The outcomes of *Quercus robur* natural regeneration after clear-cutting in the north-eastern part of Ukraine

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Abstract

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Enabling natural seed regeneration is important because natural stands grown from seeds are more productive compared to vegetative and artificial ones; they are also more resistant to adverse environmental factors and climate change. The aim of the study was to assess natural regeneration after clear-cutting in oak stands in the north-eastern Ukraine. The research was carried out in stands where regeneration cutting was carried out in years with different oak fruiting intensity. According to the recent inventory, the total regeneration quantity in clear-cut plots was from 16,800 to 28,900 stems ha^{-1}, including 12,600–19,300 stems ha^{-1} of oak (60–85% of the total number), and a greater number of the regenerated oaks was recorded in the years of medium, good and very good acorn yield. It was established that the cutting must be carried out precisely in such years, preceded by pre-harvest cultural activities to promote oak natural regeneration. The composition of the formed young stands is optimal and meets the objectives of forest management in the study region.

Keywords

acorns, oak fruiting intensity, pedunculate oak, regeneration abundance, seedlings

Introduction

Pedunculate oak (*Quercus robur* L.) is one of the most common tree species in Ukraine. The area of oak stands is 1.7 million hectares, which is 28% of the total forest area of Ukraine (Kopiy et al., 2017; Tkach et al., 2019). Oak forests perform important ecological and protective functions and are also a source of high-quality wood (Tkach et al., 2021).

Oak habitats can persist for centuries due to their long life and the durability of the dead wood. Therefore, oak is one of the most important trees for endangered invertebrates, lichens, fungi, bats and birds (Thor et al., 2010; Felton et al., 2016).

One of the important tasks of forest management in oak stands is to enhance natural regeneration of oak after clear-cutting. Natural regeneration of forests most fully corresponds to the framework of close-to-nature forest management (Brang et al., 2014; Spathelf et al., 2015; Krynytskyi et al., 2017).

Natural oak stands of seed origin are more resistant to adverse abiotic and biotic factors and climate change (Dobrowolska, 2006); they are more productive compared to vegetative and artificial ones (Tkach and Holovach, 2009).

The success of natural oak regeneration significantly depends on many factors. Among them are the mother stand characteristics before cutting such as an age, relative density of stocking, oak proportion in the composition (Březina and Dobrovolný, 2011; Chygrynets et al., 2016), the level of shrub and grass layers development (Löf, 2000; Bobiec et al., 2011; Mölder et al., 2019), late spring and early autumn frosts and extreme air temperatures (Chaar and Colin, 1999; Krstic et al., 2018). Some studies also point to such factors as sufficient light for oak trees (Březi-

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na and Dobrovolný, 2011; Kanjevac et al., 2021) and the intensity of oak fruiting in the year of mother stand cutting (Martiník et al., 2014; Schweitzer et al., 2016).

The successful oak regeneration at the seedling stage is dependent on multiple environmental factors that often influence each other, including light availability, site conditions, competing vegetation, browsing damage, and pathogens (Jensen and Löf, 2017).

The possibility of natural seed regeneration of valuable oak forests in the north-eastern part of Ukraine has recently received considerable attention (Didenko, 2008; Chygrynets et al., 2016; Rumiantsev et al., 2018; Tkach et al., 2020; Bondar et al., 2020). However, the issue remains relevant due to the negative trend towards a reduction in the area of natural oak forests in the region (Tkach et al., 2019). The aim of the study was to assess the success and state of natural regeneration of oak and other valuable species from the composition of young growth after clear-cutting in oak stands in the north-eastern Ukraine.

Materials and methods

The study site is located in the north-eastern part of Ukraine (Kharkiv region, Kharkiv Forest Research Station). The sample plots (SP) were established in 105–110-year-old oak stands of vegetative origin with a relative density of stocking of 0.72–0.84 and 80–100% of pedunculate oak in the composition (Table 1). The stands grow on the slopes with south (SP1 and SP3) and south-eastern-facing (SP2) with a slope angle of up to 10°.

The climate of the study region is temperate continental. The mean air temperature varies from + 21 °C in the summer to –7 °C in the winter. The growing season is on average 190 ± 5 days. Annual rainfall averages 492 mm, of which 280 mm falls in the growing season. The snow cover height is 18–28 cm (*Ekolohichnyy pasport Kharkivs'koyi oblasti*, 2021).

