http://silvaworld.org
SilvaWorld
e-ISSN: 2822-6127
https://prensip.gen.tr

RESEARCH ARTICLE

Mortality and Growth in a Sessile Oak [*Quercus petraea* (Matt.) Liebl.]-Dominated Young Stand Managed through Silvicultural Operations of Different Types and Intensities

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ARTICLE INFO

Article History
Received: 08.08.2022
Accepted: 29.08.2022
First Published: 14.09.2022

Keywords
Sessile oak
Cleaning-respacing
Stand silviculture
Crop tree silviculture
Mortality
Growth

ABSTRACT

A small-scale R&D project, including a block with four plots (P1-4) of 200 m^2, was established in 2001 in a 15-year-old sessile oak-dominated stand, regenerated naturally through the application of group shelterwood cutting. In each plot, "potential" final crop trees were selected, based on *vigour-quality-distribution* criteria, and painted. Silvicultural interventions (cleaning-respacing and thinning), of different types and intensities were performed in P1-3 (P4 was kept as control) as well as P5 (500 m^2), established in 2009, in 2001, 2004, and 2009. The mortality intensity between 2001 and 2019 was the highest in P4 and the lowest in P1, with the minimum stand density. Sessile oak showed the highest mortality, followed by Hungarian oak and Turkey oak. The fastest diameter growers were the "potential" final crop trees, their quadratic mean diameter (QMD) reaching values close to 20 cm at 35 (30-40) years in the plots with the lowest stand density. In all plots, trees have reached heights corresponding to the QMD of ca. 15 m, which are typical to a sessile oak stand of high productivity (production class II). The best solution for managing sessile oak young and medium-aged stands seems to be a "dynamic", crop tree silviculture, with the most valuable individuals selected as "potential" final crop trees at the end of thicket stage. These trees should be favoured by subsequent heavy intensity thinning from above, in order to produce timber with as uniform as possible radial increments of 2-3 mm, as requested by veneer and high-quality saw log buyers.

Please cite this paper as follows:

Nicolescu, V. N., Şimon, D. C., Goia, A. M., & Goanță, C. B. (2022). Mortality and growth in a sessile oak [*Quercus petraea* (Matt.) Liebl.]-dominated young stand managed through silvicultural operations of different types and intensities. *SilvaWorld*, *1*(1), 1-15. https://doi.org/10.29329/silva.2022.462.01

Introduction

Oaks (*Quercus* spp.) are the most important broadleaved trees in Europe (cover ca. 21 million ha), of which pedunculate oak (*Q. robur* L.) and sessile oak [*Q. petraea* (Matt.) Liebl.] are the most common, occurring widely across most of Europe, from Scandinavia to the Iberian Peninsula (Lemaire, 2010; Eaton et al., 2016).

In Romania, sessile oak is the dominant oak species. It covers 588,161 ha (over 8 per cent of national forest land, and over 52% of all *Quercus* species), has a mean volume of 284

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m^3 ha^{-1} and produces 7.3 m^3 ha^{-1} yr^{-1} on average (Marin, 2015). It grows in both pure and mixed stands (is a *social species*, more than pedunculate oak) with other oak species (e.g., pedunculate oak; Turkey oak, *Q. cerris* L.; Hungarian oak, *Q. frainetto* Ten.) as well as European beech, *Fagus sylvatica* L.; hornbeam, *Carpinus betulus* L.; maples, *Acer* spp.; common ash, *Fraxinus excelsior* L.; etc. (Negulescu & Săvulescu, 1957; Stănescu, 1979; Stănescu et al., 1997).

Sessile oak is a light-demanding species, but can withstand more shade than pedunculate oak, especially in youth (Ciumac, 1965; Haralamb, 1967; Petrescu, 1971). Consequently, it is regenerated under group shelterwood systems, with large gaps (up to 1.5 x mean height), and the regeneration period is recommended to be short (5-7 years) (Purcelean & Ciumac, 1965; Ciumac, 1967; Haralamb, 1967; Dămăceanu, 1984). In resulting natural regenerations, the intensity of natural mortality is high in the first years i.e., 40-50% of the initial number of seedlings in the second year (Purcelean & Ciumac, 1965; Ciumac, 1967). However, the stand density can be still high (up to 30,000 stems ha^{-1}) at the end of sapling-beginning of thicket stage (Dămăceanu, 1984). Such dense, uniform and single-layered stands, predominantly pure, with tall but slim individuals, are prone to snow bending (Petrescu, 1971).

Sessile oak is a slow-grower in the first decade (it grows in height 10-20 cm yr^{-1} during this period), when the growth is concentrated in the root system. The height growth activates afterwards and reaches up to 50 cm yr^{-1} between 10 and 25 years (Negulescu & Săvulescu, 1957; Haralamb, 1967; Stănescu et al., 1997).

The silvicultural model of Romanian sessile oak stands, imposed by the current technical norms (Anonymous, 2000a), is mostly a *stand silviculture* and includes:

- Cleaning-respacing, started when dominant height (H_{dom}) is 8-10 m (age 15-20 years). It is a *negative selection* (removal of suppressed and poorly formed trees without considering the growth of remaining ones), with moderate intensity, and keeping a canopy cover of minimum 80% (75% in stands with rich understory), and

- Thinning, started when H_{dom} is 12-13 m (age 25-30 years). They are intermediate (from above and from below) and act as *positive selection* [competing trees are removed, to maximize the growth of the best ones (Kerr & Haufe, 2011)]. The intensity of thinning (per cent of standing volume) ranges between 14 (age 21-30 years) and 6 (age 71-80 years), the age when the application of thinning halts as required by the technical norms. Canopy cover after thinning at least 80%.

In valuable sessile oak stands, the same norms recommend (so it is not mandatory) to select (at 30-40 years of age) and paint 200-300 “candidate” final crop trees ha^{-1}, based on the *vitality (vigour)* (the thickest and tallest, part of crown classes I and II, with large crowns) – *quality* (straight, vertical, healthy, without forking, wounds, insect attacks, etc.) - *distribution (spacing)* (as regularly spaced as possible) criteria, in order to reach a stand density of 90-100 trees ha^{-1} final crop trees at rotation age. In this context, one should mention that, under the current norms, with moderate-low intensity interventions halting at early ages, the target density is impossible to be reached and the sessile oak stands have 250-400 trees ha^{-1} at rotation age. This density is much higher than the one recommended in other European countries: Maximum 100 trees ha^{-1} [70-100 in Belgium (Bary-Lenger & Nebout, 1993; Wouters et al., 2000); 80-100 in Austria (Hochbichler, 1993), France (CRPF Aquitaine, 2005), and Germany (Kenk, 1984, Spiecker, 2021); 100 in Switzerland (Schütz, 1993) , Ireland (Joyce et al., 1998; Horgan et al., 2003), and France (CRPF Bourgogne, 2012)], but decreasing to 50-60 trees ha^{-1} [Czech Republic (Dobrovolný & Macháček, 2012)], 50-70 trees ha^{-1} [Sweden (Löf et al., 2016)], 60-70 trees ha^{-1} [France (Sevrin, 1997; Allegrini & Depierre, 2000; Jarret, 2004; Allegrini, 2010; Lemaire, 2010; Le Nail & Decucq, 2021)], 40-80 trees ha^{-1} [Belgium (Balleux, 2005)] or even 30-40 (5) trees ha^{-1} (Baar, 2008, 2010).

