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Growth and Development Dynamics of Young Holm Oak (*Quercus Ilex* L.) Stands after Shelterwood Cutting in Open Forest Road Conditions

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Abstract

*The Mediterranean forest region has been exposed to anthropogenic impacts for centuries, and the constant biotic and abiotic factors, together with increasing climate change, have hindered the proper management of forest ecosystems. This study presents the results of multiyear, systematic, specific and practical monitoring of the conversion of holm oak coppices using the principles of the shelterwood system. It also presents the growth and development dynamics of the stand on a permanent experimental plot from 1997 to 2017. The research was performed in the Eumediterranean vegetation zone of coniferous forest (Forest Management, Buzet branch, Pula Forestry Office, Magran Cuf management unit, compartment 83a). The plot has all the properties of a holm oak and manna ash forests (*Orno-Quercetum ilicis *H-ić/1956/1958). The basic elements of stand structure were monitored: diameter at breast height (DBH), tree height, horizontal crown projection, crown ground shading (light) and the appearance and abundance of all woody vegetation, with special emphasis on the growth and development of young generations of holm oak from seed. The paper also describes the threats limiting growth, development and survival of holm oak from seed (strong shooting tendencies of coppiced holm oak and bay laurel trees, excessive presence of shrubs). Forest management requires effective, timely and repeated tending to thin stands (already under the canopy), while also protecting young trees from wild game. The statistical method of interpolation determined the trends of stand development; trend equation with coefficient of determination (R^2) is very high. This indicates the growth and development of the stand in the direction of renewal of holm oak stands. Shelterwood cutting, with regular and timely tending of young generations of trees through a seven-year regeneration period, resulted in a high quality young high forest of holm oak, the first of its kind in the broader Mediterranean area. The indigenous stands of holm oak, as the fundamental climatogenic coniferous species of the Mediterranean species, have multiple roles such as protection from erosion, resilience to biotic and abiotic factors and forest fires, tourism and landscape functions, and other general forest functions, and therefore deserve intensive and ongoing research. Holm oak stands also play a part in conserving genetic and biological diversity, the potential and persistence of forest ecosystems, improving stand structure, stability and resilience of forest ecosystems to climate change, and in the long-term increase the commercial value of forest stands in the Croatian Mediterranean.*

Keywords: coppice, conversion, natural regeneration, shelterwood cutting, young generation

1. Introduction

In his book Naš goli krš [Our Bare Karst] (1931), renowned Mediterranean forest researcher Josip Balen wrote, »…The Mediterranean forestry comprises a distinctive part of our forestry, both in terms of rotation duration, especially for deciduous species, and by its products and relationships with agricultural crops. Mediterranean forests have two characteristics that make them stand out from other forest types: they are usually thin in the main stand stage, meaning that more attention much be paid to the lower, ground layers, and very often they appear only on small areas, in clusters…«. Later, in his contributions to understanding Mediterranean forestry, in a paper published in Šumarski list [Forestry Journal] (1935), he wrote, »The intensive influence of climatic factors, with careless human activities, has largely hindered the proper progression of forestry in the Mediterranean area.« Furthermore, renowned scientist Ivo Horvat (1965), wrote the following about the economics of forestry in the Mediterranean forests, »Economically speaking, we need to stress that investments made will not be quickly returned, and indeed it could be said that we do not know to which extent the return will be and with what depreciation. From the forestry standpoint, all silvicultural and amelioration works are positive… The invested resources need not be quickly returned in direct amounts, but indirectly, through improved regional climate, soil protection, recreation…«. These statements, though made long ago, clearly indicate the complexity of managing Mediterranean forest areas.

The areas with Mediterranean forests were settled early, with intensive population development over time. A wide range of pressures and human influences have impacted these forests since ancient times, particularly exploitation, from excessive cutting, grazing, and wild fires. Much has been taken from the forests, and little returned. This is also the main reason why the Mediterranean has largely lost its forests, resulting in deficits in the water balance, poor agricultural production, extreme climate conditions, strong erosion processes and more. This has led to a range of degradation stages, while high forests of holm oak and pedunculate oak are rare. Smaller stands of tall holm oak forests have been preserved in protected natural areas and on private lands, primarily on the islands (Brijuni, Rab, Krk, Brač, Lastovo, Mljet).

The loss of the climatogenic stands of holm oak and pubescent oak has resulted in their degradation forms, from coppices, macchia and garrigues, to rocky ground as a degradation form of holm oak, and thickets, undergrowth and rocky ground as degradation forms of pubescent oak forest. In recent decades, depopulation in rural areas has reduced these degradation processes, as the livestock fund declines and bans on grazing have led to progressive natural succession of these degraded stands. Despite this, the greatest influence on improving the quality of these forests, and ensuring their transition into higher growth forms and increasing forested areas, comes from forest experts, particularly well organised expert forest management in these areas. Due to the significance and potential of coppices, in both the ecological and commercial sense, it is the task of forestry works (conversion) to transition these stands into high growth forms, with the aim of increasing their environmental and commercial value.

Conversion (lat. conversio) is a silvicultural procedure where one forest form is transitioned into another, using the appropriate silvicultural measures. There are two types of conversion methods: indirect and direct. Indirect conversion implies using existing trees or shoots, and applying tending measures while taking advantage of the biological potential of the stand, to create the conditions for natural regeneration and transition the stand into higher forms. Direct conversion is performed by planting seeds or saplings of the same or other economically valuable tree species, when the biological potential of the stand cannot ensure success of the specific commercial measures (silvicultural) in creating conditions for natural regeneration. If conversion is performed with the same tree species, this is considered reconstruction (e.g. planting beech seeds or saplings after coppicing beech trees), while if another indigenous tree species, this is considered substitution (e.g. planting oak after coppicing black locust). This is a long-lasting and complex process that can only accelerate the intensive silvicultural procedures, while the forestry profession should give answers as to how to improve coppice management, and how to transition these degraded natural stands into high forms in the shortest period of time (Kovačić 1995).

Coppice management is among the oldest silvicultural activities, which did not receive much attention until recently. The main reason for this is low production and profitability, poor condition of coppices (such as excessively old stumps, shifts towards less valuable tree species, etc.), the influence of biotic and abiotic factors, and the lack of modern silvicultural concepts to improve coppice management and their adaptability to climate change.