In the oak stands, regeneration cutting was carried out in a strip-gradual way by continuous cutting of trees in strips 25 m wide in combination with measures to promote natural regeneration, such as soil scarification. The cut plot area was 0.25 ha (25 × 100 m). All the cut plots were left for the further natural regeneration. After continuous cutting of trees in strips, the unfelled strips between strip cuttings were left in the stands. The widths of the unfelled strips reached double or triple the width of the cut strips. In the unfelled strips, dead and damaged trees had been removed. After the closing of the regenerating young stand at the cut area, the next plot of the same size (25 × 100 m) was cut in the remaining unfelled strip, and the first thinning was carried out in the previously developed young stand.

Pre-harvest cultural activities were carried out in all plots earlier, in the summer, to promote natural oak regeneration. The activities included soil scarification and removal of undergrowth and all other species from the stands. Dead and weakened oak trees with poor acorn production were also removed.

The stand on SP1 was cut in December 2009. That year was marked by a good acorn yield with the fruiting level 4 by the Kapper's scale (Pasternak, 1990). The stand on SP2 was cut in December 2017. The year was characterized by a medium acorn yield with the fruiting level 3. The stand on SP3 was cut in December 2013; the year was marked by a very good acorn yield with the fruiting level 5.

The fruiting success in the investigated oak stands was estimated visually in points according to Kapper's scale (Pasternak, 1990). This scale consists of six levels (points), ranging from 0 to 5:
"0" – no acorn yield,
"1" – very poor acorn yield (there are very few acorns),
"2" – poor acorn yield (poor fruiting of trees in the stands),
"3" – medium acorn yield (average fruiting of trees in middle-aged and mature stands),
"4" – good acorn yield (good fruiting of trees in middle-aged and mature stands),
"5" – very good acorn yield (abundant fruiting of trees in middle-aged and mature stands).

Table 1. Characteristics of the studied oak stands and their coordinates

Research plot	Composition (%)	Age (year)	Relative density of stocking	Stock (m^3 ha^{-1})	Latitude	Longitude
SP1	Oak 80%–Ash 20%–N-Maple–Lime	105	0.79	320	36°06'09"	50°03'54"
SP2	Oak 90%–Lime 10%–F-Maple	110	0.84	270	36°18'55"	50°11'04"
SP3	Oak 90%–Lime 10%–N-Maple,F-Maple	105	0.72	250	36°16'29"	50°01'27"

Oak = pedunculate oak (*Quercus robur* L.); Ash = common ash (*Fraxinus excelsior* L.); N-Maple = Norway maple (*Acer platanoides* L.); Lime = small-leaved lime (*Tília cordata* Mill.); F-Maple = field maple (*Acer campestre* L.).

Table 2. Scale for natural regeneration assessment

Natural regeneration success rate	Regeneration abundance (%)	Number of vigorous regenerating trees at the age of 4–8 years (stems ha^{-1})
Good	≥66	≥6,000
Sufficient	40–65	3,000–5,999
Insufficient	20–39	1,500–2,999
Poor	≤19	≤1,499

In addition, in order to confirm fruiting levels, we collected acorns on accounting sites of 1 m^2 at the end of October. These sites were laid out on transects (parallel lines) every 10 m; the distance between transects was 10 m. There were three transects on each of sample plots. Accordingly, 30 sites were laid out on each of the sample plots. In total, 90 sites were established.

The acorns were collected separately from each site, followed by their distribution by quality categories: "healthy" and "damaged" (Didenko, 2008). Acorns without visible signs of damage were assigned to the "healthy" category. The "damaged" category included acorns with holes caused by acorn weevil (*Curculio glandium* Marsh.) and acorn moth (*Cydia splendana* Hbr.) as well as acorns damaged by rodents or birds.

The following year after cutting – in 2010 at SP1, in 2018 at SP2 and in 2014 at SP3 – we recorded the young seedlings up to 1 year old of oak and other species, developed from fallen seeds. Regenerating seedlings were inventoried on circular accounting sites of 10 m^2 each (R = 1.78 m), laid out along the diagonals of the clear-cut areas (Pasternak, 1990). Within each sample plot, 14 sites were established that covered at least 5% of the area of the cutting site. The seedlings were attributed to species. The abundance for each of the species was defined as a percentage ratio of the number of sites with its presence to the total number of established sites. The results of natural regeneration was assessed according to the national scale developed (Pasternak, 1990). Prior to that, the numbers of accounted oak seedlings were converted to the group of 4–8-year-old regeneration using a factor of 0.2, which takes into account seedling mortality during the first three years of life. The number of regenerating oak trees at the age of 4–8 years and their abundance were taken into account during the assessment (Table 2).