The rotation age in sessile oak stands of Romania for wood production depends on target wood assortment: between 120 and 140 years for sawlogs and between 160 and 200 years for veneer logs (Anonymous, 2000b).

Taking into account these circumstances, as well as the interest to: (i) *Reduce the management costs at young ages* and to (ii) *Reduce the rotation age*, in parallel with the *production of top-quality and large diameter sessile oak trees*, a small-scale research and demonstration (R&D) project was launched in Valea Mare Forest District (F. D.) in 2001. The target of this study was to compare two options: *Stand silviculture* vs. *single-tree oriented silviculture*, the latter option including interventions focusing around “potential”, followed by “genuine” final crop trees in order to provide them a *free-growth state* at crown level since young ages (end of thicket-beginning of pole stages of development).

Materials and Methods

The R&D work was carried out in sub-compartment 71E (44°50'42.91"N, 25°21'02.36 E), part of Working Circle IV Râncăciov, Valea Mare Forest District, Dâmbovița County Branch of National Forest Administration-ROMSILVA (Figure 1).

The main characteristics of this sub-compartment are as follows:

a. Site - Area: 6.7 ha; Elevation: 290 m; Plateau; Soil: Luvisol, of high fertility for sessile oak stands; Ground flora: *Carex pilosa*. Climate: D.f.b.x. type; Annual mean temperature: 9.9 ºC, Annual mean precipitation: 688 mm, Aridity (de Martonne) index: 35.

Figure 1. Location of research area

b. Stand (current data) - Species composition: over 90% sessile oak with scattered individuals of Hungarian oak, Turkey oak, hornbeam, European beech, field maple (*Acer campestre* L.), etc.; Mean age: 35 years (range 30-40 years), following the application of group shelterwood cuttings; Production class: II; Rotation age: 130 years; Production target: Sawn timber (d.b.h. at least 48 cm).

The fieldwork started in 2001 and consisted of the following interventions and works:

Year 2001: Establishment of a R&D block of 1,500 m^2 (30 x 50 m), with 4 plots, each of 200 m^2 (20 x 10 m) in each corner. In all plots, "*potential"* final crop trees (7 trees per plot, 350 trees ha^{-1}, at 5-7 m distance) were selected and painted, based on the *vitality (vigour)–quality-distribution (spacing)* criteria. In plot 3, all "potential" final crop trees are of sessile oak, in plot 4 two out of seven trees are of Hungarian oak, and in plots 1 and 2 two out of seven trees are of Turkey oak. All the other "potential" final crop trees (five individuals per plot) in these three plots are of sessile oak. In plots 1-3, cleaning-respacing of different types and intensities were carried out while plot 4 was kept as control.

Year 2004: A further intervention of cleaning-respacing was performed solely in plot 2.

Year 2009: New interventions (thinning) were performed in plots 1, 2, and 3. Establishment of a new R&D plot (no. 5) of 500 m^2 (25 x 20 m), where *potential* final crop trees (17 individuals of sessile oak, 340 trees ha^{-1}) were selected and painted using the same criteria as above. A cleaning-respacing was performed, targeting the *free-growth state* of such trees at crown level.

2001, 2004, 2009, 2019: Measurement of diameter at breast height (dbh), using a Haglöf caliper (precision 0.1 cm), and of four crown radii, at 90 degrees between them, using a metal ribbon (precision 0.5 cm), in all plots.

2001, 2004, 2009, 2015: Measurement of total height (h) using a Romanian hypsometer (precision 10 cm) in all plots.

2017: Assessment of presence of epicormic branches (e.g., length, diameter at insertion point, height of lowest epicormic, etc.), in all plots.

The field data were processed during the office work using Microsoft Excel and the main outputs are: Quadratic mean diameter (d_g), *dbh* increment, basal area (G), height corresponding to the quadratic mean diameter (h_g), mean crown diameter, correlation between initial *dbh* (2009) and *dbh* increment (2009-2019), correlation between *dbh* and mean crown diameter (2019).

Results

Characteristics of Silvicultural Interventions

As the initial stand density (between 7,250 trees ha^{-1} in plot 1 and 9,100 trees ha^{-1} in plot 3), as well as stocking (range 17.55 m^2 ha^{-1} in plot 2 - 20.65 m^2 ha^{-1} in plot 1) were very high in 2001, and no silvicultural interventions have been performed since the stand establishment, the intensity of first cleaning-respacing (2001) in plots 1-3 was *very high* (over 25%) by both number of trees (I_N) and basal area (I_G). Obviously, as the range of diameters was very wide in these plots (coefficient of variation before cleaning-respacing between 35 and 46%), this intervention was *from below*, removing mostly trees from inferior crown (Kraft) classes, 4 (sub-dominant) and 5 (suppressed) (Figure 2). Consequently, the initial (before intervention) coefficient of variation of diameters in plots 1-3, ranging between 43.43% (plot 3) and 49.39% (plot 1) [bigger than the "normal" one in even-aged stands, of 20-40% (Giurgiu, 1979)] was reduced to 20.55% (plot 3) -25.01% (plot 1) but remained very high (46.69%) in plot 4 (control).

The same type of intervention (from below) is obvious when taking into account the coefficient of variation of heights in the same plots: If the initial one (before intervention) was very high, ranging between 25.26% in plot 3 and 26.92% in plot 1 [bigger than the "normal" range in even-aged stands, of 10-20% (Giurgiu, 1979)], it was reduced to values between 9.43% in plot 3 and 12.94% in plot 2.

In 2004, another cleaning-respacing *from below* was performed only in plot 2, to create an obvious stands density and stocking difference between this plot and plot no 3.

In 2009, the third intervention (thinning of different types), with *high* (between 16 and 25%) to *very high* intensities, was carried out in plots 1-3 and 5 (Table 1).

Table 1. Types and intensities of interventions performed in plots 1-3 and 5 in 2001, 2004, and 2009

Plot no.	Intervention performed in ...								
	2001			2004			2009		
	I_N* (%)	I_G** (%)	Type of intervention	I_N (%)	I_G (%)	Type of intervention	I_N (%)	I_G (%)	Type of intervention
1	69.66	39.80	*From below*	-	-	-	41.86	39.30	*From above (détourage)* (Figure 3)
2	57.86	31.00	*From below*	14.93	8.54	*From below*	30.36	21.01	*From below*
3	63.74	34.52	*From below*	-	-	-	28.79	21.60	*Intermediate (mostly from below)*
5	-	-	-	-	-	-	37.50	35.12	*Intermediate (mostly from above) (détourage)*

