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Long-Term Effects of Thinning in Sub-Mountainous Thermophilic Sessile Oak (*Quercus petraea* Mill.) and European Beech (*Fagus sylvatica* L.) Coppices in the Croatian Dinarides

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Abstract: Coppicing has been neglected in recent decades, leaving gaps in knowledge on silvicultural interventions, especially the long-term effects on coppices of Southeast Europe. The recent economic crisis, the sudden increase in energy prices, and the increased demand for assorted wood products have initiated higher interest in coppices in Croatia. Thus, our work aims to define the long-term effects of thinning in sessile oak (*Quercus petraea* (Matt.) Liebl.) and European beech (*Fagus sylvatica* L.) sub-mountainous thermophilic low coppices in the Croatian Dinarides. The experiment includes two localities with thinning and control plots. Thinning was performed in 2002, with 17.71% of wood volume removed in the European beech coppice and 26.09% in the sessile oak coppice. In 2020, 1276 trees were marked, measured (DBH, tree height, number of stems per stump), and assessed for vitality, origin, and six silvicultural features revealing tree quality. In 2022, trees were again measured (DBH, tree height) to gain data on tree growth. Conventional data analysis methods were used. The results show a statistically significant positive long-term effect of thinning on tree growth, stem, and crown features and support findings that thinning, by increasing growth and quality, is a necessary intervention in European beech and sessile oak low coppices. Thinning promoted the healthiest and best quality trees/stems, resulting in a more valuable range of wood products and the potential for higher income. It had a positive impact on tree growth regardless of the tree's origin (seed or stump) and improved the growth and quality of trees among the supporting tree species. Short-term effects of thinning in trial plots suggested that thinning supported tree species diversity, but this effect diminished over time, showing no positive effect after twenty years. The study points to the need for more frequent thinning in coppices to support tree species diversity (i.e., to allow growth to less competitive tree species) but underlines the need for further research.

Keywords: *Fagus sylvatica* L.; *Quercus petraea* (Matt.) Liebl.; DBH; tree height; species composition; stem quality

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1. Introduction

Coppicing is the oldest known silvicultural system [1] and is considered recently among the most controversial ones in Europe. Low coppice is defined by its reproduction, e.g., from stool shoots or root suckers. This coppice system consists of a clear-fell removing all wood material from a logging area [1]. Even though the proportion of coppices declined after centuries of this being an important traditional management option [2–4], they still comprise over 10% of the European forest area [5]. A recent study suggests that coppices

might even extend to 14% of European forest cover [6]. The complexity of coppice management, the management aim, the area, and the effort put into coppice conversion differ significantly depending on geographical region historical and social circumstances [7]. Central and Western European countries mainly try to increase management and restore the small share of remaining coppices after decades of successful conversion efforts, as these coppices are now perceived as areas of significant multiple ecosystem services, especially due to their ecological and cultural values. Despite the benefits of, and recommendations for, using this traditional form of management [5] and the recognition of the multiple values, coppices are still generally a neglected management system in Europe [8,9].

South European countries, on the other hand, are now torn between the wish to convert coppice to high forest, which provides more valuable wood products and services, and the need to recognize that they should be protected and actively managed. The reasons for active coppice conversion include the relatively high proportion of coppice, the high proportion of un-favorable tree species used in coppice systems, and increasing interest in more valuable wood products. For example, a study from Greece showed the potential for converted stands to sequestrate more carbon by the end of their rotation, strengthening the contribution of conversion towards climate change mitigation [10]. In addition, coppices are an important part of national forests, especially in some European countries where their total share can be as high as 50% of the total forestland [11].

Nevertheless, no matter how coppices are perceived, it is obvious that their conversion is an expensive and demanding process, which usually results in longer rotations yielding more valuable products [12]. However, coppice conversion is not a favorable option for small private forest owners who are experiencing economic and energy crises as well as progressive climate change. Moreover, this interesting form of forest management, which has shaped the present cultural landscape of South Europe [13], is simple to apply, and regular rejuvenation makes the stools less prone to wind and snow damage and is mostly worked on a short rotation [1] with firewood the most important product. Thus, the recent economic crisis and sudden increase in energy prices, as well as the value of wood products, could increase efforts for coppice restoration and initiate active coppice management in the future [4,12]. Some even argued that current production from natural forests would not satisfy future world demand for timber and fuel wood, so they proposed new land management options such as alley (or avenue) coppice, which has the potential to produce both high-value timber and energy wood on the same land unit [14]. Furthermore, returning to active coppicing can be a successful strategy for biodiversity restoration, especially in protected areas where thinning is restricted [8].

Guidelines on coppice management vary widely throughout Europe and are poorly supported by scientific evidence [15], and this is also applied to knowledge of coppice forests in South-East Europe [9,16]. Furthermore, coppice is neglected in many national forest policies; consequently, there is little reliable data [5]. Taking all these issues into account, including the emerging economic and energy crises, the need to investigate the influence of silvicultural activities on wood production in coppices has become particularly relevant.

European beech (*Fagus sylvatica* L., further on beech) and sessile oak (*Quercus petraea* (Matt.) Liebl., further on s. oak) low coppices are important management systems for Southeast Europe, mainly due to their past uses [17]. Historical data for coppice forests in Croatia [18] show that beech and s. Oak coppice is the most widespread coppice in the country, while beech coppice is the most significant because of its growing stock (31.0%). In addition, most of the coppice in the Lika region is beech (61.8%). This is partly the result of the high adaptability of the two tree species to many forest sites in Croatia [16]. The proportion of beech and s. oak in the total growing stock of their respective coppice management classes is very high (77% and 61%, respectively, with s. oak covering 35,886 ha/5,309,656 m^3 and beech 108,820 ha/15,553,770 m^3) [16,18]. Recent official data [19] shows the high importance of these two tree species and points out that conversion to high forest over the previous 10-year period has occurred mostly in the s. oak coppices (s. oak 22,958.51 ha/4,177,283 m^3; beech 103,736.70 ha/17,427,844 m^3).

In Croatia, coppices represent 14.5% of forestland [19], whereas the area of Central Dinarides (the Lika region) has 29% of the forest cover under coppice management. Croatia has a long history of coppicing, which has resulted mostly in low coppices [20]. The intensity of silvicultural activities results in a variety of different types and states in which coppices can be found, from those with poor quality and low wood volume to those of the highest quality, good structure, and high wood volume [21]. One thing that is common to most coppices is the lack of silvicultural activities [22]. If we consider the way in which coppices developed in Croatia, often as the result of unsuccessful regeneration or lack of silvicultural interventions, one may conclude that coppices are most likely to be low quality and show disturbed natural processes [21]. Coppices in the Lika region are characterized by specific complex historical, economic, and societal factors. In addition, they show natural limitations and geographically are in one of the parts of Croatia most vulnerable to climate change [9,23]. They are characterized by a lack of management and few open areas in the forest [23]. Where coppices remain, because of various influences, forest practitioners should consider the options and set management goals after deciding if it is more appropriate to convert the coppice to high forest or whether it should remain under the existing management system [24].