We carried out another inventory of plants within the formed young stands at the end of 2021 (SP2 and SP3) and 2022 (SP1). At the time of the last inventory, the age of trees in the young stands was 13 years at SP1, 4 years at SP2 and 8 years at SP3.

Counting of the number and determination of the main mensuration characteristics of plants in young stands were also carried out on circular sites of 10 m^2 in size. Plant number dynamics in natural young stands was analysed based on the average number of pedunculate oak and other species per 1 ha.

Data samples were processed by methods of variation statistics using the Microsoft Excel software package. The levels of variability in the number and weight of acorns were assessed by the scale developed by Mamaev (1972). For that, the coefficient of variation (CV, %) was calculated. According to the Mamaev's scale, the following variability levels for the characteristics were identified: very low ($CV < 7\%$), low ($CV = 8–12\%$), medium ($CV = 13–20\%$), increased ($CV = 21–30\%$), high ($CV = 31–40\%$), and very high ($CV > 40\%$).

Normality tests, one-way analysis of variance (ANOVA), Tukey HSD test with a significance level of $p < 0.05$ were performed for data analyses.

The Box-Cox transformation was used to transform the data to the normal distribution, stabilize group variances and meet the homoscedasticity condition (Hammer et al., 2001). The Tukey's pairwise ANOVA (Hammer et al., 2001; Delacre et al., 2019) was used to find statistically significant differences between the statistical samples of quantity and quality of acorns (Table 3) and height and diameter between species (Table 4).

Results

Under the canopy of oak stands, after a year of a very good acorn yield with the fruiting level 5 by Kapper's scale (Pasternak, 1990), we recorded 184,500 acorns per ha with a total weight of 617.8 kg ha^{-1}. Also, under the canopy of oak stands, after a year of a good acorn yield with the fruiting level 4, the number of acorns was 16.5% less, and after a medium acorn yield year with the fruiting level 3 there was 36.3% decrease (Table 3).

We noted a significant number of damaged acorns, which varied within 29–34%. This greatly affected the number of oak seedlings (one-year-old plants) that appeared the following year. Moreover, as the intensity of oak fruiting increased, the number of damaged acorns decreased.

The year after clear-cutting, the number of young oak seedlings on the clear-cuts ranged from 30,500 to 70,400 per ha. The largest their quantities were registered in years with a highest oak fruiting intensity.

The inventories made in September 2021 and 2022 in

Table 3. Quantity and quality of pedunculate oak acorns under the canopy of oak stands designated for clear-cutting

Composition (%)	Age (years)	Acorns (stems ha^{-1} / kg ha^{-1})		
		Healthy	Damaged	Total
SP1 – good acorn crop (fruiting level 4)				
Oak 80%–Ash 20%–N-Maple–Lime	105	106,300[a]/372.1	47,800[b] / 163.0	154,100 / 535.1
SP2 – medium acorn crop (fruiting level 3)				
Oak 90%–Lime 10%–F-Maple	110	77,100[a]/288.8	40,400[b] / 141.9	117,500 / 430.7
SP3 – very good acorn crop (fruiting level 5)				
Oak 90%–Lime 10%–N-Maple,F-Maple	105	131,200[a]/443.5	53,300[b] / 174.3	184,500 / 617.8

Oak = pedunculate oak (*Quercus robur* L.); Ash = common ash (*Fraxinus excelsior* L.); N-Maple = Norway maple (*Acer platanoides* L.); Lime = small-leaved lime (*Tilia cordata* Mill.); F-Maple = field maple (*Acer campestre* L.). Different letters in the columns (a, b) indicate significant difference between treatments (p < 0.05, Tukey's pairwise ANOVA).