I_N* = intensity by number of trees; I_G** = intensity by basal area

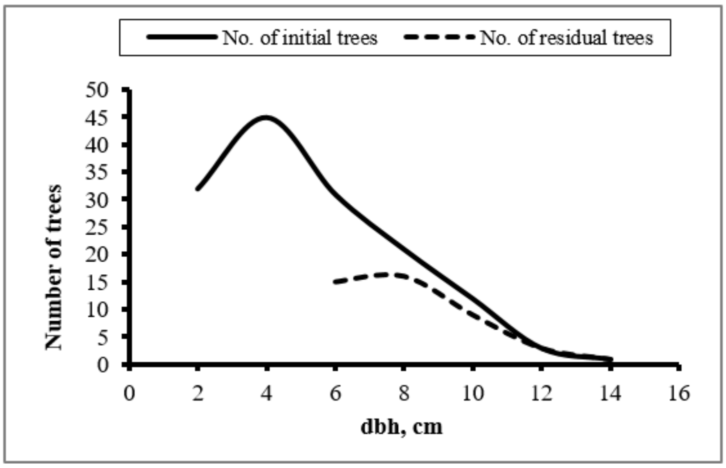

Figure 2. Typical intervention *from below* performed in plot 1 in 2001

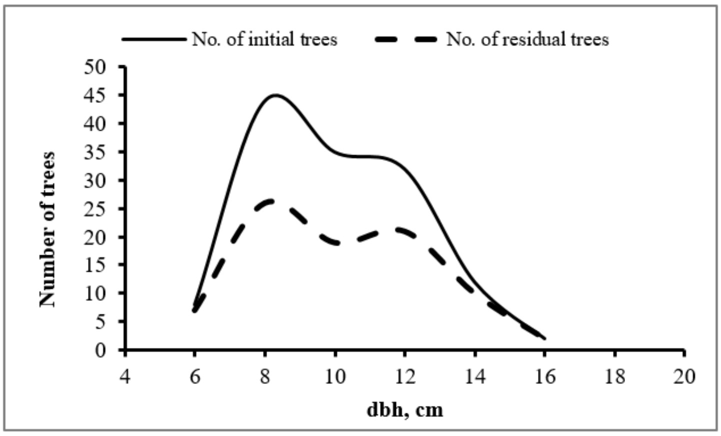

Figure 3. Intermediate (*mostly from above*) (*détourage*) intervention performed in plot 5 in 2009

Natural Mortality and Evolution of Species Composition

The natural mortality of trees (sessile oak: SOAK; Turkey oak: TOAK; and Hungarian oak: HOAK) in plots 1-4 between the establishment of R&D block in 2001 (residual stand) and 2019, as well as their dieback in plots 1-5 since the silvicultural intervention in 2009 (residual stand) are very variable (Table 2).

Table 2. Natural mortality of trees between 2001 and 2019 and in the 2009-2019 period

Plot no.	Initial number of trees in 2001	Natural mortality 2001-2019 (%)	Natural mortality 2009-2019 (%)	Share of natural mortality in 2001-2019 (%)			Share of natural mortality in 2001-2019 (%)		
				SOAK	**TOAK**	**HOAK**	**SOAK**	**TOAK**	**HOAK**
1	2,200	2.27	0	100.0					
2	3,350	14.93	23.08	90.00	10.00		88.89	11.11	
3	3,300	18.18	25.53	100.0			100.00		
4	8.300	83.73	61.43	75.97		24.03	67.44		32.56
5	1,750*	-	23.53		100.0		100.00		

*1,750 trees ha^{-1} in plot 5 in 2009 (year of establishment of that plot)

In both periods, the lowest natural mortality was registered in plot 1, with the lowest stand density after the intervention carried out in 2001 (2,200 tree ha^{-1}), while plot 4 (control), with the highest stand density in 2001 (8,300 trees ha^{-1}) showed the peak of natural mortality. The species most affected by natural mortality in both periods was sessile oak, with a share of dead trees between 75.97% (plot 4) and 100.00% (plots 1 and 3) in 2001-2019, and between 67.44% (plot 4) and 100.00% (plots 2 and 5) in 2009-2019. Hungarian oak contributed secondly to natural mortality in plot 4 (control) (ca. 24.03% in 2001-2019, and ca. 32.56% in 2009-2019 respectively), while Turkey oak contributed to 10-11% of dead trees in plot 2. All of them are light-demanding species, and all dead trees were part of low canopy, belonging to crown classes IV and V. In contrast, no trees of European beech (shade tolerant) or hornbeam (with intermediate shade tolerance) have died during the same periods, even being part of the same crown classes.

Natural mortality, combined with the three silvicultural interventions performed in 2001, 2004, and 2009, led to changes in species composition of different magnitudes in plots 1-5 (Table 3).

Table 3. Evolution of species composition by number of trees in plots 1-5 between 2001 and 2019

Plot no.	Species composition by number of trees in plots 1-5 between 2001 and 2019 (%)			
	2001	**2004 (after intervention)**	**2009 (after intervention)**	**2019**
1	75SOAK 14TOAK 11HOAK	75SOAK 14TOAK 11HOAK	68SOAK 20TOAK 12HOAK	68SOAK 20TOAK 12HOAK
2	90SOAK 9TOAK 1HOR	88SOAK 11TOAK 1HOR	85SOAK 13TOAK 2HOR	83SOAK 13TOAK 4HOR
3	98SOAK 2HOR	98SOAK 2 HOR	98SOAK 2HOR	97SOAK 3HOR
4	69SOAK 29HOAK 1TOAK 1HOR	66SOAK 31HOAK 2HOR 1TOAK	56SOAK 40HOAK 3HOR 1TOAK	37SOAK 52HOAK 7HOR 4TOAK
5	-	-	94SOAK 4HOAK 1HOR 1EB	95SOAK 3HOR 1HOAK 1EB

HOR = hornbeam; EB = European beech

These changes range from ± 1% sessile oak in plots 3 and 5, 7% less sessile oak in plots 1 and 2, to a reverse of species composition in plot 4 (control). In the latter plot, where Hungarian oak was less affected by natural mortality, it took over and reached 52% by number of trees in 2019, compared with 29% in 2001. As hornbeam and European beech trees have not died between 2001-2019 period, their share in species composition has increased from 1-2% (plots 2-4) in 2001 to 7% (plot 4) in 2019.

Effects of Silvicultural Interventions and Natural Mortality on Different Stand Parameters

Stand density (number of trees per hectare)

As mentioned, the stand density at the beginning of interventions (2001) in plots 1-4 was extremely high, ranging between 7,250 trees ha^{-1} (plot 1) and 9,100 trees ha^{-1} (plot 3). Under these conditions, the interventions performed in 2001 (plots 1-3), 2004 (plot 2), and 2009 (plots 1-3 and 5), combined with the *natural mortality* of trees, extremely variable as shown above, had reduced continuously the stand density to values ranging between 1,250 trees ha^{-1} (plot 1) and 1,750 trees ha^{-1} (plot 3) in 2019 (Figure 4).