In recent years, this issue has been addressed by measures in the Rural Development Programme of the Republic of Croatia (2014–2020), with the implementation of operation 8.5.1 Conversion of degraded forest stands and forest cultures. Execution of these measures is, in practice, performed using direct conversion methods (planting seeds or saplings), though there is a lack of research on methods of indict conversion based on shelterwood cutting principles. Conversion requires high financial investments and represents a long and uncertain process of artificial revitalisation. As a rule, this is both a large professional and financial task, particularly in the Mediterranean forests of holm oak and pubescent oak. The aim of managing (sub-) Mediterranean oak forests, in addition to their protection and conservation of their vitality, is to transition existing coppices into high growth forms, or at least to increase the share of trees from seed. Regeneration in these stands should unfold in line with the principles of shelterwood cutting (indirect conversion) in groups with a long regeneration period, beginning in the year with a high seed yield (Matić et al. 2011, Dohrenbusch et al. 2002). In order to decrease soil shading by crowns, the canopy is opened by seed cutting, as canopy shading of soil greater than 85% is a limiting factor for the development of young generations of holm oak from seed (Prpić 1986, Krejči and Dubravac 2000, 2004, Dubravac et al. 2018, Puerta-Pinero et al. 2007). Due to a lack of light, holm oak seedlings cease to grow, as seen in the fact that holm oak can rarely be seen in older development stages (Bran et al. 1990), while a relatively good share of light from 27.8% to 37.9% allows for the normal development of young holm oak saplings (Oršanić et al. 2011) Further, Krejči and Dubravac (2004) stated that, following the opening of the canopy, aggressive and lush development of accompanying tree and shrub species can be expected, and their number should be regulated under the canopy of old stand crowns. Once young trees appear, at sites where their density and quality is satisfactory, the canopy can gradually be further opened to lessen the competition between the young and old trees.

Coppices of holm oak and other species, particularly bay laurel, tend to produce a multitude of shoots. This can threaten the development and survival of trees from seed, which grow tall faster and require intensive, repeated tending. The nature of such stands does not provide the opportunity for rapid natural progression towards higher growth forms, as the same degree of degradation can be maintained for hundreds of years (Matić et al. 2011). In the process of conversion, works to protect the forest are very important, including protection from livestock and wild animals, and protection from fire.

Mediterranean forests in Croatia face three fundamental issues (Matić 1987, Matić et al. 2011): raising forests on bare karst soils (forestation), raising existing indigenous stands of holm oak and pubescent oak and their transition to higher growth forms, and protection and conservation of both indigenous and alien stands, especially from fire. Accordingly, silviculture works include establishing and raising forests (forestation), forest tending (cleaning and thinning), and forest regeneration (natural or artificial), and these works last throughout the entire lifespan, i.e. rotation, of the stand.

Understanding the structure of coppices and the quality of their habitats, while abiding by the fundamental postulates of Croatian forestry, based on management objectives, long-term management of all coppices should ensure their natural regeneration via the principle of shelterwood cutting. Above all, this results in stable, well preserved and productive stands of high growth form, i.e. high forests, with minimum investment and works required.

In Croatia, various authors have indicated the need and possibility for more rational management of coppices from the silvicultural perspective, with the aim of increasing the stability and vitality of these stands (Lasman 1906, Piškorić 1963, Šafar 1963, Šafar and Dereta 1968, Rauš and Matić 1984, Matić 1985, Matić and Rauš 1986, Matić 1987, 1993, Kovačić 1995). Phytocenological research in holm oak forests in Croatia was conducted by Baričević et al. (2013), and the issue of succession of holm oak forests on a permanent experimental plot on Rab was conducted by Rauš et al. (1994, 1997), Barčić et al. (2000).

Research on succession in holm oak forests on permanent experimental plots on the island of Rab was conducted by Rauš et al. (1994, 1997), while other research includes the tending and regeneration of the forests of the Croatian Mediterranean (Matić et al. 2011), ecological and biological properties of holm oak on the island of Rab, with emphasis on microclimate (Oršanić et al. 2011), and microclimate differences in degradation stages of holm oak forests (Ugarković et al. 2017, 2019). Most foreign authors have viewed the issues of holm oak forests through the prism of nursery production and the survival and growth of seedlings (Rey Benayas 1998, Sanzes et al. 2006), the role of climate change on holm oak mortality (Bonito et al. 2011, Barbeta et al. 2013, 2015, Cabon et al. 2018, Lull et al. 2020), and the impacts of wild animals on the natural regeneration of holm oak (Maltoni et al. 2019). The growth and development of holm oak shoots is directly proportionate to the quantity of available light (Bran et al. 1990, Puerta-Pinero et al. 2006, Gomez-Aparicio et al. 2009, Puerta-Pinero et al. 2007, Broncano et al. 1998, Gracia et al. 2001), and the natural regeneration of holm oak is strongly correlated with the size and density of trees, and soil shading by the canopy (Plieninger et al. 2004). Coppice research on the island of Sardinia (Italy) uses shelterwood cutting, leaving about 150 trees per hectare after the cut (Vacca et al. 2016). This indicates the complexity and mutual associations between the numerous morphological and biological properties of the growth and development of holm oak. However, recently there have been few studies investigating the silvicultural issues of monitoring development dynamics in older stands.

In Mediterranean countries with a higher share of holm oak coppices (such as Greece), there have been several attempts to naturally regenerate holm oak from seed (Ganatsas et al. 2003); however, this primarily pertains to silvicultural works in coppices based on thinning to enable conversion of growth forms. According to Hatzistathis et al. (1996) and Zagas et al. (1998), this can involve light thinning (10% of total volume), moderate thinning (20 of% total volume) and intensive thinning (30% of total volume). The best results were obtained with moderate thinning. In countries where forest pressures are markedly higher, such as Italy (Marca et al. 1995, 1998), in the Gargan forest along the western Adriatic, approximately 10,000 ha of holm oak forests are in demand for heating wood, and these coppices are managed with a short rotation (15 years), though occasional fires and impacts from livestock have degraded the quality of these woods. Experiments were conducted to regenerate coppices, to convert them into high growth forms, and to leave them to natural succession. The results showed that, with a long rotation, that was an acceptable solution, taking the ecological and economic factors into account, though the costs were higher and edaphic conditions poorer. The results also confirmed that leaving the forest to natural succession was the least acceptable solution (La Marca et al. 2008).

Understanding the issues of coppice management in Croatian coastal regions, and abiding by the scientific research conducted to date, in 1997, the Croatian Forestry Institute began to establish experimental plots (12 plots in total) for the transition of coppices into high growth forms, based on the methods of indirect conversion applying shelterwood system principles. The fundamental climatogenic tree species of the Eumediterranean coniferous forests, holm oak, was selected for the experiment. The aim of the research was to describe stand structure, possibilities for natural regeneration, growth and development dynamics of young generations of holm oak, and to propose effective, timely and adequate silvicultural measures. The first specific results of these studies were presented by Viličić et al. (1998), Dubravac (2001) and Krejči and Dubravac (2000, 2004). In June 2014, the results to date were presented at a conference in Pula for the employees of Hrvatske šume [Croatian Forests] from coastal regions, and included a tour of the experimental plots. Since then, research has continued to permanently monitor the growth and development of young high forests of holm oak (Dubravac et al. 2009, 2011, 2014, 2017, 2018), and the results have been presented at numerous domestic and international conferences, in oral and poster presentations. A significant portion of the research results have been included in two international projects:

⇒ SEE-ERAnet, coppices of Southeast Europe: Multifunctional coppice management (2007–2008)

⇒ COST ACTION FP1301: (EuroCoppice) – Innovative management and multifunctional use of traditional coppice forests – responses to future environmental, commercial and social changes in the European forestry sector (2013–2017).