Table 4. Natural regeneration in young stands after clear-cutting

Mensuration characteristics	Statistical parameters	Oak	Ash	N-Maple	F-Maple	Lime	Elm
		SP 1– 13-year-old stand					
Quantity	stems ha–1	12,600	3,400	500	–	300	–
	(%)	75	20	3		2	
Height	$M \pm m$ (m)	4.0 ± 0.55[a]	3.6 ± 0.53[a]	3.8 ± 0.52[a]	–	3.7 ± 0.33[a]	–
	max/min (m)	5.5/2.4	5.0/2.4	4.5/3.0		4.2/3.0	
	CV (%)	14	15	14		9	
Diameter	$M \pm m$ (cm)	2.7 ± 0.95[a]	2.1 ± 0.49[b]	2.1 ± 0.39[a]	–	2.6 ± 0.41[a]	–
	max/min (cm)	4.7/0.9	3.0/1.1	2.6/1.4		3.5/1.6	
	CV (%)	36	23	19		16	
Abundance	%	100	69	24	–	18	–
		SP 3 – 8-year-old stand					
Quantity	stems ha^{-1}	19,300	1,000	1,400	–	900	–
	(%)	85	5	6		4	
Height	$M \pm m$ (m)	2.2 ± 0.30[a]	2.4 ± 0.43[b]	2.4 ± 0.47[a]	–	2.4 ± 0.37[a]	–
	max/min (m)	3.0/1.5	3.0/1.5	3.2/1.6		2.9/2.0	
	CV (%)	14	18	19		19	
Diameter	$M \pm m$ (cm)	1.5 ± 0.57[a]	1.9 ± 0.91[b]	1.8 ± 0.31[a]	–	1.9 ± 0.23[a]	–
	max/min (cm)	3.1/0.2	4.3/0.3	2.1/1.0		2.5/1.6	
	CV (%)	38	47	18		12	
Abundance	%	100	24	48	–	30	–
		SP 2 – 4-year-old stand					
Quantity	stems ha^{-1}	17,200	700	6,500	1,800	1,100	1,600
	%	60	2	23	6	4	5
Height	$M \pm m$ (m)	0.6 ± 0.15[a]	0.9 ± 0.23[b]	1.0 ± 0.25[b]	0.9 ± 0.25[b]	0.6 ± 0.14[a]	0.8 ± 0.16[b]
	max/min (m)	1.1/0.4	1.4/0.6	1.4/0.6	1.5/0.5	1.0/0.4	1.1/0.6
	CV (%)	24	24	25	27	22	19
Abundance	%	100	18	81	54	42	48

Species in the composition of young stands: Oak, Ash, N-Maple, F-Maple, Lime, Elm.

Oak = pedunculate oak (*Quercus robur* L.); Ash = common ash (*Fraxinus excelsior* L.); N-Maple = Norway maple (*Acer platanoides* L.); F-Maple = field maple (*Acer campestre* L.); Lime = small-leaved lime (*Tília cordata* Mill.); Elm = Scots elm (*Ulmus glabra* Huds.); $M \pm m$ – mean value of a mensuration characteristic and its average deviation; max – maximal value of a mensuration characteristic; min – minimal value of a mensuration characteristic; *CV* (%) – coefficient of variation. Different letters in the columns (a, b) indicate significant difference between treatments ($p < 0.05$, Tukey's pairwise ANOVA).

13-, 8-, and 4-year-old stands showed that natural young stands with predominance of pedunculate oak in the composition were formed in all plots after clear-cutting. The oak proportion was 60–85% of the total number of plants, depending on the age of the stands (Table 4).

13-year-old stand

In the composition of 13-year-old stand developed after clear-cutting a year after good acorn yield (fruiting level 4), there were 12,600 pedunculate oak trees per hectare (75% of the total number). Other species included common ash (*Fraxinus excelsior* L.) – 3,400 stems ha^{-1}, or 20%, Norway maple (*Acer platanoides* L.) – 500 stems ha^{-1}, or 3%, and small-leaved lime (*Tília cordata* Mill.) – 300 stems ha^{-1}, or 2%.

Pedunculate oak and common ash trees were uniformly distributed through the area (their abundances were100% and 69%, respectively), while Norway maple and small-leaved lime trees grew in groups (with abundances of 24% and 18%, respectively).