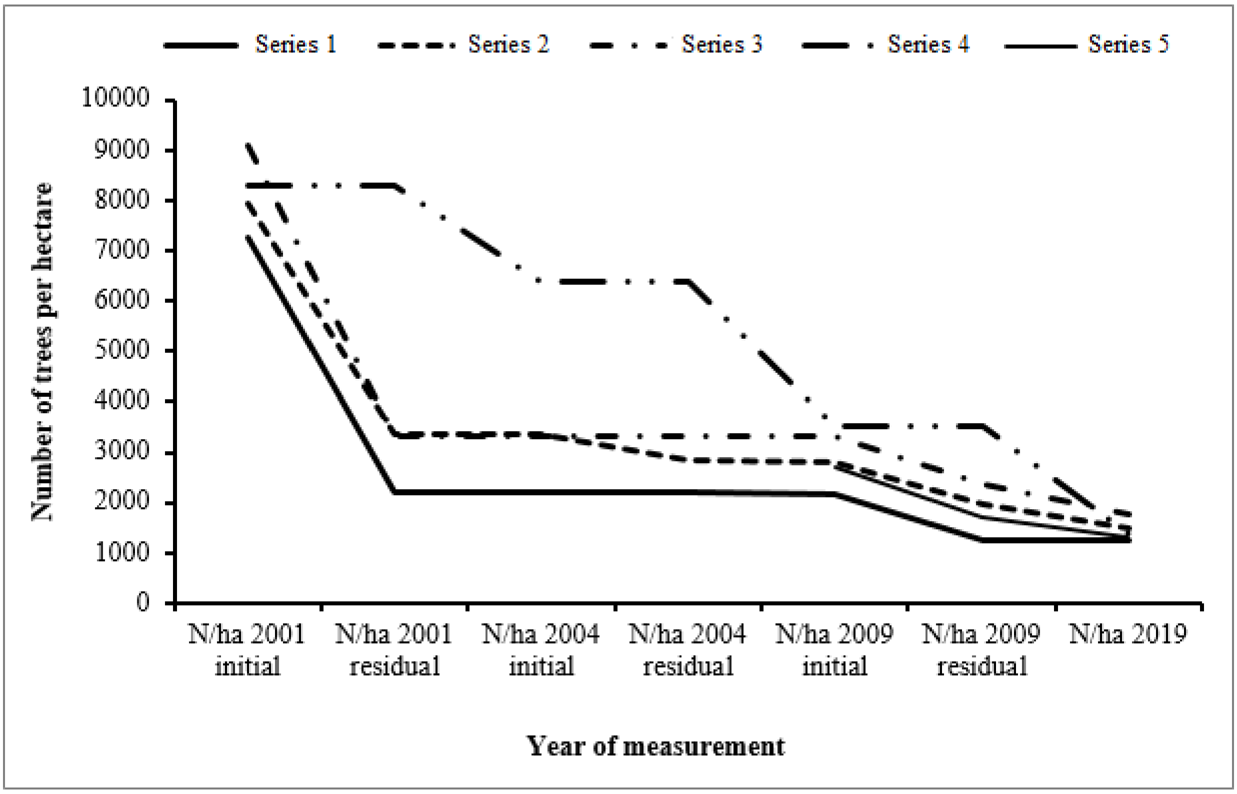

Figure 4. Evolution of stand density in plots 1 (series 1), 2 (series 2), 3 (series 3), 4 (series 4), and 5 (series 5) between 2001 and 2019

This reduction in stand density is due primarily to the three silvicultural interventions (2001, 20014, and 2009) performed in plots 1-3, where the natural mortality over the 2001-2019 period counts for less than 20%. On the contrary, the main source of reduction of stand density in plot 4 (control) in the same period is the natural dieback, accounting for over 83%.

Quadratic mean diameter (QMD) of all trees and potential final crop trees in plots 1-5

The increase of this parameter of all trees in plots 1-4 between 2001 (after intervention) and 2019 ranges between 6.30 cm (91.44%, in plot 3) and 9.10 cm (174.33%, in plot 4) (Table 4).

Table 4. Evolution of quadratic mean diameter of all trees in plots 1-4 in 2001-2019 period

Plot no.	QMD in ... (cm)				Increment of QMD between 2001 and 2019	
	2001 residual	2004 residual	2009 residual	2019	cm	%
1	8.48	9.38	11.81	15.86	7.38	87.03
2	6.78	7.79	10.36	14.26	7.48	110.32
3	6.89	7.53	9.70	13.19	6.30	91.44
4	5.22	6.16	8.77	14.32	9.10	174.33

The highest increase of QMD was found in plot 4 (control), where the reduction of stand density was not affected by silvicultural interventions but solely by natural mortality (over 83%). As almost exclusively the suppressed trees were eliminated, the increase of QMD, even occurring naturally, can be considered as “artificial”.

In these circumstances, it is more relevant to consider the evolution of this parameter and its increment between 2009 and 2019 solely in trees existing in plots 1-5 in 2019 as well as in “potential” final crop trees in the same plots was taken into account (Table 5).

Table 5. Evolution of quadratic mean diameter of all trees and "potential" final crop trees in plots 1-5 between 2009 and 2019

Plot no.	QMD 2009 (cm)	QMD 2019 (cm)	Increment of QMD 2001-2019		Range of dbh increment 2009-2019 (cm)	Share of trees with min 5 cm dbh increment between 2009 and 2019 (%)
			cm	%		
a. All trees						
1	11.81	15.86	4.05	34.29	0.3-7.2	36.00
2	10.89	14.75	3.86	35.45	0.5-11.1	10.00
3	10.19	13.19	3.00	29.44	0.5-6.1	11.43
4	11.59	14.33	2.74	23.64	0.4-6.4	18.52
5	11.27	15.04	3.77	33.45	0.3-8.1	20.00
b. Potential final crop trees						
1	13.85	19.94	6.09	43.97	4.6-7.1	85.71
2	11.74	16.79	5.05	45.49	1.3-11.1	14.29
3	11.84	15.52	3.68	31.09	2.1-5.4	14.29
4	11.99	15.59	3.70	30.90	0.3-5.6	33.33
5	13.10	18.40	5.30	40.45	2.0-8.1	52.94

The absolute increase of QMD of all trees between 2009 and 2019 is maximum in plot 1 (4.05 cm), with the lowest stand density (1,250 trees ha^{-1}) in 2009, and minimum in plot 4 (control) (2.74 cm), which was overcrowded in 2009 (3,500 trees ha^{-1}). The effect of stand density is obvious in the share of trees with minimum 5 cm dbh increment between 2009 and 2019: It ranges between 10.00% (plot 2) and 36.00% (plot 1). In 2019, the proportion of trees reaching 20 cm in diameter (maximum 24.2 cm in sessile oak, 26.0 cm in Hungarian oak, and 27.9 cm in Turkey oak) ranged between 2.86% (plot 3), and 24.00% (plot 1). The majority of these trees, showing mean annual radial increments between 2.5 and 3 mm, are of sessile oak (100% in plot 5) and Turkey oak (83.33% in plot 1). All trees at least 20 cm in dbh in 2019 have grown over 10 cm in diameter between 2001 and 2019, with a maximum of 18.2 cm (Turkey oak tree in plot 2, 27.9 cm in diameter in 2019).

The effect of stand density on dbh increment is more obvious when considering solely the "potential" final crop trees, which have been favoured during the application of the three interventions in 2001, 2004 and 2009. In both absolute and relative terms, the highest increase was found in plots 1 (6.09 cm, 43.97%) and 5 (5.30 cm, 40.45%), compared to 3.68 cm (31.09%) in plot 3. In plots 1 and 5, the QMD of "potential" final crop trees is close of 20 cm, a threshold which was targeted since the beginning of this R&D project for a stand of 35 (30-40) years of age. As above, the share of "potential" final crop trees with minimum 5 cm dbh increment between 2009 and 2019 is maximum (85.71 %) in plot 1, with the minimum stand density (1,250 trees ha^{-1}) in 2009, followed by plot 5 (52.94%), with a similar stand density (1,300 trees ha^{-1}) in the same year.