The results of these projects were published in the papers by Dekanić et al. (2009), Stajić et al. (2009), and in the silviculture guide for coppices (Nicolescu et al. 2017).

This paper provides a synthesis of the systematic findings to date of research conducted on the transition of holm oak coppices by shelterwood cutting during the period from 1997 to 2017.

2. Materials and Methods

2.1 Study Area

The research was conducted on permanent experimental plots established in the Eumediterranean vegetation zone of coniferous forests, Buzet branch, Pula Forestry Office, Magran Cuf management unit, compartment 83a (Fig. 1A). Forest openness (roads) is 28.35 km/1000 ha, where 4.91 ha of classic forest fire tracks are managed, with 27 km of forest fire tracks with forest road elements (Fig. 1B). The plots have all the properties of holm oak and manna ash forests (*Orno-Quercetum ilicis* H-ić/1956/1958) according to Rauš et al. (1992). The pedological analysis indicated a limestone substrate, with soil type of ilimerised terra rossa, with neutral reaction (pH in water) in the humus horizon. According to the WRB classification, this is cambisol soil, with a low phosphorus content, good

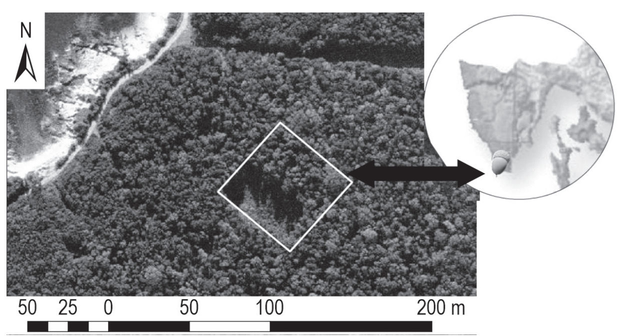

Fig. 1A Aerial photo of experimental plot, Pula Forestry Office, Magran Cuf management unit, compartment 83a

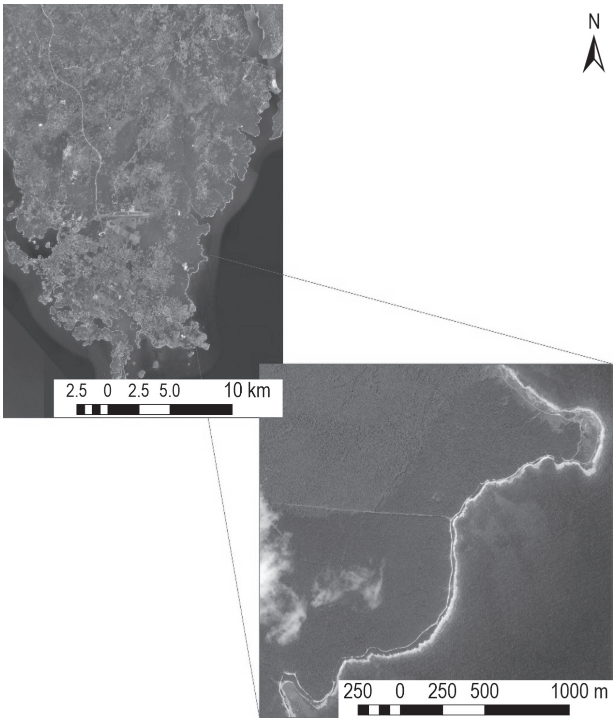

Fig. 1B Forest roads in management unit Magran Cuf

potassium content in the A horizon, satisfactory% nitrogen, and can be mechanically considered a light clay (Dubravac et al. 2006). According to the climate classification of Croatia (Seletković and Katušin 1992), the plot is situated near the border between the Csa and Cfsax climate regions. In terms of its position near the sea coast, it certainly falls within the Csa climate region, with mild winters and dry summers, and at least three times more precipitation in the wettest winter month than in the driest summer month.

2.2 Working Method

Fig. 2 shows the schedule of performing shelterwood cutting, silviculture works and the course of the 20-year research period (1997–2017). The permanent experimental plot was established in 1997 in a preserved holm oak (*Quercus ilex* L.) coppice with a dense canopy (Fig. 3), 50x50 m in size. In order to protect the plot from wild animals, prior to shelterwood cutting, the plot was surrounded with a 2 m tall wire fence. Over the years, the measurements of structural elements and young generations were performed in autumn during the non-vegetative period, while all tending was performed in summer. The measurements of abundance of woody vegetation (shrubs and trees) was performed along two transects, 2x50 m in size (total area of 200 m^2) laid in the middle of the plot with a distance of 10 m between them. All woody vegetation was recorded by species of trees and shrubs, and their origin (seed/coppice), and they were categorised into age and height categories (Viličić 1992). After the final

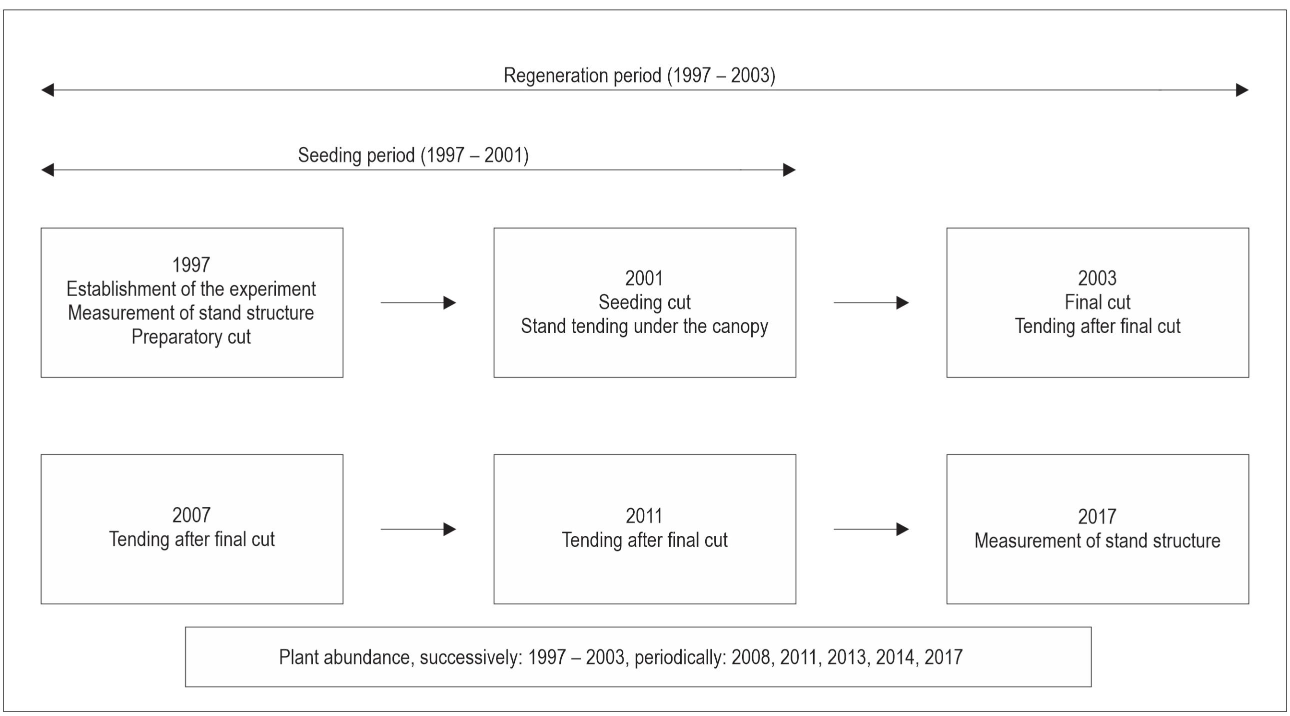

Fig. 2 Schedule of works during shelterwood cutting, silvicultural works and measurements of young generations on experimental plot