Wood production in low coppice is strongly influenced by tree species, rotation age, production target, and site conditions [1,13]. Thinning is an important factor affecting many features of low coppice; since most of these coppices are poorly managed (or unmanaged), thinning is needed to increase productivity [5,9,21,23]. Stem shape provided insight into which trees have the potential to provide valuable assortments of different products at the end of the rotation, e.g., larger, straight trees, without curvatures or forks, with a small decrease of diameter along the trunk, are likely to provide higher income (Figure 1). The influence of origin and thinning on tree shape and the potential for valuable products in low coppice have been neglected in recent scientific research. Thinning affects coppice structure, density, tree growth [25], species composition, and stem development [26], as well as in-stand ecological factors such as light, heat, moisture, etc. Coppice development can only be regulated by tending measures (e.g., thinning, cleaning); thinning is also beneficial in the preparation of coppice for conversion [27,28]. Thinning, performed appropriately and in a timely manner, can significantly influence the development of coppices [28–30] not only in terms of tree diversity and quality but also tree health [26]. It could also be instrumental in enhancing stand resistance to climatic stress [31,32], especially drought [33]. This has resulted in this technique attracting more attention in relation to the need for the adaptation of forests to climate change [34]. Thinning beech stands are regarded as a good adaptation tool [35] and have been suggested for the more valuable coppices, such as those with beech and oak species, the focus of this study for both adaptation and wood production. Most recent studies focus on the effects of thinning on the response of these species to drought [26,33], especially oaks in the Mediterranean area where water is already a scarce resource. The traditional aim of thinning, which is to increase the size and quality of remaining trees, has shifted towards increasing the resistance or resilience of trees to drought [36–38]. In addition, recent studies have highlighted thinning as important for conservation and to increase biodiversity [8], especially for some generalist and early successional species groups [6].

Long-term studies, which analyze the quality and growth of thin compared to unthinned coppice, are rare since such long-term research is expensive and time-consuming but crucial to demonstrate the long-term effects of thinning on coppices. For example, a synthesis of experiments from a wide geographical range using different thinning intensities found this to be a suitable approach to improve the growth response of remaining trees to drought [26]. The most recent study [36] reveals a knowledge gap on the long-term effects of thinning on coppice, highlighting the need for research on this topic.

(**a**) (**b**) (**c**)

Figure 1. Examples of deformities of tree stems (from left to right): (**a**) high stem deformity (high biodiversity value, no timber value), (**b**) small straightness, medium curvature, large forking, (**c**) low stem deformity, well-shaped stem—tree no. 27 (large straightness and taper, no curves, no forking).

In response, our research aims to define the long-term effects of thinning on two sub-mountainous thermophilic low coppices. Oak and beech in the Croatian Dinarides. Our research will try to provide answers to the following question: is there a long-term positive effect of thinning in terms of (1) species diversity, (2) stem growth, and (3) stem/crown shape?

2. Materials and Methods

2.1. Study Area and Experiment Establishment

The mountain area of Croatia extends to the furthest northwestern part of the Dinaric Mountains area. This is the highest region of Croatia, the High Karst zone, built mainly of Mesozoic limestones. It is divided into two economically and geographically different subregions, the significantly larger Lika and the smaller Gorski Kotar. Lika is located in the central part of the Dinaric Alps, or Dinarides, and it is considered to bridge the continental and Mediterranean areas of the Republic of Croatia. The altitude ranges from 510 m to 1101 m (the highest peak), and the geology is mostly dolomites and limestone [39,40].

The climate of the Lika region ranges from continental to alpine, where the influence of the sea is excluded by the Velebit Mountain. The mean January temperature is −1.7 °C, and July temperature is 19.1 °C. The annual rainfall is 1496 mm, with most in autumn and spring [41].

Two trial plots (Beech14 and Oak103) were established in an area with a climate classified by Köppen as Cfsbx [18,19,23,42], meaning it is temperate, moderately warm with a fully humid precipitation regime [43]. The main site characteristics of these plots are as follows (Table 1):

The experiment started in 2002 when research on the short-term effects of thinning on low coppice was established in several localities of Lika in 2002 [23,42]. The trial included different types of coppices (e.g., shrub-like coppice, low coppice, and coppice in different transition stages in conversion to high forest). Out of these trial plots, the ones set in the most important coppices of this region (beech low coppice and s. oak low coppice) were used to study the long-term effects of thinning in 2020. Thus, in the spring of 2020, two trials were selected from the 2002 experiment in different localities in both beech low coppice and s. oak low coppice. These experiments (Beech14, 15.27094/N 44.69155, and Oak103, E 15.33114/N 44.74706, respectively) included one thinned trial plot (0.25 ha) and one control (0.25 ha). Initially, in 2002, prior to thinning, thinned and control trial plots were set at the same locality, spatially connected to each other [23,42]. They are positioned

in a way that terrain characteristics are the same (elevation, aspect, slope) for thinned and control plots. Trial plots were set in the stand of the same species composition [23,42]. Thus, the influence of terrain and species composition on growth, species composition, and silvicultural characteristics after thinning is the same in both thinned and control plots.

Table 1. Main site characteristics of trial plots [18,19,44].