In addition, one should emphasize the very important output that the increase of QMD of "potential" final crop trees between 2001 and 2019 is very variable: 6.17 cm (0.32 cm yr^{-1}, in plot 4), 7.13 cm (0.38 cm yr^{-1}, plot 3), 9.03 cm (0.47 yr^{-1}, plot 2), and 10.65 cm (0.56 cm yr^{-1}, plot 1). In plot 5, the increase of QMD between 2009 (plot establishment) and 2019 was close to the one in plot 4 (0.53 cm yr^{-1}). These results confirm the "speeding up" effect of lower stand density and silvicultural interventions [i.e., thinning from above (détourage) or intermediate thinning, mostly from above (détourage), in plots 1 and 5] on the dbh increment not only of all trees but particularly of "potential" final crop trees.

The values of QMD before and after silvicultural interventions performed in 2001, 2004, and 2009 can also be used to define their type (Table 6).

Table 6. QMD of initial trees, extracted trees and residual trees in cleaning-respacing and thinning carried out in plots 1-4 in 2001, 2004, and 2009

Plot no.	QMD in ...								
	2001			2004			2009		
	Initial trees	Extracted trees	Residual trees	Initial trees	Extracted trees	Residual trees	Initial trees	Extracted trees	Residual trees
1	6.02	4.55	8.48	9.38	-	9.38	11.56	11.21	11.82
2	5.30	3.88	6.78	7.52	5.69	7.79	9.71	7.55	10.36
3	5.12	3.77	6.89	7.53	-	7.53	9.23	7.85	9.70
4	5.22	-	5.22	6.16	-	6.16	8.77	-	8.77

In 2001 and 2004, as the QMD of extracted trees is much lower than the one of initial trees, the cleaning-respacing was definitely a negative selection, and from below. In 2009, the only thinning from below was carried out in plot 2, while its character approached an intervention from above (or détourage) or intermediate in the other plots.

Height corresponding to the quadratic mean diameter (h_g) of all trees in plots 1-4

The increase of this parameter of all trees in plots 1-4 between 2001 and 2015 (last year of height measurements) ranges between 5.21 m (53.71%, in plot 1) and 7.29 m (108.97%, in plot 4) (Table 7).

Table 7. Evolution of height corresponding to the quadratic mean diameter (h_g) of all trees in plots 1-4 in 2001-2015 period

Plot no.	h_g in ... (m)				Increment of h_g between 2001 and 2015	
	2001 residual	**2004 residual**	**2009 residual**	**2015**	**m**	**%**
1	9.70	10.36	12.54	14.91	5.21	53.71
2	9.30	9.67	12.22	14.84	5.54	59.57
3	9.05	9.84	12.24	14.77	5.72	63.20
4	6.69	8.25	11.31	13.98	7.29	108.97

As in case of QMD, the highest increase of h_g was found in plot 4 (control), where the reduction of stand density was affected solely by natural mortality (over 83%), eliminating almost exclusively the suppressed trees, so artificially increasing the value of h_g. In plots 1-3, regardless the type and intensity of interventions carried out in 2001, 2004, and 2009, the increase of h_g was similar in both relative (5.2-5.7 m) and absolute terms (54-63%). As the initial h_g (2001) in those plots had a quite narrow range (9.05-9.70 m), the values of h_g were similar in all plots 2015 (14.8-14.9 m).

In 2015, the values of coefficient of variation of heights, with values between 9.43% (plot 3) and 25.15% (plot 4) in 2001, after the cleaning-respacing intervention, ranged between 5.47% in plot 3 and 12.66% in plot 4. It confirms the relative uniformity of tree heights, characteristic to an even-aged, mono-layered stand, composed mostly of light-demanding species.

Mean slenderness (stability) index

The evolution of this parameter [$SI = (h/dbh)*100$] of all trees in plots 1-4 between 2001 and 2015 (last year of height measurements) indicates a continuous decrease, with values ranging between 5 and 19 (Table 8).

Table 8. Evolution of slenderness (stability) index of all trees in plots 1-4 between 2001 and 2015

Plot no.	SI in ...				Evolution (+ or -) of SI between 2001 and 2015	
	2001 residual	**2004 residual**	**2009 residual**	**2015**	**m**	**%**
1	114	110	106	104	10	8.77
2	137	124	118	118	19	13.87
3	131	131	126	126	5	3.82
4	128	134	129	116	12	9.38

As the natural mortality was the only factor affecting the decrease of SI in plot 4, one should not use it in interpreting the results but take into account only the evolution of SI in plots 1-3. The decrease was the most important in plot 2, as the increase in QMD was much higher than the one in h_g, while the increase of QMD and h_g were much closer in plots 1 and 3, so the decrease of SI was lower. However, the only plot where the SI shows a good stability of trees is plot 1, where it approaches the level of 100.

Correlations between different biometrical parameters

The requirement to select "potential" final crop trees at the end of thicket stage of development exclusively among the thickest (and tallest) individuals is obvious when considering the correlation between initial dbh (2009) and dbh increment between 2009 and 2019 (Figures 5a, and 5b).