The average height of the oak trees in the studied young stand was 4.0 ± 0.55 m. The admixed species had a lower height. The height of common ash was 3.6 ± 0.53 m, Norway maple 3.8 ± 0.52 m and small-leaved lime 3.7 ± 0.33 m. The average diameter of the oak in the studied stand was 2.7 ± 0.95 cm. The admixed species had smaller diameters. The diameter was 2.1 ± 0.49 cm for both com-

Fig. 1. Pedunculate oak and other species in 13-year-old natural stand.

mon ash and Norway maple (2.1 ± 0.39 cm) and 2.6 ± 0.41 cm for small-leaved lime. This was the result of the timely silvicultural interventions, which included thinning of the dense groups of admixed species (Norway maple, small-leaved lime and common ash) regeneration inhibiting oak growth. The thinning created optimal conditions for the further successful growth of oak trees, i.e. sufficient amount of overhead light and shading from the sides by admixed species. The above activities also provided the desired composition of young stands with a predominance of oak and a sufficient number of other species (Fig. 1).

The coefficients of variation in height ranged from 9 to 14%, revealing low and medium variability of the value. For diameter, the coefficients of variation were 16–36%, which indicates average, increased, and high variability of the studied characteristic. This variability is due to the differentiation of trees after canopy closing and the beginning of their intensive growth in diameter. In general, significant variability in the average diameter is typical for stands in this age.

8-year-old stand

In 8-year-old stand developed after clear-cutting following the year with a very good acorn yield (fruiting level 5), the number of oaks was 19,600 stems ha-1 (85% of the total tree number). Other species included common ash (1,000 stems ha–1, or 5%), Norway maple (1,400 stems ha^{-1}, or 6%) and small-leaved lime (900 stems ha^{-1}, or 4%).

Pedunculate oak was uniformly distributed over the plot; the abundance was 100%. Norway maple had non-uniform distribution with 48% abundance, while both common ash and small-leaved lime grew in groups, with 24% and 30% abundance, respectively. The average oak tree height was 2.2 ± 0.30 m. The admixed species had a slightly higher height of 2.4 m.

The average diameter of the oak trees was 1.5 ± 0.57 cm. The admixed species had a higher diameter: both common ash – 1.9 ± 0.91 cm, small-leaved lime – 1.9 ± 0.23 cm, and Norway maple – 1.8 ± 0.31 cm.

In 2021, silvicultural activities were carried out in the studied young stand. They included thinning of the dense groups of regenerating admixed species, but despite this, even in 2022, the oak had a lower height and diameter compared to other species. However, this is not extremely crucial: there is no threat of displacing oak from the com-

Fig. 2. Pedunculate oak and other species in 8-year-old natural stand.

position of the young stand in the near future, since the share of other species is only 15% in total (Fig. 2).

The coefficients of variation in height ranged between 14% and 19% that are evidence for the medium variability of the value. The coefficients of variation in diameter were 12–47%, indicating even very high diameter variability. This variability is due to the beginning of a tree differentiation after the canopy closing and intensive growth in diameter.

4-year-old stand

In the 4-year-old stand developed after clear-cutting following the year with a medium acorn yield (fruiting level 3), the number of oak trees was 17,200 stems ha^{-1} (60% of the total tree number). Among other species, Norway maple (6,500 stems ha^{-1}, or 23%), field maple (1,800 stems ha^{-1}, or 6%), Scots elm (1,600 stems ha^{-1}, or 5%), small-leaved lime (1,100 stems ha^{-1}, or 4%) and common ash (700 stems ha^{-1}, or 2%) were found.

Both pedunculate oak and Norway maple were uniformly distributed through the plot, with 100% and 81% abundances, respectively. Field maple (*Acer campestre* L.), Scots elm (*Ulmus glabra* Huds.) and small-leaved lime had non-uniform distribution with 54%, 48% and 42% abundances, respectively. Common ash grew in groups; the abundance was 18%.

The average oak height in the studied stand was 0.6 ± 0.15 m. The admixed species had a higher height, except for the small-leaved lime (0.6 ± 0.14 m). The height of common ash was 0.9 ± 0.23 m, field maple – 0.9 ± 0.25 m; the height of Norway maple was 1.0 ± 0.25 m and Scots elm, 0.8 ± 0.16 m.

Based on the research results, it has been established that there is a serious threat of oak displacement from young stand by more fast-growing admixed species in this plot, in particular, Norway and field maples, Scots elm and small-leaved lime, which are very evenly distributed over the area. To overcome this threat, it is necessary to take measures to regulate the composition of the young stand by thinning out dense groups of admixed species as soon as possible.