	Trial Plots			
Name of trial plots	**Beech14**		**Oak103**	
Tree density (tree/ha)	654		1053	
Basal area (m^2/ha)	17.68		22.03	
Stem volume (m^3/ha)	138		131	
Average tree height (m) in 2020 and 2022.	16.26	17.14	14.98	15.66
Average DBH (cm) in 2020 and 2022.	14.29	15.43	12.70	16.26
Tree species	**Thinning**	**Control**	**Thinning**	**Control**
Carpinus betulus L.	2	2	10	-
Fagus sylvatica L.	164	215	-	-
Quercus petraea (Matt.) Liebl.	-	26	84	171
Ostrya carpinifolia Scop.	3	40	92	131
Pyrus pyraster (L.) Burgsd.	1	4	1	-
Abies alba Mill.	-	1	3	-
Prunus avium L.	-	1	-	-
Sorbus torminalis (L.) Crantz	-	4	2	24
Acer pseudoplatanus L.	-	1	45	8
Cornus mas L.	-	1	-	1
Fraxinus ornus L.	-	1	73	143
Acer obtusatum Waldst. et Kit. ex Willd.	-	-	-	16
Acer campestre L.	-	-	3	3

Beech14 represents the most extensive coppice type in the Lika region. The standing volume before thinning in 2002 was 140.20 m^3 ha^{-1} (Table 2). The intensity of thinning by volume was 17.71% (24.84 m^3 ha^{-1}) [23,42]. It was the first silvicultural intervention in this coppice since its regeneration. After thinning, 200 seed-originating trees per ha and 1197 stump-originating stems per ha remained. The residual stand basal area was 20.40 m^2 ha^{-1}, while the stand volume was 115.36 m^3 ha^{-1}. The main tree species were beech (94.01% of species composition), s. oak (2.29%) and supporting tree species (i.e., those other than beech and s. oak—3.7%). In 2003, during the severe drought, 172 trees (basal area 1.81 m^2 ha^{-1}, wood volume 9.43 m^3 ha^{-1}) died, of which 164 were of vegetative origin, most of which (156) were beech. The most recent management plan, released in 2018, showed that Beech14 had 654 trees/stems per hectare, a basal area of 17.68 m^2 ha^{-1}, and a standing volume of 138 m^3 ha^{-1}.

Oak103 is typical of low s. oak coppice in this region. The standing volume before thinning in 2002 was 195.69 m^3 ha^{-1} (Table 2). The intensity of thinning by volume reached 26.09% (51.06 m^3 ha^{-1}) [23,42]. This was the first intervention in a fully closed stand, which was a mixed cleaning-thinning. After this operation, 524 seed-originating trees ha^{-1} and 1281 stems of vegetative origin per ha remained. The residual stand basal area was 23.36 m^2 ha^{-1}, while the residual stand volume was 144.63 m^3 ha^{-1}. The main tree species were s. oak (75.39% of species composition), hophornbeam (*Ostrya carpinifolia* Scop.) (11.80%), and supporting tree species (12.8%). In 2003, during a severe drought

period, 68 trees died, of which 23 were of seed origin and 45 were of coppice. Dead s. oaks were mostly seed-originated (23 trees), while 13 dead stems were of vegetative origin. In 2018, when the last complete coppice measurement was carried out, Oak103 had 1053 trees/stems per hectare, a basal area of 22.03 m^2 ha^{-1}, and a standing volume of 131 m^3 ha^{-1}.

Table 2. Available data on trial plots prior to measurements in 2020 [23,42].

	Beech14		**Oak103**	
Stand volumen before thinning in 2002.	140.2 m^3 h^{-1}		195.69 m^3 ha^{-1}	
Stand volumen after thinning	115.36 m^3 h^{-1}		144.63 m^3 ha^{-1}	
Intesity of thinning	17.71% (24.84 m^3 ha^{-1})		26.09% (51.06 m^3 ha^{-1})	
Residual stand basal area	20.40 m^2 ha^{-1}		23.36 m^2 ha^{-1}	
Remained seed-originating trees per ha	200		524	
Remained stump-originating stems per ha	1197		1281	
Main tree species in the plot	Beech	94.01%	S. oak	75.39%
	S. oak	2.29%	Hophornbeam	11.8%
	Other	3.7%	Others	12.8%
Loss after drought in 2003.	172 trees 164 vegetative origin 156 beech trees		68 trees 23 seed (all S. oak) 45 vegetative origin (13 S. oak)	
	basal area 1.81 m^2 ha^{-1}, wood volume 9.43 m^3 ha^{-1}			
Measurment from 2018 (Forst management plan)	654 trees/stems per hectare		1053 trees/stems per hectare	
	Basal area of 17.68 m^2		Basal area of 22.03 m^2 ha^{-1}	
	Stand volume of 138 m^3 ha^{-1}.		Stand volume of 131 m^3 ha^{-1}	

2.2. Study Design

The trial plots are part of a research project funded by Croatian Forest Ltd. (Zagreb, Croatia), which aims to enhance coppice management in the Lika region. As mentioned, four trial plots, with a total area of 1 ha, were established, within which 1276 trees/stems (Beech14—466 trees/stems, Oak103—810 trees/stems) were permanently marked and measured in spring 2020 and 2022. The location and number of trial plots were limited by the short duration of the project (2022–2023). Each tree was given a unique code in a database, which enabled in-depth statistical analysis and provided insight into the growth and development of individual trees. Trees in control plots were marked with yellow paint, and trees in the thinned plots were marked with white paint. Trees were marked in the direction of measurement for faster and more efficient repeated measurements and data control, with special attention paid to avoiding systematic error. Field measurements were uploaded into the electronic database.

2.3. Measurements of Height and DBH

Forest tree species, tree origin, number of stems per stool, status of the trees/stems (living or dead), diameter at breast height (DBH) of all trees/stems on the stool in the trial plot, height (h) of all trees/stems on the stool were recorded. Tree/stem height was measured with a Haglöf/Vertex IV dendrometer with an accuracy of 0.1 m. For each tree, two DBH measurements were made using tree calipers (0.1 cm accuracy), with the mean calculated and recorded so stem distortions would not significantly influence the values. Bent-over trees/stems were not measured but noted. Trees/stems with apparent damage to the top (broken) or leaning trees were counted with only the DBH measured.

2.4. Assessment of Silvicultural Characteristics

For each tree, six silvicultural characteristics were visually assessed according to the criteria defined by Perić [45]. These characteristics were categorized as follows:

- Tree/stem straightness (S), visually assessed as deviation from the vertical axis of the stem, low stem straightness points to the degree of stem deformation (large—straight, medium—crooked, small -deformed);
- Taper/degree of decreasing diameter along the trunk, visually assessed by how much the stem is similar to the ideal cylinder (T_shape), large taper points to stem similar to the ideal cylinder (large, medium, small);
- Curvature showing how much the tree/stem is curved, or how many curves the stem has (C) (large–more than two curves, medium—two curves, small—one or no curve);
- Crown width (C_WIDTH) (large, medium, small);
- Forking (F) (large—the tree has more than one principal stem that is forked below one-third of its height; medium—the tree has more than one principal stem that is forked higher than one-third of its height; small—the tree has one principal stem or two principal stems that are forked in the tree crown);
- Crown symmetry (C_sym) (symmetric, asymmetric).

Each parameter was then graded: 1—high, 2—medium, 3—small. For crown symmetry, grade 1 was given to the trees with a symmetric crown and grade 2 for those with asymmetric crowns. The origin of a tree (seed or stump regeneration) was also coded, GEN for trees originating from seed and VEG for those originating from the stump.