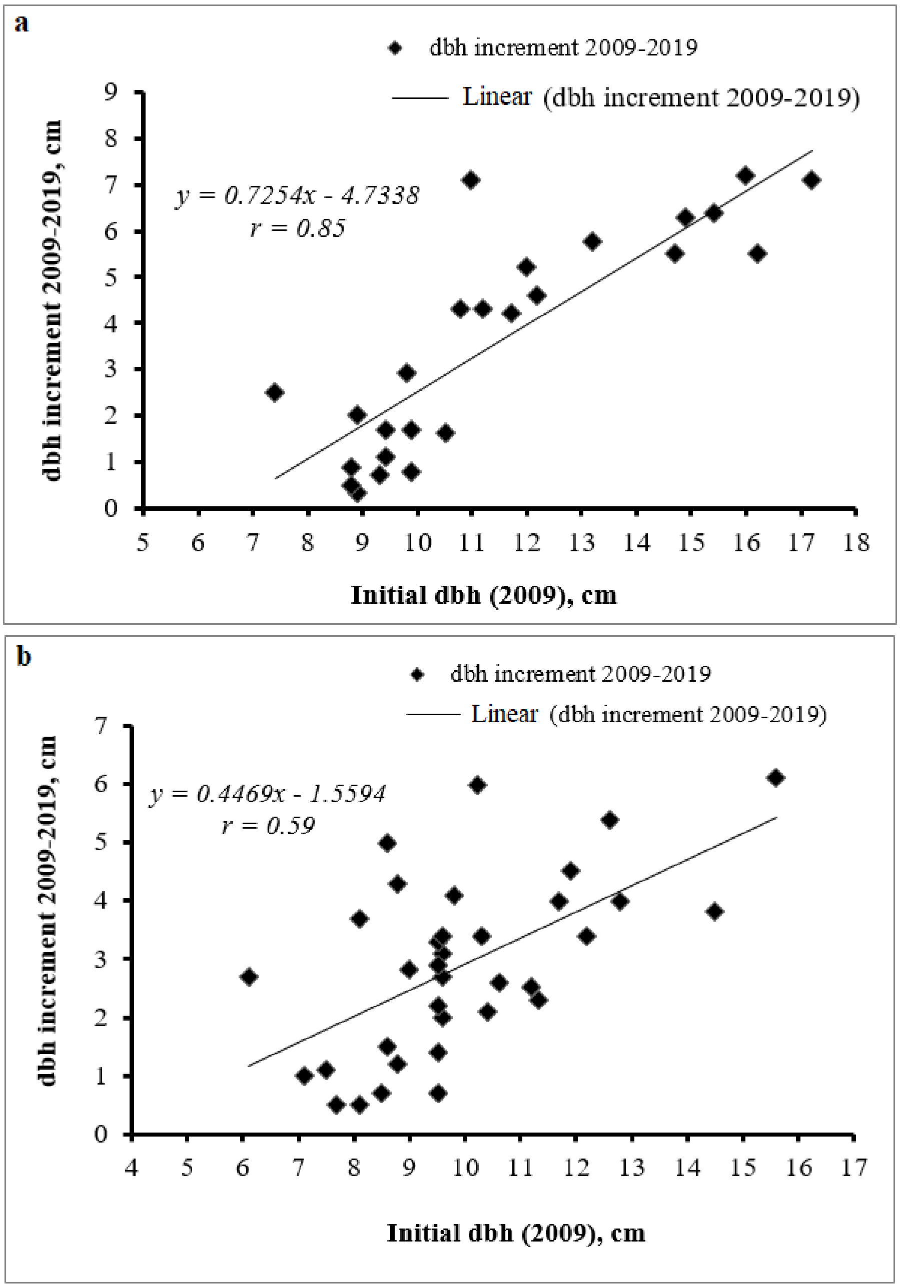

Figure 5. Correlation between initial dbh (2009) and dbh increment (2009-2019) of trees of plots 1 (a) and 3 (b)

The high values of coefficient of correlation (r) between these biometrical traits, ranging between 0.59 (plot 3) and 0.85 (plot 1), explains the need to select those valuable individuals among the thickest ones, as they are the most important growers in diameter.

This need originates also from the strong correlation between the dbh and mean crown diameter (Figure 6).

This strong correlation (r from 0.86 in plot 3 to 0.94 in plot 2) shows the need to select the "potential" final crop trees among thick (and tall) individuals, which also posses large crowns and grow quicker in dbh than thinner trees, with smaller crowns.

Such conclusion is confirmed by the relationship between stand density, QMD and mean crown diameter: The trees in plot 1, with the lowest stand density (1,250 trees ha^{-1}) in 2019, had the largest quadratic mean diameter (15.86 cm) as well as the largest crown (overall mean crown diameters 317 cm). On the other hand, trees in plot 3, with the highest stand density (1,750 trees ha^{-1} in 2019), had the smallest QMD (13.19 cm) as well as smallest crown (overall mean crown diameter 239 cm). Trees in the other three plots, with different overall mean crown diameters (285 cm in plot 5, 275 cm in plot 2, and 247 cm in plot 4), occupy intermediate positions in-between these extremes.

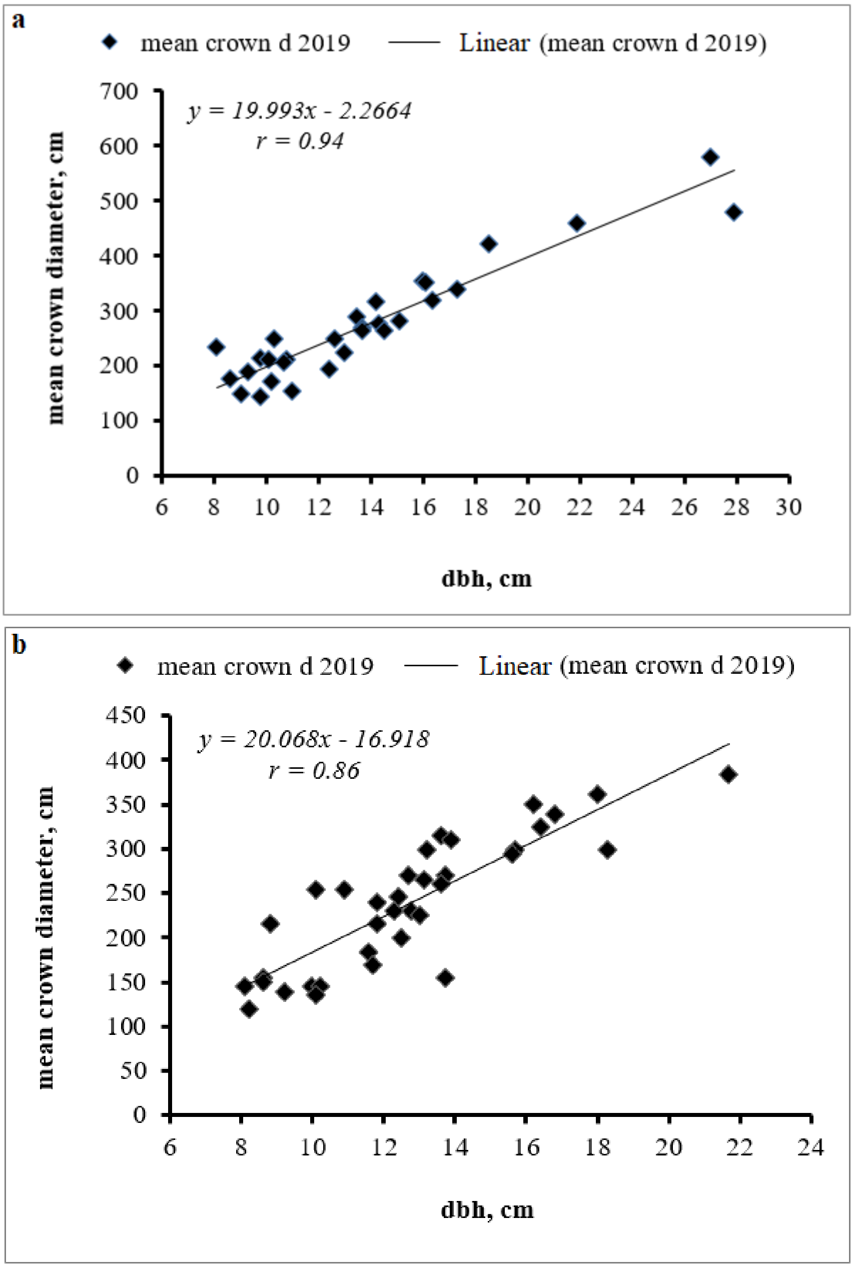

Figure 6. Correlation between dbh and mean crown diameter of trees in plots 2 (a) and 3 (b) in 2019

Stocking (basal area)

Stocking in the five plots had successive increases (between interventions) and decreases (because of silvicultural interventions as well as natural mortality of trees) in plots 1-5 between 2001 and 2019 (Figure 7).