cut (2003), tending was performed several times that summer, and again on two occasions in 2007 and 2011. Measurements of the abundance of young generations in the set transects (200 m^2 sample) were performed each year successively from 1997 to 2003, and later periodically, in 2008, 2011, 2013, 2014 and 2017. During the final measurement in 2017, the structural elements of the young high growth holm oak trees was measured, including diameter at breast height and height. The height curve was calculated, as well as the number of trees and basal area per hectare. Due to the calculation of the stand structure (number of trees) in 2017, the method of measurement was methodologically changed. Unlike the previous ones, the measurement was performed by measuring the chest diameters of all trees by species (total bench) on a subplot sample of 10x50 m (500 m^2). All trees 0.6 cm thick with millimeter accuracy were included. A sample of 30 trees was taken for the purpose of making the height curve.

Geometric sequence interpolation is a useful tool if between two given numbers, *x* and *y*, the numbers *z* need to be interpolated so as to make a geometric string (Arya et al. 2016, Schoenberg 2011). Average annual rates of change ($\overline{S}$) for periods in which there were no measurements were calculated by the formula:

$$\overline{S} = \left(\sqrt[n-1]{\frac{Y_n}{Y_1}} - 1 \right) \times 100 \tag{1}$$

Where:

Y_1 and Y_n are recorded numbers of tree species

$Y_2, Y_3, \ldots, Y_{n-1}$ are unknown values.

Based on the calculated average annual rate of change, we calculated the number of trees for years in which there was no measurement according to the formulas:

$$Y_2 = Y_1 \times \left(1 + \frac{\overline{S}}{100}\right); \; Y_3 = Y_2 \times \left(1 + \frac{\overline{S}}{100}\right); \ldots ;$$
$$Y_{n-1} = Y_{n-2} \times \left(1 + \frac{\overline{S}}{100}\right); \tag{2}$$

The calculated values $Y_2, Y_3, \ldots, Y_{n-1}$ were then interpolated into an existing array of measured values.

Trend equation with coefficient of determination (R^2) of Polynomial Regression Model in the 3rd degree are shown in Fig. 8.

Searching for the trend on the base of recorded and interpolated values of the abundance of young generations in the set transects, we found that the data are not captured by the Linear Regression Model, so we used Polynomial Regression and increased the degree in the model, tending to increase the performance of the model. However, increasing the levels in the model also increases the risk of excessive and insufficient data fit (Šošić, 2006).

Table 1 Structure of management classes of holm oak coppices in Croatia by forestry district and ownership structure (surface area, wood volume and yield)

Forestry district	Hrvatske šume d.o.o. (state forests)			Private forests		
	Surface area	Wood volume	Yield	Surface area	Wood volume	Yield
	ha	m^3	m^3	ha	m^3	m^3
Senj	1617.41	137,599	4707	1373.60	70,565	2030
Buzet	6537.45	308,747	7902	4964.06	304,272	8863
Split	196.93	8815	221	6402.52	217,176	5809
Total	8351.79	455,161	12,830	12,740.18	592,013	16,702

Forestry district	Croatia – other users			Total		
	Surface area	Wood volume	Yield	Surface area	Wood volume	Yield
	ha	m^3	m^3	ha	m^3	m^3
Senj	63.64	5226	61	3054.65	213,390	6798
Buzet	37.91	6088	119	11,539.42	619,107	16,884
Split	23.11	2980	97	6622.56	228,971	6127
Total	124.66	14,294	277	21,216.63	1,061,468	29,809

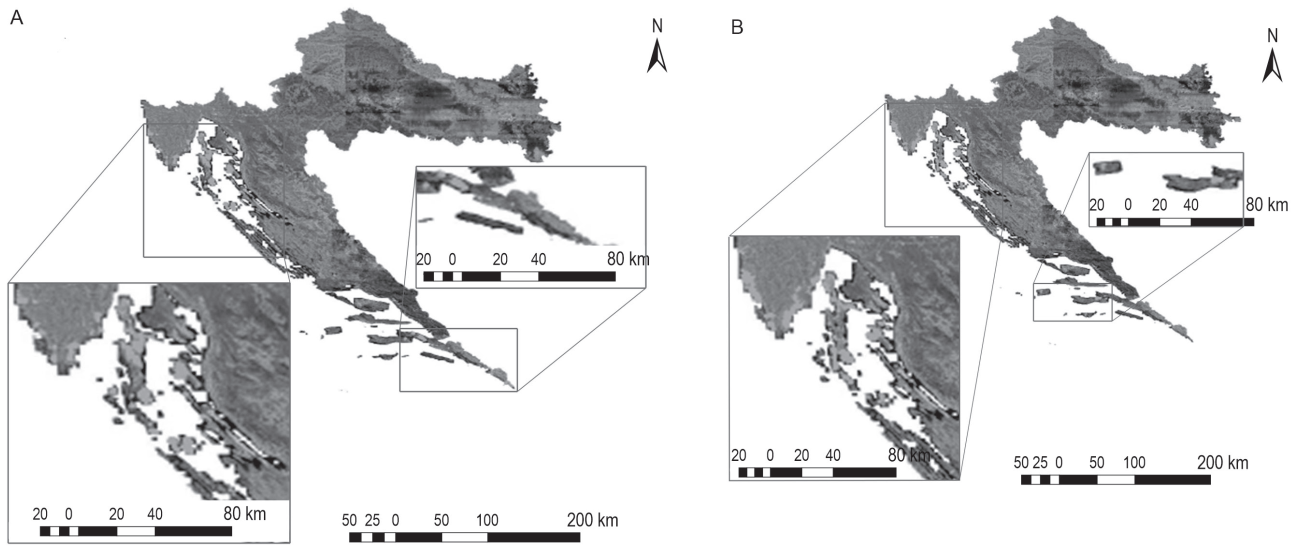

Fig. 3 Spatial distribution of management classes of holm oak coppices, A) in Hrvatske šume (state forests), B) in private forests

3. Results and Discussion

3.1 Structure of Holm Oak Coppices in Croatia

The Forestry Management Plan (ŠGOP: 2016–2025) lists that the total area of coppices in Croatia is 359,610 ha, or 13% of the total area of 2,759,039 ha of forests and forest lands. Of the total coppice area, 55% of these areas lie within state forests, and 45% are on private lands. Coppices contribute to 11% of the total area of state forests, and 25% of private forests.