2.5. Statistical Analysis

Descriptive statistics were carried out for all variables analyzed, for continuous variables mean+-+ standard deviation, and for categorical variables frequency and relative frequency. The differences in DBH (cm) and height (m) for the years 2020 and 2022 were analyzed by repeated measure analysis of variance (RMANOVA) according to model (1). RMANOVA is usually used when several measurements are taken on the same experimental unit (tree); the measurements tend to be correlated with each other. This collection of conditions is referred to as a between-subjects factor when a dependent variable is tested on independent groups. For example, coppice type, thinning/control, and tree origin (vegetative or seed generated) of the sample trees, with each group being subjected to a distinct condition. A within-subject factor (s) (year) is created when a dependent variable (DBH, h) is measured repeatedly for each sample tree across a set of conditions. The main effects (e.g., coppice type, treatment, origin, their interactions, and the effect of the year (repeated), as well as all interactions with the year) are included in the model.

$$\begin{gathered}\text{Yijkl} = \mu + \text{COPPICE TYPEi} + \text{TREATMENTj} + \text{ORIGINk} + (\text{COPPICE TYPE} \times \text{TREATMENT})\text{ij} + \\ (\text{COPPICE TYPE} \times \text{ORIGIN})\text{ik} + (\text{TREATMENTxORIGIN})\text{jk} + \text{YEARSl} + (\text{YEARS} \times \text{COPPICE TYPE})\text{li} + \\ (\text{YEARS} \times \text{TREATMENT})\text{lj} + (\text{YEARS} \times \text{ORIGIN})\text{lk} + (\text{YEARS} \times \text{COPPICE TYPE} \times \text{TREATMENT})\text{lij} + \\ (\text{YEARSxCOPPICE TYPE} \times \text{ORIGIN})\text{lik} + (\text{YEARS} \times \text{TREATMENT} \times \text{ORIGIN})\text{ljk} + \text{eijkl}\end{gathered} \tag{1}$$

μ = Overall mean
COPPICE TYPEi = effect of COPPICE TYPE, i = 1,2 (Beech12, Oak103);
TREATMENTj = effect of TREATMENT, j = 1,2 (control, thinning);
ORIGINk = effect of ORIGIN, k = 1,2 (VEG, GEN);
YEARSl = effect of YEARS (repeated), 1,2 (2020, 2022);
eijkl = random error $\approx N(0,\sigma^2)$.

Differences for variables of silvicultural features: tree/stem straightness (S), decreasing diameter along the trunk (T shape), Curvature (C), Forking (F), Crown width (C_width), Crown symmetry (C_sym) according to treatments (control and thinning) were subjected to the Chi2 test, if the expected frequency per cell was <5, Fisher's exact test was used.

For all statistical analyses, a significance level of 5% was considered statistically significant. Graphic displays were made in the statistical packages STATISTICA [46] and

SAS9.4. [47]. Statistical analysis was performed with the SAS statistical package [47] using proc glm for RMANOVA and proc freq for Chi2 and Fisher's exact test.

3. Results

3.1. Descriptive Statistics

3.1.1. Number of Trees/Species Composition

Beech is the dominant species in the Beech14 trial plots, comprising between 73% (control) and 96.4% (thinning). A total of 170 beech stems were recorded in the thinned trial plot, with no seed-originating trees. In the control plot, 92.2% of trees were of vegetative origin, and 7.8% originated from seed. Beech14 shows a higher number of tree species in control than in thinned plots (11 and 4, respectively), although the numbers are low (1 to 4 trees in the trial plot). In the thinned plot, only *Carpinus betulus* L. and *Ostrya carpinifolia* Scop are present. and *Pyrus pyraster* (L.) Burgsd. were present (Table 2). In control plots, *Quercus petraea* (Matt.) Lieb., *Abies alba* Mill., *Prunus avium* L., *Sorbus torminalis* (L.) Crantz, *Acer pseudoplatanus* L., *Cornus mas* L., and *Acer campestre* L. were found in addition to the beech.

The control plot of Oak103 had more trees than all other trial plots. After thinning, the number of trees, as well as the ratio of coppice trees, was reduced. The control plot shows that this is a typical form of mixed coppice of s. oak, *Ostrya carpinifolia* Scop. and *Fraxinus ornus* L. with a relevant number of accompanying species (Table 3).

Table 3. Frequency of forest tree species in Beech14 and Oak103 trial plots, including thinning and control plots.

	Trial Plots			
	Beech14		**Oak103**	
High altitude (m)	560–660 m			
Slope (°)	5°–35°			
Aera (ha)	15.96 ha			
Tree species	**Thinning**	**Control**	**Thinning**	**Control**
Carpinus betulus L.	2	2	10	-
Fagus sylvatica L.	164	215	-	-
Quercus petraea (Matt.) Liebl.	-	26	84	171
Ostrya carpinifolia Scop.	3	40	92	131
Pyrus pyraster (L.) Burgsd.	1	4	1	-
Abies alba Mill.	-	1	3	-
Prunus avium L.	-	1	-	-
Sorbus torminalis (L.) Crantz	-	4	2	24
Acer pseudoplatanus L.	-	1	45	8
Cornus mas L.	-	1	-	1
Fraxinus ornus L.	-	1	73	143
Acer obtusatum Waldst. et Kit. ex Willd.	-	-	-	16
Acer campestre L.	-	-	3	3

In the Oak103 trial plot, 184 trees of vegetative origin were recorded in the thinned trial plot, and 129 originated from seed. In the control plot, 82.5% of trees were of vegetative origin, and 17.5% originated from seed. The number of tree species recorded in Oak103 shows similar numbers of tree species in thinned and control plots (9 and 8, respectively). As in the case of Beech14, some are only sporadic.

3.1.2. DBH and Height

The difference in the number of tree/stem height measurements and DBH measurements occurred due to deformations of individual trees, which made it impossible and unnecessary to measure heights. Descriptive statistics of DBH and height show higher values of height and DBH in plots where thinning has been conducted and, as expected, a far greater number of trees/stems in the control plot (Table 4).

Table 4. Descriptive statistics for DBH and height for coppice type (beech coppice, s. oak coppice), treatment, and origin for both years 2020 and 2022.