The height variation coefficients were within the range of 19–25%, indicating moderate to high variability of the value. This variability is due to the relatively intense growth in height.

It should be noted that, in general, the quantity of oak regeneration in all studied young stands was sufficient for the formation of biologically sustainable and productive forests. The management activities should be aimed at growing stands with such composition and structure.

Discussion

Our results show that in years with a higher oak fruiting intensity, oak stands produce a larger number of healthy acorns, from which oak seedlings arise the following year. In general, the intensity of oak fruiting is one of the most important factors determining the success of the natural regeneration of oak forests (Krynytskyi et al., 2006; Didenko, 2008; Martiník et al., 2014; Schweitzer et al., 2016; Dobrovolný et al., 2017; Rumiantsev et al., 2018). According to Martiník et al. (2014) and Dobrovolný et al. (2017), successful natural regeneration of oak stands occurs immediately in the years following mast years (in the years of cutting) when the number of acorns is sufficient to produce viable oak seedlings. However, oak belongs to tree species that do not bear fruit every year, that is, it has periodicity of fruiting, i.e. alternation of mast and non-mast years. According to some studies (Klimo et al., 2008; Gradečki-Poštenjak et al., 2011; Prévosto et al., 2015), oak masting averages five years (oaks produce acorns once every two to eight years).

We also found that the largest numbers of acorns were concentrated under the oak trees with well-developed crowns and no signs of decline. Thus, our results confirm the findings of Krynytskyi et al. (2006) for the Right-Bank Forest-Steppe of Ukraine (Lviv region). These findings also emphasized that the largest number of healthy acorns was concentrated under the wide canopy of model oak trees. These trees had a good health condition: there were no signs of decline and damage by biotic and abiotic factors.

According to some studies (von Lüpke, 1998; Tobisch, 2010; Březina and Dobrovolný, 2011; Spathelf et al., 2015; Tinya et al., 2020; Stimm et al., 2022), successful natural regeneration of oak can only occur in small areas. It could be at the time of shelterwood cutting when the stand is cut gradually over 20 or more years, or clear-cutting when gaps are cleared. On the other hand, the use of clear-cutting (making gaps in stands) raises debates about the gap size necessary to provide the sufficient light for oak seedling survival and successful competition for nutrients with faster-growing tree species (Kohler et al., 2020; Tinya et al., 2020).

According to Kohler et al. (2020) and Tinya et al. (2020), complete removal of all trees in a relatively short time – less than ten years – could also affect the plant living conditions and oak forest biodiversity. Brang et al. (2014) and Puettmann et al. (2015) suggested avoiding clear-cutting when focusing on the successful oak natural regeneration due to the inconsistency with the principles of close-to-nature forest management. Schweitzer et al. (2016) have a different opinion; their results indicate that clear-cutting can ensure a successful oak regeneration. However, this is possible only with a significant number of pedunculate oak seedlings regenerating prior to the cutting or a sufficient number of acorns in the year of cutting. A proper regulation of the competition for light and soil nutrients among tree species at the initial stage of young tree growth (up to 3–4 years of age) is also required. Our study also shows that clear-cutting in mast years (fruiting level 3 and above) can ensure successful natural regeneration of oak.

Didenko (2008) investigated 180–190-year-old natural oak forests with 90% of oak in the composition in Left-Bank Forest-Steppe of Ukraine. According to his study, almost 127,000 of one-year-old oak seedlings were accounted per ha under the stand canopy after a very good yield year (fruiting level 5; 400,000 acorns per ha). The number of oak seedlings reached 40 per 1 m^2. Based on the further study of this oak regeneration, Didenko (2008) concluded that at a density of one-year-old seedlings above 15 stems m^{-2}, there is almost no threat of the oaks being suppressed by less desirable vegetation. Under such conditions, from 3 to 10 oak trees remain per 1 m^2 at the age of 10 years (6 oaks per m^2 on average). In our case, the density of oak seedlings ranged from 3 to 7 stems m^{-2} the year after cutting, and two oak trees per 1 m^2 in 8- and 14-year-old stands. However, even this number was sufficient for growing young stand of the desired composition.