The total area of management classes of holm oak coppices in Croatia is 21,216.63 ha, of which 8351.79 is under the regular management of »Hrvatske šume d.o.o.«, Zagreb, while 12,740.18 ha is in private forests and an area of 124.66 ha is managed by other legal entities. Therefore, a relatively small share of holm oak coppice areas (39%) is under regular management by Hrvatske šume d.o.o., Zagreb. The fragmented distribution of the management classes of holm oak in Croatia, in terms of ownership structure (i.e. Hrvatske šume d.o.o. and private forests) is shown in Fig. 3. Table 1 lists the distribution of these forests by forest management district and ownership structure, with data for surface area, wood volume and yield. Table 1 clearly shows that the highest share of managed classes of holm oak coppice in Croatia is in Buzet (78%), Senj (19%), and then Split (3%). Wood volume is highest in Buzet (68%), then Senj (30%), and Split (2%), and yield was also highest in Buzet (62%), then Senj (37%), and lowest in Split (1%). However, private forests show a different ratio. The highest surfaces are found in Split (50%), then Buzet (39%), and least in Senj (11%), while wood volume was highest in Buzet (51%), then Split (37%), and Senj (12%), similar to yield, which was highest in Buzet (53%), then Split (35%), and lowest in Senj (12%).

3.2 Stand Structure on Experimental Plot

The basic structure data are shown in Table 2. At the time of establishment of the experimental plot (1997), the holm coppice was 51 years old, with the following basic structural data: 1312 trees/ha, 22.97 m^2 basal area and 163.50 m^3 wood volume. The measurement in 2001, after performing the seeding cut in the stand aged 55 years, showed 834 trees/ha, a basal area of 16.18 m^2, and volume of 110.42 m^3. In 1997, holm oak accounted for 87% of all trees on the plot, while the rest (13%) were deciduous hardwoods (pubescent oak, Turkey oak and bay laurel). After the seeding cut in 2001, this percentage was reduced to less than 10% of the total number of trees.

Table 2 General structural data on experimental plot

Data on experimental plot	Year of measurement	
	1997.	2001.
Age, years	51	55
Number of trees, N/ha	1312	824
Basal area G/ha, m^2	22.97	16.18
Volume V/ha, m^3	163.50	110.42
Crown covered ground, %	85/57*	49,7

3.3 Shelterwood Cutting and Measurements on the Plot

During the non-vegetation period in 1997, when abundant and vital natural shooting appeared throughout the regenerated area, the preparatory cut was conducted. This reduced soil shading by the canopy from 85.0% to 57% (Table 2*), taking account of the fact that relative light of 15% is not sufficient for the development of holm oak trees, which instead experience growth stagnation and drying (Prpić 1986, Puerta-Pinero et al. 2007). All morphologically weak, deformed or excess trees were removed, particularly from the secondary part of the stand, therefore permanently breaking up the canopy. Trees were then more regularly spaced within the stand, and the remaining trees and crowns received increased access to light, accelerating yield and enabling seeding over the entire area. Further, in order for the young generation of holm oak from seed to obtain more light, and after reviewing the state of shoots and young trees and years of good seed yield, in March 2001, a seeding cut of 32% of the wood mass was conducted. This reduced soil shading by the canopy to 49.7%, which marked the completion of the regeneration period. Shoots were given sufficient light for their development, enabling young trees to develop and strengthen, by regulating the light conditions on the regenerated surface (Anić et al. 2013). In addition to light, water balance in the soil, evapotranspiration and temperature were regulated, and the soil properties specific to Mediterranean conditions improved (Gomez-Aparicio et al. 2009). Tending the young generations of holm oak from seed under the canopy of the main stand was also performed in the summer of the same year, when shoots of holm oak, bay leaf and shrubs were removed from stumps, and other undesired species removed (negative selection). The effects of this tending are visible in Fig. 4, and the well regenerated area with numerous vital shoots and new growth can be seen in Fig. 5. After excellent regeneration of the area with a young generation of new high growth holm oak, the final cut was performed in winter 2003, where the remaining old trees were removed from the regenerated area, thereby completing the change in generations and ending the 7-year long regeneration period. The final cut was conducted during the non-vegetative period (in winter) to maximally prevent or minimize any damage to young trees. The appearance of the regenerated area is shown in Fig. 6. After the final cut, tending was performed on multiple occasions: in summer of the same year (2003) and in two subsequent years (2007 and 2011).

In order to examine the ability of natural regeneration of the young generation of holm oak by performing

Fig. 4 Stand after tending under canopy, 2001

Fig. 5 Well regenerated holm oak stand on the plot, with a total of 79,250 holm oak plants from seed per hectare, after the seeding cut (2001)

Fig. 6 Young holm oak high forest after the final cut (2003) with 81,100 plants from seed per hectare

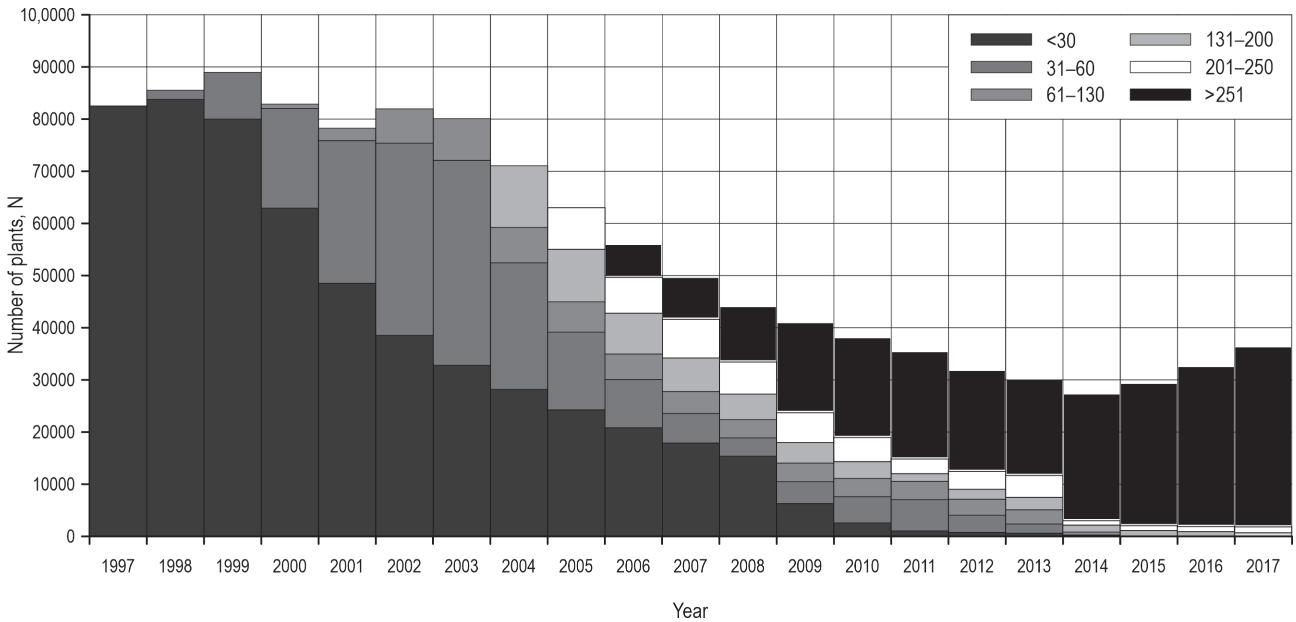

Fig. 7 Development according to height classes in measurement years with interpolation

shelterwood cutting, and to monitor the subsequent dynamics of growth and development of the young tall trees, the abundance of all woody vegetation of young trees and shrubs was monitored every year from 1997 until the final cut in 2003 (during the regeneration period). These measurements were later repeated in 2008 and 2011. The results are presented in Table 3.