COPPICE TYPE	TREATMENT	ORIGIN	N	DBH2020 (cm)	DBH2022 (cm)	N	H2020 (m)	H2022 (m)
				Mean ± Std Dev	Mean ± Std Dev		Mean ± Std Dev	Mean ± Std Dev
Beech14	CONTROL	GEN	23	14.61 ± 7.25	15.38 ± 7.18	21 [1]	12.25 ± 2.67	13.46 ± 2.77
	CONTROL	VEG	271	14.20 ± 5.56	14.90 ± 5.56	220 [2]	12.25 ± 2.43	13.26 ± 2.39
	THINNING	VEG	161	20.23 ± 7.84	21.18 ± 7.83	145 [3]	17.43 ± 3.10	18.95 ± 3.44
	[1] 2 seed origin stems died in the control plot during the measurement process—not possible to measure the height [2] 51 vegetative origin stems significantly deformed—not possible to measure the height [3] 16 vegetative origin stems significantly deformed—not possible to measure the height							
Oak103	CONTROL	GEN	83	15.61 ± 4.73	16.16 ± 4.74	78 [1]	12.96 ± 2.44	13.90 ± 2.41
	CONTROL	VEG	398	13.01 ± 4.23	13.69 ± 4.26	280 [2]	11.83 ± 2.58	12.69 ± 2.56
	THINNING	GEN	128	17.37 ± 7.72	18.08 ± 7.75	120 [3]	13.78 ± 3.73	14.51 ± 3.79
	THINNING	VEG	182	13.41 ± 4.76	14.06 ± 4.82	158 [4]	11.79 ± 2.89	12.43 ± 3.02
	[1] 5 seed origin stems significantly deformed—not possible to measure the height [2] 118 vegetative origin significantly deformed—not possible to measure the height [3] 8 seed origin stems significantly deformed—not possible to measure the height [4] 24 vegetative origin stems significantly deformed—not possible to measure the height							

3.1.3. Other Criteria

Nevertheless, descriptive statistics for both Beech14 and Oak103 show that thinning promoted growth and increased the number of quality trees/stems (Tables 2 and 5). The amount of trees/stems with significant defects (breakage, leaning, etc.) was higher in the control plots for both Beech14 and Oak103. In a thinned trial plot of Beech 14, nine stems died in the two years between measurements, so there is no data on DBH and height. Sixteen stems, all of them of vegetative origin, were so deformed or bent over that the height was not measured. In the control plot of Beech14, two stems died while many more trees (53 trees/stems in total, out of 51 of vegetative origin) were significantly deformed and bent over, so the measurements were not possible. In the thinned trial plot of Oak103, three trees/stems died between the two measurements, and 32 trees/stems were so deformed and bent over; consequently, the height measurements were not possible. Out of those 32 trees, 8 were seed-originating, and 24 were of vegetative origin. The control plot of Oak103 had 16 trees/stems that died, so no subsequent measurements were taken. One hundred twenty-three trees were significantly deformed or bent over, out of which 5 were of generative origin.

In both Beech14 and Oak103, the maximum number of stems per stump was 3, with the majority having just one stem per stump. The highest number of trees with more than one stem per stump, 19, was recorded in the thinned trial plot of Oak103, with eight trees exhibiting this in the thinned trial plot of Beech14. Both Beech14 and Oak 103 control plots had fewer trees with more than one stem per stump but had higher numbers of deformed trees and rotten stumps.

Table 5. Results of the repeated measure analysis of variance for DBH (cm) and h (m).

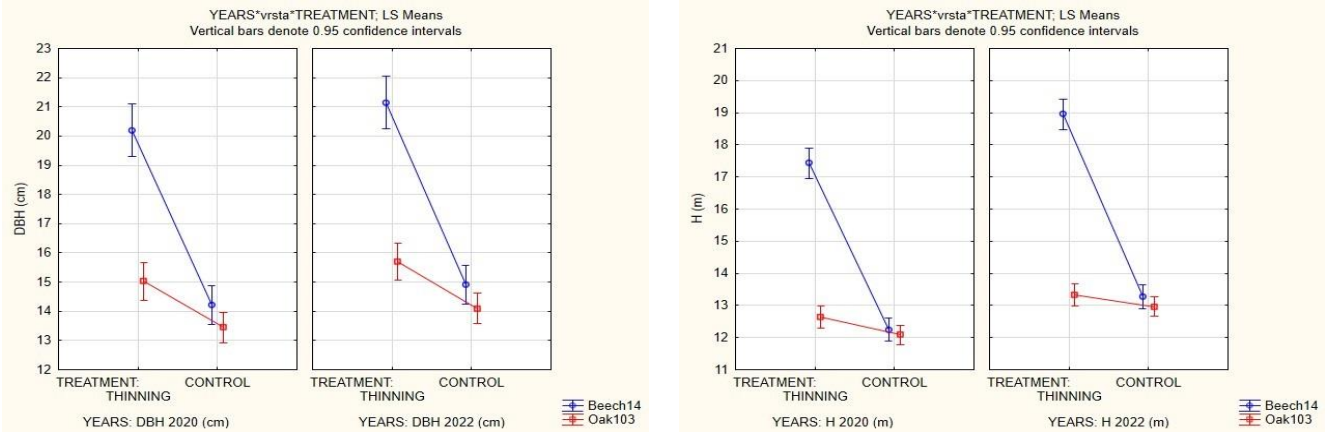
	DBH (cm)			h (m)		
Source of Variability	**MeanSquare**	**F Value**	***p* > F**	**MeanSquare**	**F Value**	***p* > F**
Between Subjects Effects *						
COPPICE TYPE	**1099.13**	**17.02**	**<0.0001**	**821.87**	**50.98**	**<0.0001**
TREATMENT	**4291.19**	**66.44**	**<0.0001**	**2314.56**	**143.56**	**<0.0001**
ORIGIN	**650.83**	**10.08**	**0.0015**	**135.92**	**8.43**	**0.0038**
COPPICE TYPE × TREATMENT	**3716.58**	**57.54**	**<0.0001**	**2928.55**	**181.64**	**<0.0001**
COPPICE TYPE × ORIGIN	140.93	2.18	0.1399	33.40	2.07	0.1503
TREATMENT × ORIGIN	151.92	2.35	0.1254	48.15	2.99	0.0843
Error	64.59			16.12		
Within Subjects Effects *						
YEARS	**80.21**	**708.56**	**<0.0001**	**140.745**	**503.75**	**<0.0001**
YEARS × COPPICE TYPE	**1.95**	**17.23**	**<0.0001**	**8.905**	**31.87**	**<0.0001**
YEARS × TREATMENT	**2.84**	**25.10**	**<0.0001**	**1.255**	**4.49**	**0.0343**
YEARS × ORIGIN	0.13	1.15	0.2846	0.595	2.13	0.1449
YEARS × COPPICE TYPE × TREATMENT	**2.22**	**19.62**	**<0.0001**	**11.995**	**42.93**	**<0.0001**
YEARS × COPPICE TYPE × ORIGIN	0.33	2.91	0.0883	0.105	0.37	0.5424
YEARS × TREATMENTxORIGIN	**0.63**	**5.58**	**0.0183**	0.00	0.01	0.9292
Error (years)	0.11			0.28		

* Mean Square = Sum of Squares (TypeIII)/df; Results in bold are statistically significant at a significance level $p < 0.05$.