Starting around 12 m^2 ha^{-1} in plots 1-4 after the first intervention in 2001, basal area has increased up to rather similar values (from 21.76 m^2 ha^{-1} in plot 4 to 25.63 m^2 ha^{-1} in plot 2) in all plots (including no 5) in 2019. However, the evolution of stocking between the last intervention (2009) and 2019 shows a very high variability. The increase of basal area ranges between 0.61 m^2 ha^{-1} (2.88%) in plot 4 (with the highest stand density of 3,500 trees ha^{-1} and a mortality of 61.43%) and 11.00 m^2 ha^{-1} (80.29%) in plot 1 (with the lowest stand density of 1,250 trees ha^{-1} and no mortality). In the other plots, basal area has increased 6.60 m^2 ha^{-1} (38.13%) in plot 3, 8.25 m^2 ha^{-1} (55.55%) in plot 5, and 9.24 m^2 ha^{-1} (56.38%) in plot 2.

The effect of different types of intervention on individual trees was also assessed in terms of occurrence of *epicormic branches*, a major threat in oaks (more on pedunculate than on sessile) to produce top-quality wood for A-class lumber, veneer and solid furniture. In plots 1-4, the share of trees with epicormics in 2017 ranged between 20% (plot 3) and 40% (plot 1); sessile oak, as well as Hungarian oak trees were the most affected. However, the "potential" final crop trees, with the largest diameters, heights and crowns, have been the least affected (maximum one tree per plot) (Table 9).

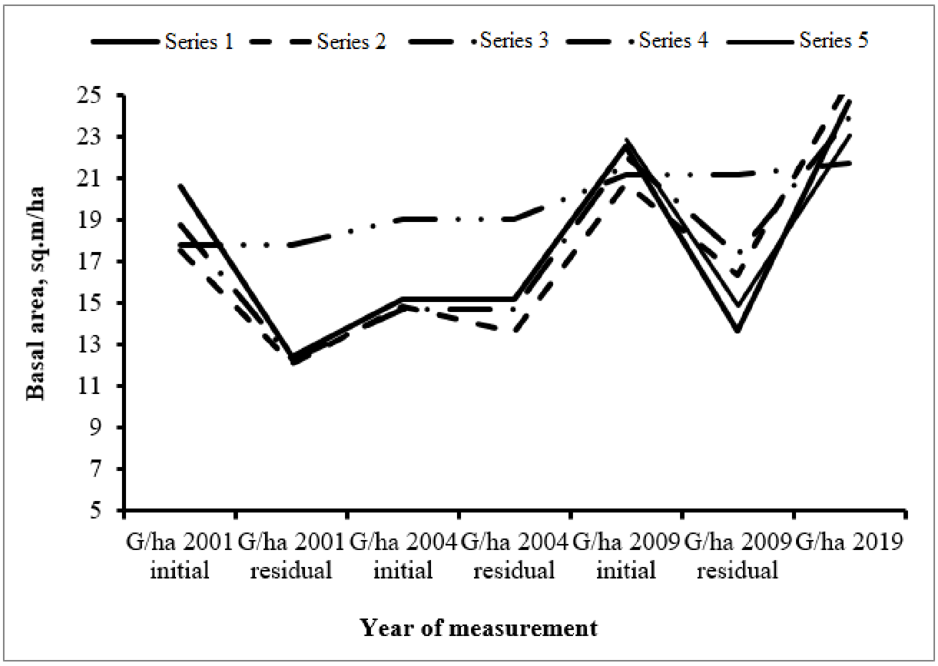

Figure 7. Evolution of stocking (basal area) in plot 1 (series 1), plot 2 (series 2), ..., plot 5 (series 5) between 2001 and 2019

Table 9. Occurrence of epicormic branches in plots 1-4

Plot no	Total number of trees	No and % of trees with epicormics	Of which		Number of "potential" final crop trees	Of which with epicormics	
			SOAK	Others (HOAK, EB, HOR)		No.	%
1	25	10/40	7	3	7	1	14
2	35	9/26	9	-	7	-	-
3	41	8/20	7	1	1	1	14
4	33	12/36	4	8	6	1	17

HOAK = Hungarian oak, EB = European beech, HOR = hornbeam

In plot 5, 21 trees (30% of all trees, of which 17 of sessile oak, the rest of Hungarian oak, hornbeam and European beech) out of 70 showed epicormic branches. As in plots 1-4, only one "potential" final crop tree out of 17 (6%) showed epicormics.

Across the five plots, these branches occurred mostly on slender trees with small and unbalanced crowns, from the lower canopy (Kraft classes IV and V). There was a very small proportion of epicormics on "potential" final crop trees, which grow vigorously, and have large diameters and crowns.

Discussion and Conclusion

In the young sessile oak thicket, as no silvicultural interventions have been carried out since the establishment, the stand density and stocking were very high (N = 7,250-9,100 trees ha^{-1}; G = 17.55-20.65 m^2 ha^{-1}) in 2001 so there was a clear need for cleaning-respacing. Taking into account the high variability of diameters and qualities, this intervention was a negative selection, removing the smaller and badly formed trees, and heavy (intensity 57-69% by number of trees N and 31-39% by basal area G). Such intensities are higher in terms of N and similar in terms of G with the levels of 40% (by N) and 35% (by G) described by Ciumac (1969).

Following the second major intervention (2009), not as heavy as the one in 2001 (intensity 28-41% by N and 21-39% by G), the stand density was reduced to 1,250-2,350 trees ha^{-1}. The minimum stand density in 2009 is similar to the one recommended in countries like France [1,100-1,200 trees ha^{-1} (Sardin, 2008; Sardin & Mothe, 2010; Anonymous, 2022)], Belgium [ca. 1,200 trees ha^{-1} (Baar, 2010)] or Ireland [1,000-1,300 trees ha^{-1} (Joyce et al., 1998)] but much lower than the one proposed in Romania [2000-4000 trees ha^{-1} (Ciumac, 1975), 2,100-2,400 trees ha^{-1} (Anonymous, 2000a)] at the same age. Reducing the stand density to those levels is also a valid strategy to increase the forest resilience to drought (Zamora-Pereira et al., 2021). Sessile oak's annual tree-ring width depends strongly on the water availability of summer months in the actual year of ring formation (Móricz et al., 2021).

Stocking after the interventions performed in 2009 (13-17 m^2 ha^{-1}) is similar to the one recommended in France [14.2 m^2 ha^{-1} (Jarret, 2004), 14.7 m^2 ha^{-1} in "dynamic" silviculture and

16.8 m^2 ha^{-1} in "classical" silviculture (Sardin, 2008)] and Belgium [14-18 m^2 ha^{-1} (Balleux, 2005)] under similar stand conditions.

The mortality process, affecting mostly trees in lower crown classes (IV and V), confirms the low shade tolerance of all oak species, with sessile oak as most affected. Its higher needs for light lead even to the change of species composition in favour of more shade tolerant Hungarian oak (Negulescu & Săvulescu, 1957; Stănescu, 1979), as in case of plot 4 (control). However, natural mortality has not affected at all the shade-tolerant (European beech) or intermediate shade-tolerant (hornbeam) species, their share in species composition increasing lightly, with positive effects on biodiversity.