The number of holm oak trees from seed during the shelterwood cutting period was relatively constant during the successive annual measurements (1997–2003), ranging from 79,250 to 90,100 (mean of about 80,000 trees). In 2008, this was reduced to 44,500 trees, and then further in 2011 to 35,750 trees. Oršanić et al. (2011) reported an exceptionally high number of shoots and young trees per hectare (from 480,000 to 1,190,000) on the island of Rab, though on a small sample with an experimental plot size of only 2x2 m. The same authors also reported a high average

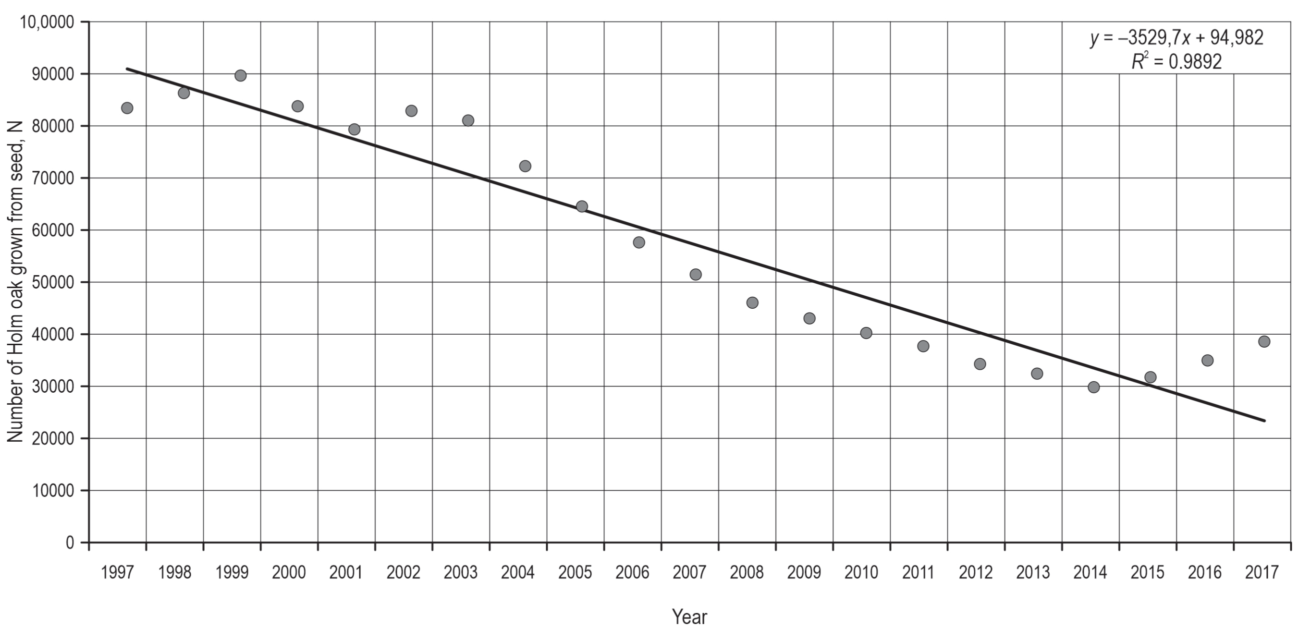

Fig. 8 Overview after interpolation for all years

mortality rate (57.26%) after 27 months. Long-term research that includes monitoring during development and survival stages would provide more realistic figures for the young generation. Research in pedunculate oak stands (Matić 1993) showed that the optimal number of the main tree species should be between 24,000 and 32,000 per hectare. Therefore, it can be assumed that in the regeneration of holm oak stands, similar optimal abundances can be expected.

The abundance of the competitor plants, above all coppice shoots of holm oak and bay laurel, and other tree species from seed or coppice, and shrubs that limit the unhindered development of holm oak from seed was uneven (Table 3). Shelterwood cutting (conducted in 1997, 2001 and 2003) had a strong influence on their appearance and height development over the study period. However, the highest impact was from the multiple tending sessions under the canopy (2001) and later tending after the final cut performed during the summer (2003, 2007 and 2011). In addition to their abundance, which after the final cut (2003) accounted for 80% of the total number of woody vegetation (400,050/ha), their height development is also important. Coppice shoots are known to have a significantly higher growth rate than plants emerging from seed. In 1906, Lasman measured a 2 m height increase of a one-year shoot in his research on the shoots of holm oak forests on the island of Rab. This was also confirmed in this study, with the remark that the height growth of coppice shoots of bay laurel (once such example of a coppice bay laurel, over 3 m tall) was much greater than the height growth of coppice shoots of holm oak.

Since the emergence and survival of young generations of holm oak from seed is the main factor for the regeneration and conversion of holm oak coppices into tall stands, after previously considering the total vegetation, we examined the abundance and height development of young generations of holm oak from seed during the entire study period. Table 4 and 5 shows the development by height classes, number of trees in absolute and relative amounts, successively measured during the shelterwood cutting period (1997–2003), and the dynamics of growth and development after the final cut periodically (2008, 2011, 2013, 2014, 2017). The grays highlighted in Tables 4 and 5 are statistically interpolated values. Fig. 8. Shows high coefficient of determination (R^2=0.9892).

In the first year of measurement (1997), all holm oak trees from seed were in the <30 cm height class. In the second measurement (1998), only 2% of holm oak had passed into a higher height class (<60 cm), while 7 years after the first measurement (in 2003), 41% of trees were <30 cm, 49% of trees were 31–60 cm, and 10% of trees were in the height class 61–130 cm. The measurement in 2008 showed that 51% of trees were in the height class 61–130 cm, and 41% of trees were in taller classes, where most (24%) were in the height class >250 cm. In the final measurement in 2017, all trees were over 150 cm in height, with 95% over 2.5 m tall (Fig. 7).

The entire course of the research on the experimental plot was also photographed, and an overview of stand development after the final cut (in 2003) and its subsequent development to 2013 is shown in Fig. 9. Fig. 10 shows the young high forest stands of holm oak (»A« in 2017), 16 years old, formed through natural regeneration by shelterwood cutting (indirect conversion method), as the first of its kind in the broader, regional area. Today (in 2020), this young holm oak forest grown from seed is 19 years old, and in terms of its appearance and structure, will soon undergo its first thinning, positive selection (Fig. 10 B).