One of the key phases of the natural young stand development is the phase of initial growth of young seedlings. In this age, their survival is most threatened by less desirable shrub and grass vegetation due to faster height growth (Harmer et al., 2005; Annighöfer et al., 2015; Krstic et al., 2018; Mölder et al., 2019; Kanjevac et al., 2021). Some studies (Ligot et al., 2013; Kohler et al., 2020; Kanjevac et al., 2021) emphasize the threat of suppression of oak seedlings in the first years after the appearance by faster-growing and shade-tolerant tree species, such as European beech (*Fagus sylvatica* L.), common hornbeam (*Carpinus betulus* L.), Norway and field maples, silver (*Tilia tomentosa* Mill.) and small-leaved limes, common ash, Scots elm, etc. These species have the potential to overgrow and eventually suppress oak seedlings if light conditions are unfavourable for a long time (Ligot et al., 2013). With increasing available light, the influence of competing vegetation on the growth of pedunculate oak seedlings is diminished. Accordingly, young oak seedlings require a large amount of light for both survival and further successful development (Kanjevac et al., 2021). In this regard, some authors (von Lüpke, 1998; Ligot et al., 2013; Kuehne et al., 2020; Stimm et al., 2022) highlight the need for removing competing vegetation as early as possible when growing young oak stands, especially in the initial phase of regeneration.

According to our results, after clear-cutting in years with oak fruiting level 3 and higher, natural young stands on the clear-cut areas dominated with pedunculate oak. The oak proportion was 60–85% of the total number of plants, depending on the age of the stand. The presence, already at the age of four years, of more fast-growing and shade-tolerant species in young stands indicates a potential threat of oak shading. In the future it will cause oak loss because it is a light-demanding species and cannot tolerate long-term upper shading (Březina and Dobrovolný 2011; Tkach et al., 2021).

Kanjevac et al. (2021) and Govedar et al. (2021) also noted the presence of competing species for oak (in particular lime and hornbeam) in natural young stands in the north-eastern part of Serbia. Therefore, forest tending should be done timely to regulate competitive relations in natural young stands. The tending includes thinning or completely removing of the dense groups of undergrowth of other tree species around the oak, with manual brush cutters or mechanical tools (von Lüpke, 1998; Ligot et al., 2013; Kanjevac et al., 2021; Tkach et al., 2021, 2022; Stimm et al., 2022). The effectiveness of a particular tending method for natural young oak stands was not considered in this article, as this was not the aim of the study.

Other causes of poor natural regeneration of oak forests are browsing or plant damage by animals, damage to fallen acorns by insects, birds and rodents, as well as plant diseases (Chaar et al., 1997; Bobiec et al., 2011; Březina and Dobrovolný, 2011; Kohler et al., 2020; Dobrosavljević et al., 2020). Our results showed that the share of damaged acorns (i.e. acorns with holes from the acorn weevil and the acorn moth and those damaged by small mammals or birds) was 29–34%. This greatly affected the number of oak seedlings (one-year-old plants) that appeared the following year. However, the number of the remaining healthy acorns was sufficient for the successful natural regeneration of oak stands on clear-cut areas.

Thus, the natural regeneration of oak forests is extremely essential as an element of close-to-nature forest management; under certain conditions, it provides the development of young stands of the desired composition. The formed natural oak forests meet the purpose of forest management, in particular, the cultivation of biologically stable and productive stands and biodiversity conservation. Such forests effectively perform important nature protective, recreational and health-improving functions as well as provide high-quality wood.

Conclusions

The natural regeneration of oak forests was successful in sites after clear-cutting on the south and south-eastern-facing slopes with a slope angle of up to 10°. The clear-cutting was the complete removal of all trees in oak stands in a single action in sites of about 0.25 ha. The width of the cutting strips was 25 m, which was approximately equal to the average height of the stand. The number of all trees in the natural young stands at the age of 4–13 years after clear-cutting was up to 30,000 stems ha^{-1}, including up to 20,000 stems ha^{-1} of oak (up to 85% of the total number).

The microclimatic conditions formed in such sites are favourable for the growth and development of pedunculate oak seedlings. At that, parent stand must be cut in years with high oak fruiting intensity. Cultural techniques should be performed in the parent stands to encourage natural oak regeneration. The techniques include a soil scarification and removing of the undergrowth, all other undesired species, and dead and weakened oak trees with poor fruiting and signs of decline.

The success of the natural regeneration of oak forests largely depends on the oak fruiting intensity in the year when the stand is cut. In addition, special attention must be given further to the regulation of competitive relations between oak and other vegetation.

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