3.2. DBH and Height Analysis

The results of RMANOVA (Table 5) show statistically significant differences between beech and s. oak's DBH and heights. There is also a statistically significant difference between DBH and height in the different treatments (control, thinning) and in tree/stem origin (VEG, GEN). Out of 'between subject effects' interactions, the only one that appeared to be statistically significant for both DBH and height is the interaction between species and treatments.

* Results in bold are statistically significant at a significance level $p < 0.05$, ** MS—Mean Square = Sum of Squares (TypeIII)/df; Results in bold are statistically significant at a significance level $p < 0.05$. These results show that DBH and height do not behave similarly when the tree species are subjected to different treatments (Figure 2a,b). Both DBH and height increase and are statistically significant in the thinned than in the control beech plots. In the case of within-subjects effects, statistical significance is proven for the effects of years, which is logical since DBH and height significantly increased over the two years. In the case of double mutual interactions with years, statistical significance is shown for year and coppice type and year and treatment. This analysis shows that DBH and height during the two years analyzed do not behave the same for beech and s. oak coppice (coppice type) and for treatment (control, thinning). Out of the triple interactions, statistical significance is proven only for the interactions of DBH and height between years, coppice type, and treatments, which was expected based on the previous results. For DBH, statistical significance is also proven for the interaction between years, treatment, and origin, which reveals that DBH does not behave the same over the years analyzed for different treatments and origins.



(**a**) (**b**)

Figure 2. Changes in tree/stem DBH (**a**) and height (**b**) in 2020 and 2022.

3.3. Analysis of Silvicultural Features (Stem/Crown Shape)

The results of the analysis of silvicultural characteristics (stem/crown shape) (Table 6) for beech trees show statistically significant differences between the trees in the control plots for tree/stem straightness (S), decreasing diameter along the trunk (T shape) and Curvature (C). In the case of s. oak, statistical differences are confirmed for decreasing diameter along the trunk (T shape), Curvature (C), Forking (F), Crown width (C_width), and Crown symmetry (C_sym). The only variables that are statistically different for both beech and s. oak, are T shape and C.

Table 6. Results of Chi2 and Fisher's exact test for variables: tree/stem straightness (S), decreasing diameter along the trunk (T shape), Curvature (C), Forking (F), Crown width (C_width), and Crown symmetry (C_sym) and treatment.

		BEECH				S. OAK			
Variable	**Level**	**CONTROL**	**THINNING**	**Total (%)**		**CONTROL**	**THINNING**	**Total (%)**	
S*	1	84	79	163 (35.43)	**Chi2 = 18.91; df = 2; *p* < 0.0001**	106	56	162 (20.10)	Chi2 = 1.35 df = 2; *p* = 0.5096
	2	153	66	219 (47.61)		268	170	438 (54.34)	
	3	59	19	78 (16.96)		123	83	206 (25.56)	
	∑	296 (64.35%)	164 (35.65%)	460 (100)		497 (61.66%)	309 (38.34%)	806 (100%)	
T_shape	1	92	97	189 (41.09)	**Chi2 = 34.53; df = 2; *p* < 0.0001**	113	82	195 (24.19)	**Chi2 = 16.99 df = 2; *p* = 0.0002**
	2	164	52	219 (46.96)		246	180	426 (52.86)	
	3	40	15	55 (11.96)		138	47	485 (55.95)	
	∑	296	164	460		497	309	806	
C	1	5	1	6 (1.3)	**Fisher Chi2 = 13.96; df = 2; *p* < 0.0006**	108	78	186 (23.08)	**Chi2 = 7.08 df = 2; *p* = 0.0291**
	2	138	49	187 (40.65)		285	148	433 (53.27)	
	3	153	114	267 (58.04)		104	83	187 (23.20)	
	∑	296	164	460		497	309	806	
F	1	11	6	17 (3.72)	Chi2 = 5.07; df = 2; *p* = 0.0790	38	22	60 (7.57)	Chi2 = 0.13 df = 2; *p* = 0.9386
	2	87	65	152 (33.26)		232	148	380 (47.92)	
	3	196	92	288 (63.02)		218	135	353 (44.51)	
	∑	294 (64.33)	163 (35.67)	457		488 (61.54)	305 (38.46)	793	
C_WIDTH	1	48	42	90 (19.69)	**Chi2 = 5.97; df = 2; *p* = 0.0505**	67	98	165 (20.68)	**Chi2 = 42.58 df = 2; *p* < 0.0001**
	2	182	91	273 (59.74)		233	137	370 (46.37)	
	3	64	30	94 (20.57)		189	74	263 (32.96)	
	∑	294	163	457		489 (61.28)	309 (38.72)	798	
C_sym	sym	30	22	52 (11.38)	Chi2 = 1.13; df = 1; *p* = 0.2888	19	41	60 (7.52)	**Chi2 = 23.97; df = 1; *p* < 0.0001**
	asym	264	141	405 (88.62)		470	268	738 (92.48)	
	∑	294	163	457		489	309	798	

* Note: levels: 1 (High), 2 (Medium), 3 (Low); df Degree of freedom; sym: symmetric, asym: asymmetric. Results in bold are statistically significant at a significance level of $p < 0.05$.

4. Discussion

We examined the effects of thinning in beech and s. oak low coppices in the central Dinarides (Lika region) on composition, origin, tree/stem DBH, tree/stem height, and stem/crown shape. The period of twenty years provides data on the long-term thinning effects, for which published data are limited [36]. Thus, the comparison of acquired results with other studies is restricted. Coppices included in the research are representative of beech and s. oak coppices at lower elevations of the mountainous Dinaric region [23,42], the most widespread coppice types both here and in Croatia in general [19] (Figure 3).