Table 3 Descriptive statistics (young crop of trees and shrubs)

Species	Valid N	Mean	Std. dev.	CI -95%	CI +95%	Minimum	Lower Quartile	Median	Upper Quartile	Maximum	Coef. var.
Holm oak grown from seed	15	66,006	19,730	55,080	76,932	35,750	44,500	71,926	83,600	90,100	29.9
Holm oak grown from coppice	15	17,465	14,942	9190	25,739	2250	7700	14,950	18,250	59,550	85.6
Laurel	15	52,706	22,633	40,173	65,240	18,700	38,750	45,489	79,550	85,850	42.9
Other stem plants	15	35,925	2416	34,587	37,263	30,000	35,100	36,422	37,900	38,500	6.7
Bushes	15	82,633	59,016	49,951	115,315	6550	25,700	80,750	124,550	182,500	71.4
Total	15	254,735	104,170	197,048	312,422	101,350	151,750	266,500	336,200	403,350	40.9

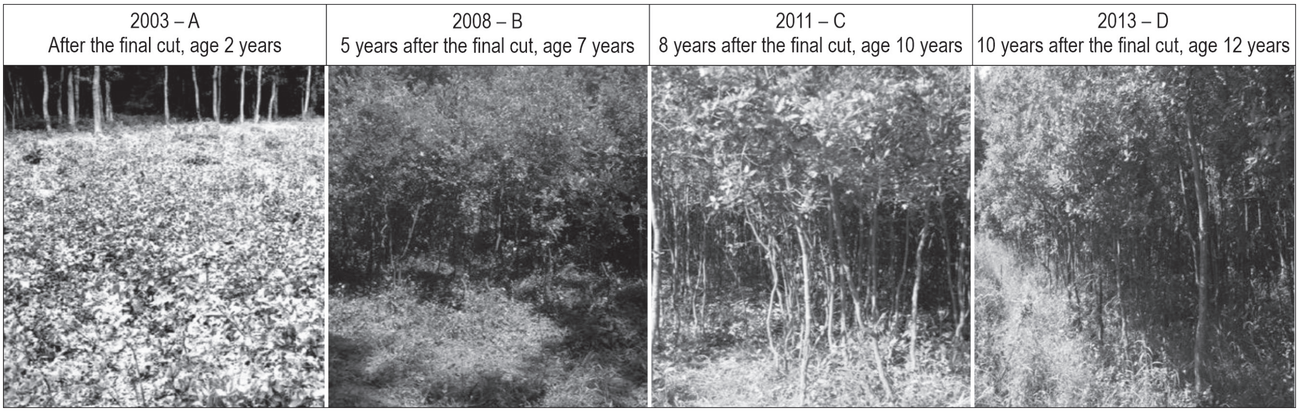

Fig. 9 Development of young holm oak high forest from 2003 to 2013

After the final cut in 2003, insignificant damage from wild animals (core peeling) was detected, though it was assessed that this would not hinder the further development of the stand, as the young trees were tall enough to minimize damage from animals. Research on the Island of Cres, in the Punta Križa management unit (Viličić et al. 1998), found that damage from wild game on plants less than 130 cm tall could be a limiting factor in the development of young holm oak grown from seed. During the shelterwood cutting experiment, working hours spent were also monitored. Approximately 35 working days per hectare were spent on tending under the canopy, and about 45 days per hectare tending the young stands after the final cut

Table 4 Holm oak from seed in measurement years, 1997–2003, 2008, 2011, 2013, 2014, 2017 and statistical interpolation for years 2004–2007, 2009–2010, 2012, 2015–2016.

Year	Holm oak grown from seed
1997	83,600
1998	86,600
1999	90,100
2000	83,900
2001	79,250
2002	83,000
2003	81,100
2004	71,926
2005	63,790
2006	56,575
2007	50,176
2008	44,500
2009	41,368
2010	38,457
2011	35,750
2012	32,174
2013	30,300
2014	27,531
2015	29,579
2016	32,891
2017	36,680

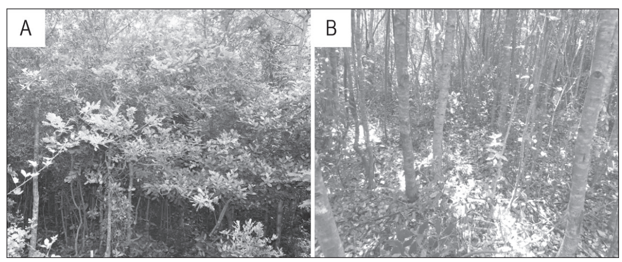

Fig. 10 Young holm oak high forest developed by shelterwood cutting (indirect conversion), age 16 years (A, 2017); Young holm oak high forest developed by seeding cuts (indirect conversion), today, age 19 years, 14 years after final felling (B, 2020.)

Table 5 Number of trees and basal area per ha and mixture ratio, measured in 2017

Tree species	Tree number/ha	Mixture ratio/%	Basal area/m^2	Mixture ratio/%
Holm oak	36,720	88	23.44	85
Pubescent oak	600	1	0.87	3
Manna ash	1000	2	0.71	3
Bay laurel	3040	7	1.86	7
Sorb tree	320	1	0.64	2
Total	41,680	100	27.52	100

(Krejči and Dubravac 2004). This indicates a significant financial investment, which in practice will represent a high personnel and financial expenditure.

Considering that the management of holm oak coppices under the management of Hrvatske šume cover an area of 8351.79 ha, this practice would be difficult to implement on this entire surface, particularly given the 80-year rotation. The Ordinance on Forest Management (OG 97/2018, Art.27) states that the rotation in coppices transitioned into high forests via natural methods is reduced by 30% from the rotation for stands of that tree species in high forest form during the time needed to naturally transition these coppices into high forests using the shelterwood cutting principle. The research presented here indicates the possibility of implementing regeneration using the shelterwood system, though on smaller, selected areas, abiding by the habitat conditions and set objectives, with the need for more intensive management. Anić and Mikac (2008) stated that in recent years regeneration by shelterwood cutting on small surfaces has also raised the need to regenerate pedunculate oak on small surfaces, given the extenuating circumstances (such as restoring stands damaged by high wind breakage or drying). This, in particular, applies to special purpose forests, private forests, and recreational forests. Stands of managed holm oak coppices, given their structure, habitat conditions, fragmented distribution, environment, pronounced overall value, and commercial and ecological value further indicate the justification of this type of regeneration on small surfaces.

