees.

In the course of its life, the root system of oak takes different shapes. In youth, the oak usually develops one taproot, which rapidly penetrates into depth or may be substituted by a greater number of substitute vertical roots (Köstler et al. 1968; Schüte, Kim 1993; Mauer et al. 2002). The intensity of growth into depth is notable. Biebelriether (1962) informed that the taproots of oak trees from sowing reached into the depth of 40–60 cm at three years of age, 80–100 cm at 10 years and 80–110 cm

Table 4. Global solar radiation in the period from 1 May to 30 September at Lanžhot site

Site	Location	Measuring point	Radiation ($Wh \cdot m^{-2}$)	% of the maximum
Lanžhot	NM	open area	728,529	100.0
		1	356,586	48.9
		7	605,611	83.1
	SM	open area	728,529	100.0
		1	110,668	15.2
		7	202,739	27.8
	EM	open area	728,529	100.0
		1	268,907	36.9
		7	537,752	73.8
	WM	open area	728,529	100.0
		1	205,533	28.2
		7	455,997	62.6

NM – northern margin, SM – southern margin, EM – eastern margin, WM – western margin, 1 – margin of stand crown projections reaching into the plot, 7 – at a distance of 7 m from the margin of crown projections towards the centre of the plot

at 30–40 years. The intensive growth into depth slows down after the tenth year of age (Polomski, Kuhn 1998). At the age of 10–15 years, horizontal branches develop in the upper part of the taproot, and at the age of 30–50 years, the original root system dominated by perpendicularly growing taproot or substitute taproots changes into the heart-shaped root system (Köstler et al. 1968). However, the young oaks we analysed developed a shallow root system with a large proportion of L malformations (even oak trees from sowing). Thus, the root system penetration into greater depths was apparently inhibited by some factor. Similarly, Slavík et al. (1957) recorded the impaired development of taproot, which was irregular and crooked in seedlings from sowing growing under the stand and on the margin of the gap. In the gap, the authors observed at all locations (with the exception of a zone near the stand marginal trees) a much sturdier taproot, penetrating deep into the A2 horizon or into the more firmly packed B horizon already in the first growing season. Mariotti et al. (2015) specified that the allocation of both shoot and root system biomass in sheltered plants was reduced relative to unprotected plants, and biomass was allocated mostly to the shoot system. In contrast, plants without shelters invest more resources toward a larger, wider root system.

Our research of soil moisture indicated that soil moisture content near the stand margin dropped below 20% on all locations (NM, SM, EM, WM) during a greater part of the growing season. This soil moisture decrease was not primarily (or completely) induced by solar radiation but rather by the considerably increased root density (root competition). Adult oak trees feature a heart-shaped anchoring root system with the forked main lateral roots from which anchors, usually aslant and rarely perpendicular, penetrate into a depth of 150–200 cm (Köstler et al. 1968). According to these authors, some 80% of root mass falls to horizontal roots, which distinctly differ from the vertical ones. Although the strong root system of oaks can reach into deep soil layers, the main root biomass occurs in upper soil horizons. An analysis of two 150-year-old pedunculate oaks done by Lucot and Bruckert (1992) also demonstrated that the root system had two clearly defined parts: a superficial system at a depth of 0–60 cm and a deep root system reaching below 60 cm. The density of the superficial root system was higher inside a circle of 3 m in diameter from the stem and some roots reached as far as to a distance of 20 m from the stem. The deep root system occurred namely inside a circle sized 2.0–2.5 m in diameter and the deep roots were concentrated at a depth of 60–120 cm. The distribution of horizontal skeletal roots was in line with the distribution of fine roots, the main absorption organs of the tree.

Slavík et al. (1957) informed that there exists a clearly defined zone around the stand marginal trees, the soil moisture content of which differs from that in the gap centre. Within this root zone, they found only a slight differentiation showing in the mild increase of moisture content towards the stem. The soil moisture suddenly changed behind a certain boundary in the direction from the stem. According to the authors, drying out of the stem surroundings and assumed rhizosphere exhibited a larger amplitude than the neighbouring area of the gap, namely on sunny days. Our analyses confirmed that the decreasing soil moisture content was induced primarily by the high density of fine roots in the soil in the layer 30–40 cm and especially in the layer 70–80 cm. As compared with the stand (P), the biomass of fine roots in the layer 30–40 cm increased twice and up to twelve times in the layer 70–80 cm on the margin of the regenerated plot (A). On the margin of stand crown projections (1), the biomass of fine roots in the layer 30–40 cm was the same as in the stand (P) while in the soil layer 70–80 cm it was greater up to ten times.