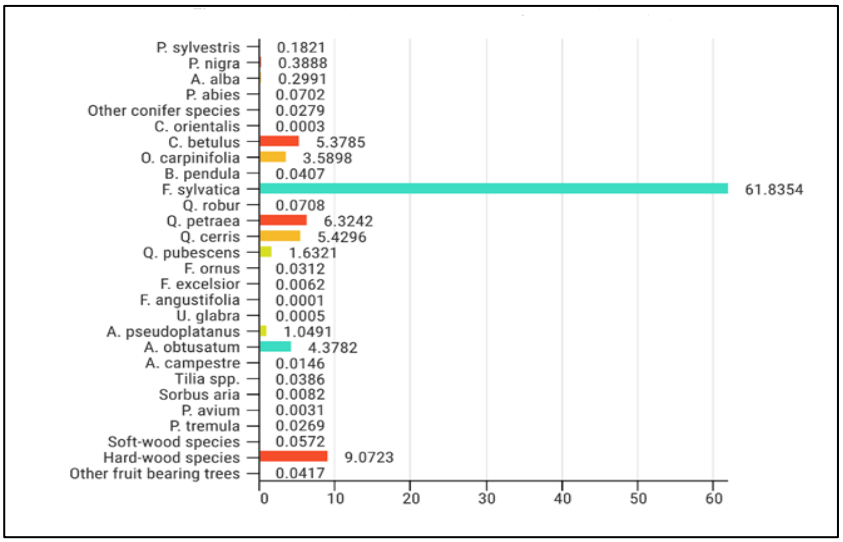


Figure 3. The proportion of forest tree species by growing stock in the coppices of Lika region showing that beech and s. oak is the most significant coppice species [19].

The proportion of coppice in the Forest administration area of Gospić is significant (29%), and these are mainly commercial [19]. This makes coppice management one of the most important forest management issues in the country. The Lika area has specific ecological and socio-economic factors which significantly influence forest management. These include a lack of workforce, limited applicability of mechanization due to rough and steep terrain, landmines from the war, depopulation, and lack of adequate planting material. All of these have led to an extremely challenging management situation [9]. Complexity and expenses resulted in the abandonment of most of the coppices. Despite this, through the recent "Enhancement of coppice management in Lika region" project, the State has demonstrated increasing interest, both in the active conversion of such coppice and in promoting active management. This is an acknowledgment of coppices as a significant component of this rural area, from ecological/protective function [48], social, as well, and economic points of view. Moreover, coppicing is a sustainable forestry practice.

4.1. Effects of Thinning on Species Composition and Tree Origin

In terms of species composition, thinning reduced forest tree species diversity in Beech14. The number of tree species in thinned vs. control plots in Oak103 was similar, with improved growth and quality of trees among the supporting tree species. There is no clear evidence of what happened in the last twenty years in these coppices. Data was collected only for the purposes of management plans (small samples), and no further silvicultural interventions were performed. The analysis of the short-term effects of initial thinning in these plots suggested thinning supported tree species diversity. Moreover, supporting tree species diversity was one of the thinning goals. Since there have been no additional silvicultural interventions, it could be interpreted that the increased growing space, stimulated by thinning, increased the growth of stronger trees/species. This could be mitigated by consequent thinning, which was not conducted. Since twenty years is a

long time span, species competition and self-thinning again were at play. We can propose that more frequent thinning would have a beneficial effect on tree species diversity, similar to what it had after initial thinning. The mechanism of the transformation of coppices into high forests, spontaneous or under human influence, remains unknown. Various factors influence this progression towards stands dominated by single-stemmed and seed-originated trees [49]. Nevertheless, lowering tree competition (especially interspecies competition) by thinning provides more opportunities for the maintenance and development of tree species diversity. Thinning serves as a valuable opportunity to regulate resources for the growth and development of diverse tree species as well as to support main tree species growth and stem quality.

4.2. Effects of Thinning on Tree/Stem Growth

Tree/stem coding was used in this research, and unique identifiers were recorded on a database. This enabled in-depth statistical analysis that provided insight into the growth and development of individual trees. This differs from most studies, which use only the mean stand values. This enabled more detailed insight into the growth and condition of individual trees/stems, setting the context for further long-term observations. Study reveals positive thinning effects. Thinning promoted the healthiest and best quality trees/stems. Thinning had a positive impact on tree growth regardless of the tree's origin (seed or stump). After twenty years, no trees of generative origin remained in the Beech14 thinned plot. Higher DBH and height values were recorded in plots where thinning was performed.

Statistical analysis reveals the long-term effect of thinning on the growth of trees/stems in both coppices. Trees on thinned plots had faster growth than trees on control plots. Moreover, trees originating from seeds generally showed a slower increase in DBH. This supports the productive capacity of coppices. Height tree growth was also significantly higher for thinned plots, but there is no statistically significant difference between trees of different origins.

It underlines the beneficial influence of thinning, supporting initial short-term results from research in this area [23,42]. This data can provide important insights into coppice management in Croatia as well as wider Europe. The complexity and uniqueness of Illiric beech and s. oak coppice supports the need for further investigations into both the short and long-term effects of higher thinning intensities.

The analysis of collected data includes descriptive statistics, which can provide insight into the type of coppices (tree species ratio concerning their origin and thinning effect) selected. This information has already been recognized as important in previous research carried out in coppices e.g., [23,42]. The origin of trees, their growth, vitality, quality/stem shape, and tree origin ratio indicate the biological potential of tree/coppice and their ability to adapt, increase wood volume, and their potential for successful restoration or conversion [23,27,42]. This study has demonstrated a positive (statistically significant) long-term effect on growth and quality in both beech and s. oak coppice.

The favorable short-term effect of thinning on coppice growth has been shown previously [23,42] in the same research area. Other studies conducted in the broader area confirm the same effect as the DBH. The positive effects of thinning on DBH were found for beech and s. oak [50,51], as investigated in this research, but for other oaks as well [52]. In these studies, the effect on tree height was variable, positive or negative. Now, the positive long-term effects of thinning on coppice growth for both DBH and height have been supported by the results in both Beech14 and Oak103 sites. In addition, previous studies, although few and mostly undertaken under Mediterranean conditions, confirm the long-term benefits of thinning on growth. For example, an Italian case study of a beech coppice in conversion to high forest over 22 years indicated that this quickly showed a positive response to active conversion practices based on periodic medium-heavy thinning [28]. The most recent study on *Quercus subpyrenaica* EH del Villar [36] found a similar result over 20 years, which declined slightly with canopy closure. The authors found that thinning improved the oak's basal area increment, more marked in small-diameter

trees, and that thinning reduced oak sensitivity to short-term drought. Another study on *Quercus pyrenaica* Willd. coppices [37] supports the claim that thinning favors the growth of *Q. pyrenaica* trees, especially when stand density reduction is high (extracted ca. 50% of the basal area). Un-thinned plots displayed more natural mortality, i.e., self-thinning, similar to our findings. Long-term (15 years) demographic responses of holm oak (*Quercus ilex* L.) [38] to thinning from below (−30% basal area) were positive; the effect on stem growth decreased over time but remained significant 15 years after thinning.