3.4 Structure of Young Holm Oak High Forest, 2017

In terms of its management, the stand structure (measured in 2017) is an even-aged, high forest, while its development stage is young (first age class, 16 years) with a full canopy (Fig. 9 A). Since the stand is currently in the first age class, for which wood volumes are not calculated (Ordinance on Forest Management, OG 97/2018, Art.23, para.4), below is an overview of the basic structural data on the number of trees, basal area and ratios (Table 5). The young stand of holm oak grown from seed has a total of 41,680 trees per hectare, of which 36,720 are holm oak, 600 pubescent oak, 1000 manna ask, 3040 bay laurel and 320 sorb trees. In the overall ratio, holm oak accounts for 88% of all trees (this stand can be considered pure, even though the Ordinance stipulates a cut-off of 90%), manna ash 2%, pubescent oak and sorb each 1%, and bay laurel 7% (a high number of thin trees, with an average diameter of 2.5 cm). The total basal area is

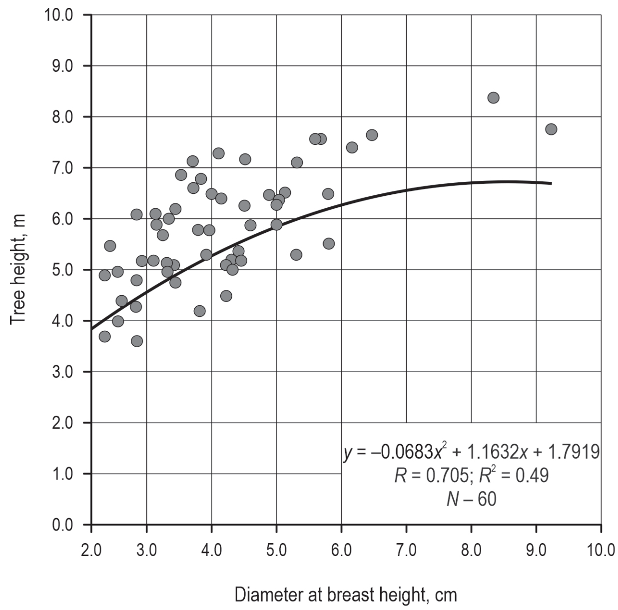

Fig. 11 Holm oak height curve

27.52 m^2, of which 23.44 m^2 (85%) is holm oak, 0.87 m^2 (3%) is pubescent oak, 0.71 m^2 (3%) is manna ash, 1.86 m^2 (7%) is bay laurel and 0.64 m^2 (2%) is sorb tree.

The measurements of young holm oak high forests in 2017 on a sample of 30 trees found that the average value of DBH was 4.03 cm (Fig. 10 A) and the average height was 5.89 m (Fig. 10 B). Fig. 11 shows the height curve.

Following the fundamental postulates of Croatian forestry, long-term management must take into account the objectives of management, natural regeneration and the implementation of shelterwood cutting in preserved holm oak coppices. This gives the best results and permanent solutions, given that the climatogenic communities are long-lived, highly stable and resilient to pests and fires (Matić et al. 2011). This was also corroborated by the results of this long-term study. Given the high cost and long time needed for indirect conversion, which also requires a high level of professional engagement, the need for this type of procedure is nonetheless clear. Smaller surfaces should be selected to implement shelterwood cutting in accordance with the management objectives. There are multiple benefits to applying indirect conversion, such as the shelterwood system, as outlined below.

In the long-term, these forests increase commercial value, provide multiple valuable functions, improve the structure, stability of forest ecosystems and their resilience to climate change, and with that the survival of the forest ecosystems of the Croatian

Mediterranean. Furthermore, the economic component should not be ignored, as every improved forest ecosystem, particularly degraded stands into highly productive stands, results in added value, higher production and long-term increases in the value of forests and forest lands. The economic benefits are also seen through the benefits in private forests, the possibility of seeking out support from the European Agricultural Fund for Rural Development, which can contribute to increasing the returns on investment in forestry, promoting innovative ideas and competitiveness of forest companies and the sustainable management of forests, and also providing the supply of wood and forest biomass, and creating new job.

Furthermore, indirect conversion gives higher quality trees, which is of exceptional importance for the stability of future stands from the aspect of ecotype adaptability (e.g. such stands are a source of future high quality seed stands). Today, forest contribution to CO_2 fixation from the atmosphere and ensuring a positive balance in the uptake and release of CO_2 is particularly significant. It is well known that after clearcutting, at least 30 years are required in order for new trees to re-establish a positive balance of CO_2 uptake and release, while natural regeneration (indirect conversion) ensures longer CO_2 uptake and assimilation into biomass. During natural regeneration, there are also no sudden habitat changes, degradation or loss of humus and mineral part of the soil, or drying and changes to the water regime. Young plants emerge quickly, blocking direct sunlight from hitting the soil, while also ensuring continuity for the abundant fauna in these forests. This is of the utmost importance for biodiversity, where the general values of the forests of the Croatian Mediterranean are fully expressed.

4. Conclusions

A long-term systematic scientific study monitored the course of development of a young generation holm oak forest in a preserved holm oak coppice through the implementation of shelterwood cutting principles (as a form of indirect conversion). The study covered the shelterwood cutting period, immediately after the completion of this period, with subsequent periodic measurements of the growth dynamics of the young generation. All the important factors of natural regeneration were monitored, and the obtained results give the following conclusions:

⇒ the effectiveness of the implementation of shelterwood cutting principles gave excellent results in coastal holm oak coppices

⇒ the frequency and intensity of seed production, with high preservation of soil, ensures suitable conditions for regeneration and natural conversion into high growth forms, and this is applicable on small surfaces

⇒ after the appearance of seedlings, professionally planned shelterwood cutting, with a seeding period of 4 years and a regeneration period of 7 years, resulted in a young high growth holm oak forest

⇒ soil shading by the canopy (light) is an exceptionally important factor for the development of young holm oak trees from seed, and the relative light penetration after the 49.7% seeding cut ensured the unhindered development of holm oak trees

⇒ the emergence and survival of the young generation of holm oak from seed requires effective, timely and repeated tending (already starting under the canopy), with the protection of regenerated areas from wild animals, due to the strong shooting tendencies of coppiced holm oak and bay laurel, and due to the excessive shrub layer

⇒ stands of managed holm oak coppice, considering their condition, habitat conditions, fragmented distribution, environment, pronounced general value and economic and ecological value indicate the justification of regeneration on small surfaces

⇒ activities include all works aimed at improving the management of forests and forest lands in Mediterranean forest areas, and silvicultural works should be based on the management objectives and a series of ecological and commercial factors (soil, stand condition, location, fire protection), and the available budget

⇒ the obtained results are applicable in practice, and will facilitate forest ecosystems in adapting to new changes, with the aim of achieving the set management goals, preserving and improving the existing forest ecosystem functions and services provided by the indigenous stands of holm oak

⇒ the statistical method of interpolation determined the trends of stand development with high coefficient of determination (R^2=0.9892), indicating the growth and development of the stand in the direction of renewal of holm oak stands

⇒ stands of holm oak, as the fundamental climatogenic species of coniferous Mediterranean forests, have multiple roles in erosion control, resilience to biotic and abiotic factors, forest fire prevention, tourism and landscape, and the overall general functions of forests, and therefore, these forests deserve intensive and long-term research. Vital stands of holm oak preserve genetic and biological diversity, the sustainability of forest ecosystems, improve stand structure, the stability and resilience of forest ecosystem to climate change, and in the long-term, increase the commercial value of forest stands of the Croatian Mediterranean.

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