The lack of water induced not only the smallest rooting depth of young oaks on the regenerated plots but also a radical change in the root system development into the L shape. A likely reason for the malformation is the fact that the deep root system of adult trees growing on the stand margin takes up all groundwater. Therefore, the taproots of marginal young oaks on the regenerated plot do not penetrate into depth but rather spread horizontally with the soil surface in order to make use of water from atmospheric precipitation only. The changes were recorded on all cardinal points of the regenerated plot and were induced by the greater root density of marginal oak trees towards the centre of the regenerated plot. Since the roots of pedunculate oak reach as far as ca. 2–4 m behind the crown projection, the orientation according to crown projections is useful in practice. As stated by Slavík et al. (1957), the gap area with the higher soil moisture content is distinctly demarcated by the circumference of the root zones of adult marginal trees. This boundary is also a place of the sudden change of ecological conditions.

The marginal trees of the stand respond by accelerated growth and by the branching of roots in the direction towards the centre of the regenerated area. According to Slavík et al. (1957), the boundary of soil moisture drawing towards the gap centre slightly shifted within the three years of monitoring. The reason is that unlike in the stand with the closed canopy and root competition, the soil moisture content on the regenerated area increased after the trees had been felled. This is why the adult trees responded to the situation by shooting their roots to spaces with a greater water supply. Solitary oak trees show similar and often even stronger effects. The negative effects are observed at all locations (NM, SM, WM, EM) confirming once again that the effect of light is not in question because in solitary trees one cannot speak about insufficient solar radiation. Libus and Mauer (2009) recorded a distinctly increased density of fine roots reaching to a depth of 120 cm under the entire diameter of the crowns of solitary trees and a critical water deficiency in the upper soil layers. That the effect of solar radiation and weather oscillations (precipitation and related oscillation of soil moisture) is not in question is documented also by the fact that the impact of the stand margin does not fade out with time but persists.

Thus, the impaired development of young oaks in the immediate vicinity of the stand margin and up to a certain distance from the crown projections of marginal trees primarily results from the competition of roots for water. This can be proved also by the boosted growth of young plants after the roots of old trees are disabled by digging around their circumference as described for example by Fabricius (1929 ex Köstler et al. 1968). Nevertheless, our studies (Mauer et al. 2002) as well as the works of other authors (Schüte, Kim 1993; Kühne, Bartsch 2005) indicate that the root system distribution does not always have to be regular in the trees of the adult stand. Therefore, it happens that a young plantation does well on some part of the margin of the regenerated plot even under the crown projections or at places where a grown-up oak tree is missing in the stand margin.

CONCLUSIONS

The paper analyses biometric parameters of aboveground part growth, mortality, root system architecture in young pedunculate oaks and root density of the soil profile on the margin of regenerated stands of pedunculate oak on alluvial sites in dependence on the location (NM, SM, WM, EM) of the regenerated plot in relation to cardinal points and on the distance from the margin of the adult stand. Complementary surveys were performed to determine soil moisture content and solar radiation at the same measuring points. Main conclusions derived from the implemented surveys are as follows:

(*i*) The greatest impact of the stand is observed at all times on the margin of the regenerated area; it weakens towards the centre of the regenerated plot and fades away ca. 7 m behind the crown projection of trees of the neighbouring adult stand regardless of locations (NM, SM, WM, EM). From the stand margin towards the centre of the regenerated plot, mortality is decreasing while the aboveground part length, root collar diameter, root system size and the depth of skeletal roots are increasing;

(*ii*) The density of roots of 2.0–10.0 mm in diameter and namely fine roots in the soil markedly increases under the entire area of crown projections of stand marginal trees with no regard to locations (NM, SM, WM, EM). At these places, both planted oaks and oaks from sowing create a shallow root system deformed into L;

(*iii*) Although some differences in global solar radiation were recorded, soil moisture under crown projections of stands reaching into the regenerated plot decreases below 20%;

(*iv*) The reason for the irregular growth of young oaks on the margins of the regenerated area is the high density of roots of marginal adult trees of the neighbouring stand, which induces a critical water deficiency under their crown projections.

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