In addition, thinning prepares coppices for conversion and accelerates this long process [29,53–55]. Since the regrowth of beech after cutting is often poor and stump mortality can be high [1], beech coppice in the area is likely to be converted, highlighting the importance of the long-term effect of thinning. This research supports the conclusion that thinning has long-term positive effects on tree growth.

In addition to these positive effects, some studies [26] have suggested thinning helped to mitigate growth reductions during drought in broadleaves, but the benefits have decreased over time since the last intervention. This highlights the need to determine how long the positive thinning effect lasts, particularly in the context of climate change. There is still a gap in knowledge regarding the effect on broadleaved forests [26], especially temperate oak coppice, of long-term thinning with respect to increasing adaptation capacity, making this research a rare contribution to this topic.

4.3. Effects of Thinning on Silvicultural Characteristics (Stem/Crown Shape)

Our findings support the claim that thinning has long-term effects on tree quality, producing not only larger trees but also better-quality ones, resulting in a more valuable range of wood products and the potential for higher income. This could bring coppices in the Lika region into more active management and increase socio-economic benefits.

Bošeľa et al. (2016) [56] showed that the method of tending beech stands significantly influences not only the quality and quantity of production but also their vitality. Another study [38] highlights that the loss of stools from mortality appeared to be faster than the loss of stems in un-thinned plots, particularly in drought conditions or when rainfall was limited. Some even argue that the thinning of beech and s. oak coppice is justifiable during rotation periods due to climate changes, although this was not previously the tradition in Europe [50]. Higher dieback of beech trees in trial plots points to the possible shift in vegetation and higher beech sensitivity on lower mountain elevations. Slightly higher dieback of trees in thinned vs. control plots could suggest higher species competition due to more intensive growth stimulated by thinning. Nevertheless, the long interval after thinning could point to the wearing off of the thinning effect, as observed in the aforementioned studies [36,38]. Even though we observed a similar tendency in trial plots of Beech14 and Oak103, our research cannot clearly support such claims, as the number of trees affected was low compared to the total number of trees in the trial. On the other hand, the number of significantly deformed trees in trial plots and analysis of silvicultural characteristics, assessed visually, clearly support claims that, in the long run, thinning positively affects tree quality.

Recent research on the influence of thinning on coppice biodiversity suggests active management could prevent the homogenization of vegetation and the loss of some rare plant species [38,57]. Thus, we recommend more phytosociological research into the evaluation of thinning effects, as this could be positive in increasing active coppice management. Furthermore, research on short-term and long-term effects of silvicultural interventions should be intensified and supported by new findings (e.g., on wood quality and products, the amount of rot, living or dead stumps, effects of thinning on biodiversity, etc.), especially for beech coppices.

The variety of historical circumstances and natural diversity in Europe in general and in South-East Europe in particular have created great diversity of coppice and management practices [58,59]. Large areas of coppice are still present in some countries, particularly in South-East Europe. Coppice is an interesting management form and has been used for sim-

ple and quick fuel production throughout human history. The newly-arisen energy crises increase the relevance of coppice in the green economy [60] and meet the growing needs for wood products, supporting the historical perception of coppice as highly valuable and important for securing economic, ecological, and cultural benefits. Despite past calculations on financial profitability, which concluded that a significant increase in fuelwood prices would be needed to raise the yield value of coppice compared to high forests [61], recent market price analysis shows that this is not far-fetched. In addition, there is evidence that trees that regenerate vegetatively have a higher resistance to drought when they are young. However, there is a lack of research for different species and coppice ages [62]. Thinning is a crucial tool to support production, adaptation, and conservation and is essential for conversion processes with detectable long-term effects. Research into thinning benefits has implications for forest management, supporting forest tree species richness, higher tree quality, and increased growth, producing larger, more valuable trees, which may be used for other products, not just traditional fuelwood. In the case of rural, depopulated areas, where coppice played a significant role traditionally and where significant areas remain, the initiation of thinning in neglected coppices could be beneficial in socio-economic terms. Even two decades ago, it was evident that the silviculture of coppices must be redefined for new uses [63]. Nowadays, for most private forest owners as well as poor rural areas, coppices are again of interest.

However, published data is still scarce since research efforts have declined in recent decades. This study has shown that thinning has positive long-term effects on the growth of low coppice. In addition, trees in thinned plots had less damage and better stem and crown shapes. Thus, thinned coppice was found to be more prepared for conversion to high forest and had higher growth and better tree quality. Thinning supports recent interest in more active coppice management and related forestry efforts; therefore, it should be supported by more scientific research and feature more prominently in forest policy in Croatia and beyond.

4.4. Study Limitations and Further Research Directions

The limitations of further research are diverse. It is not surprising that there is low data availability on the topic at present. Many coppices have already been converted to high forests, while some are in inaccessible areas. Studies mostly focus on coppices that are transitioning to high forests or on unmanaged and abandoned coppices. Thus, this comparative study of unmanaged vs. thinned coppices in the same ecological context provides valuable input on the effect of silvicultural interventions. This is certainly needed since there is still a necessity for closer examination of coppice dynamics in different ecological contexts (50). However, this kind of research is rare even in Southeast Europe, where coppices are still present in higher numbers since there are not many managed coppices. The high complexity of social, economic, and ecological aspects in the areas where coppices remain has already been discussed, which will undoubtedly influence further research on the topic. Nevertheless, the study included some gaps which should be tackled in the future. Firstly, no additional thinning interventions were conducted after the initial one, so the effects of timely thinning, as well as different thinning intensities, should be further investigated. Secondly, it would be beneficial to investigate the actual quality of beech logs since there could be losses due to wood decay fungi. Acquired data should be discussed only in relation to actual tree age and characteristics. Thus, the additional trial should be set, sample trees cut, and the actual quality and price of logs calculated.

5. Conclusions

Coppices are significant components of rural areas, from ecological/protective functions and social and economic points of view. Coppicing is a sustainable forest activity/practice supporting general biodiversity. It is argued that the importance of coppice will grow in the future. Even though coppice management is one of the most important forest management issues in Croatia, published data on the long-term thinning effects are

limited. Study reveals positive thinning effects on the growth of trees/stems and their silvicultural characteristics. Nevertheless, more support for the diversity of tree species should be given by silvicultural interventions. The short-term study showed a positive effect of thinning on tree species diversity, but the long-term study revealed a diminishing effect years after thinning. This highlights the need for more frequent thinning. This study presents valuable examples of research principles for long-term thinning effects but also underlies the necessity of more detailed research.

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