The evolution of QMD (range 13-15 cm in 2019) in both all trees as well as "potential" final crop trees, especially after the intervention in 2009, has confirmed the positive effect of lower stand density on diameter increment. Plot 1, with the lowest stand density, had shown the largest increase in QMD, "potential" final crop trees in this plot, as well as in plot 5, being close to 20 cm in QMD, and showing a mean radial increment up to 2.5-3 mm yr^{-1}. This value is similar to the target radial increment of sessile oak in France [2-2.5 mm yr^{-1} (Jarret, 1996)], Austria [2.5 mm yr^{-1} (Hochbichler, 1993)], Belgium [maximum 3 mm yr^{-1} (Bary-Lenger & Nebout, 1993)], Switzerland [2-2.5 mm yr^{-1} (Schütz, 1993)]. Interestingly, in France, the quality standards for A-class sawlogs allows for radial increments of maximum 4 mm yr^{-1} (Baylot & Vautherin, 1992). Lemaire (2010) mentions that all users of high-quality logs for veneer and barrel production require wood with uniform/regular and wide growth rings (2-4 mm) or even wider (over 4 mm). Turkey oak, which grows quicker in youth in both height and diameter than all other native oaks (Negulescu & Săvulescu, 1957; Haralamb, 1967; Stănescu, 1979), has reached the largest diameter in 2019 (27.9 cm).

The height corresponding to QMD, with values of ca. 9 m in plots 1-3 in 2001, has grown similarly until 2015, as mostly being the effect of site potential over the trees not of stand density/stocking after silvicultural interventions, reaching ca. 15 m in 2015. This value characterizes fully the high growing potential of local site conditions, as the stand belongs to the production class II [h_g 14.1 m at 35 years of age (Giurgiu & Drăghiciu, 2004)].

The positive effect of lower stand density on trees was also confirmed by the reduction of slenderness (stability) index in all plots; however, the only plot where its values approach 100 is no. 1, with the maximum QMD and height corresponding to QMD.

The basal area, with a series of increases and decreases owing to silvicultural interventions and diameter increment (plots 1-3), as well as a continuing increase in plot 4 (control), has reached values over 21 m^2 ha^{-1} in 2019. This is higher than the values considered as "critical" [14-18 m^2 ha^{-1} (Balleux, 2005)] in order to avoid any loss in increment and resulting wood volume.

Sessile oak is considered a species particularly prone to the occurrence of epicormic branches (Colin et al., 2010), a major defect reducing the quality class of sawlogs. In the EU standards, the quality of sessile oak sawlogs is reduced from A to B or even C, if the knots are larger than 15 mm in diameter (Baylot & Vautherin, 1992; Anonymous, 1997). In our R&D experiment, silvicultural interventions have not had a major detrimental effect on the production of epicormic branches. This is especially true in case of "potential" final crop trees, vigorous and growing vigorously, with large crowns, less prone to the occurrence of epicormics and which should be favoured by heavy crown thinning (Courraud, 1987; Schütz, 1990; Sevrin, 1997; Joyce et al., 1998; Colin et al., 2010).

The results of this R&D work show that, in the "dynamic" silviculture, the positive selection (and painting) of "potential" final crop trees, at the end of thicket stage (during the last cleaning-respacing, when mean height is 6-8 m), followed by a heavy intervention around their crowns, as proposed in other European countries such as France (Allegrini & Depierre, 2000; CRPF Aquitaine, 2005; Allegrini, 2010; Deleuze & Renaud, 2010; Le Nail & Decucq, 2021) and Belgium (Wouters et al., 2000; Baar, 2008), is a feasible option. The number of such trees (ca. 300 individuals ha^{-1}), selected and painted based on the *vigour-quality-spacing* criteria, should be 2-3 (4) times the number of trees which will presumably form the final stand at the rotation age (final crop trees) (Petrescu, 1971; Kerr & Evans, 1993; Savill et al., 1997; CRPF Aquitaine, 2005; Colin et al., 2010). By selecting and painting them, therefore making such trees more visible and easier to locate, the further tree marking for thinning is facilitated, and both silviculturists and loggers are helped in their efforts to protect the most valuable trees and produce high-quality, healthy, and large trees (Lanier, 1979).

Obviously, the "potential" final crop trees should be favoured by further interventions with crown thinning (full or partial), removing the most aggressive competitors at crown level, in order to provide the "genuine" final crop trees, selected as early as the first (sometimes second) thinning, a free-growth state. Consequently, the crown development and correlated diameter increment are speed up (Baar, 2010; Lëtzebuerger Privatbësch, 2011; CRPF Bourgogne, 2012; Dobrovolný & Macháček, 2012; Le Nail & Decucq, 2021), confirming the fact that, in young and medium-aged oak stands, the bigger trees grow usually much faster than the smaller ones (Gadow & Hui, 1999). Or, in other words, the taller the initial tree size compared with neighbours (e.g., quantified by the initial percentile), the better the primary individual growth potential and the perspective of a tree (Pretzsch, 2021).

Interestingly, the application of crown thinning in oak stands is not a new issue; it was advocated by Broilliard (1881) and used in French forests ever since; in Romania, such thinning in sessile oak stands was proposed by Ciumac (1965, 1969), after stating that all "genuine" final crop trees belong to the upper storey so need to be released from competition, but never formalised and used in practice.

Taking into account all these outputs, what means/instruments should we use in the control of early silviculture of sessile oak stands in Romania, instead of mandatory canopy cover (80%) after intervention? In this respect, based on our results, as well as other works in the same field, two options are to be considered:

a. The use of stand density, of maximum 2,000 stems ha^{-1} after the last cleaning-respacing (when mean height is 6-8 cm) and 1,100-1,300 trees ha^{-1} following the application of first thinning (mean height 11-13 m), as also proposed in countries such as France (Jarret, 2004; Sardin, 2008; Sardin & Mothe, 2010).

b. The use of an even level of stocking (critical basal area) throughout the whole life of the stand, at the level of 14-18 m^2 ha^{-1} after each intervention (Sardin, 2008; Sardin & Mothe, 2010). A higher level of basal area after intervention (23-25 m^2 ha^{-1} on average), as proposed in the UK (Kerr & Haufe, 2011), seems to be too high for our sessile oak stands.

However, our opinion is that, in valuable stands (i.e., production classes I and II), targeting sawlog or veneer log production, the selection and painting of at least "genuine" final crop trees in Romanian oak (sessile, pedunculate) stands must become mandatory. This solution was proposed in Romania long ago (e.g., Anonymous, 1956; Ciumac, 1973), but never put into practice as being only recommended.

We fully agree with Lemaire (2010), Sardin (2008), Sardin and Mothe (2010), Le Nail and Decucq (2021) that, in favourable site conditions, the use of a "dynamic" silviculture is the best option.

On the other hand, the use of "détourage" in managing pole stage stands, by focusing exclusively around the upper crowns of the most valuable crop trees, is definitely a solution, but only for one or two interventions, followed by crown thinning, as also proposed by Lemaire (2010) and Sardin (2008). However, such intensive intervention should favour solely trees with large crowns, part of the "genuine" final crop trees group, selected and painted among the "potential" final crop trees at the end of thicket stage.

Sessile oak silviculture requires a lot of silvicultural investment at early ages but the future results in economic terms are striking so all efforts are worthwhile.

Acknowledgment

The authors wish to thank their colleagues and friends from the Dâmbovița Branch of National Forest Administration-ROMSILVA for their help during the fieldwork phase of the R&D project.

Conflict of Interest

The authors declare that they have no conflict of interest.

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