Regeneration of hilly-mountainous oak forests in Serbia – past experiences and future perspectives

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Abstract

The regeneration of oak forests in the hilly and mountainous areas is one of the most serious and complex problems forestry practitioners face in Serbia. The success of regeneration depends on the individual or combined (often synergistic) influence of numerous biotic, abiotic, and management factors. While there is significant knowledge and experience about this process in practice so far, there is still great uncertainty regarding its proper execution and control over the influencing factors. The paper critically evaluated the available literature and current experiences from practice through a questionnaire. A comprehensive literature search was conducted, taking into consideration various databases and search engines, mostly composed of peer-reviewed publications from ISI-listed journals. A total of 187 papers were included in the base. Aiming to better understand the current state and the main problems in the regeneration of hilly-mountainous oak forests in Serbia, surveys were performed among forest practitioners. Based on this, the paper synthesized the current knowledge and addressed future perspectives in hilly-mountainous oaks management. More specifically, the factors that dominantly influence the regeneration process, their modes of action, behavior in the case of modifications, as well as the possibilities of their interaction are defined. The success of regeneration is determined by canopy openness, microclimatic conditions, presence of competitive vegetation, initial number of seedlings, and seedling growth and health, as revealed in the literature. The proposed methods for more successful regeneration and restoration of oak forests, include producing high-quality seedlings, using advanced weeding methods, developing a specific strategy for restoring native oak forests, assessing genetic resources and long-term monitoring. Overall conclusion of the conducted literature analysis is that there is a great need for conducting further long-term research on improving the regeneration systems in hilly-mountainous oak forests in Serbia.

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Keywords

Quercus frainetto; *Quercus cerris*; *Quercus pubescens*; *Quercus petraea*; Regeneration; Southeast Europe

Contents

1 Main oak forests on hilly and mountainous regions of Serbia

The specific ecological conditions that characterize the area of Serbia and wider Southeast Europe cause heterogeneous forest vegetation, which makes forest management in this area very complex. Within the European continent, the area of forests is the smallest in Southeast Europe (it occupies 30,446,000 ha or 23.5%), however, with the greatest biodiversity (Alexandrov and Iliev 2019). Cultural and historical drivers have particularly influenced the development of forestry in this area, where there is generally a long tradition of managing natural forests (O'Hara et al. 2018). On a smaller area, this situation is reflected in the territory of Serbia, where very heterogeneous ecological conditions are expressed in the form of different climatic influences, relief, parent rocks, soils and hydrological networks. To this are added the historical events (wars, population migrations, technological and social development), which significantly influenced the current state of forests.

In terms of vegetation, Serbia is very diverse and complex. Oak forests in hilly and mountainous regions are characterized by more than 30 associations as either climate-zonal (e.g. *Quercetum-frainetto cerridis* Rudski 1949. s.l.), extra-zonal (e.g., *Querco petraeae-Carpinetum betuli* Rudski 1949) or azonal forests (e.g., *Quercetum petraeae-cerridis* B. Jovanović 1979. s.l) (Tomić and Rakonjac 2013). The current state of the main oak forests (Turkey oak- *Quercus cerris* L., sessile oak- *Quercus petraea* (Matt.) Liebl, Hungarian oak- *Quercus frainetto* Ten. and pubescent oak- *Quercus pubescens* Willd.) in hilly and mountainous regions of Serbia is shown in Table 1 according to Banković et al. (2009).

Q. cerris forests are one of the most widespread forests in Serbia (occupying 345.200 ha), that is 15.33% of the total forest land. Coppice stands of this species are dominant, so the conversion of part of the inventory is one of the important tasks of the forestry profession. *Q. petraea* is one of the most important tree species in Serbia, and its forests occupy 173.200 ha, or 7.69% of the total forest land. Precisely these forests are an important landscape link between the *Q. frainetto* and *Q. cerris* forests and the beech forests. From an economic point of view, *Q. petraea* wood is one of the most valuable in our conditions, while the dominant copice origin limits the technical value. *Q. frainetto* grows most frequently in the climate-zonal community with *Q. cerris*, which is the biggest climate-zonal community in Serbia. *Q. frainetto* forests occupy 159.600 ha (7.09% of the total forest land). They are a distinguished element of submontane areas in Serbia (particularly Šumadija), and a significant element of the habitats of the main game species and other wildlife. The basic problem of these forests is their dominant coppice origin. *Q. pubescens* forests in Serbia occur fragmentarily on 10.400 ha (0.46% of the total forest land). All forests are of coppice origin, and due to their rarity, they deserve the status of protected forests in the future. As *Q. pubescens* forests are mostly found on extreme sites, they serve protective functions. The distribution of these species is shown in Figure 1.

Table 1. Characteristics of *Q. cerris*, *Q. petraea*, *Q. frainetto* and *Q. pubescens* dominated forests in Serbia (Banković et al. 2009).

		Unit	*Q. cerris*	*Q. petraea*	*Q. frainetto*	*Q. pubescens*
Area	State forests	ha	116,000.0	89,600.0	42,400.0	8,000.0
		%	33.6	51.7	26.6	76.9
	Private forests	ha	229,200.0	83,600.0	117,200.0	2,400.0
		%	66.4	48.3	73.4	23.1
Volume	State forests	m^3	17,764,345.4	12,156,204.9	5,796,742.7	763,575.4
		%	8.1	5.5	2.6	0.3
		m^3/ha	153.14	135.7	136.7	95.4
	Private forests	m^3	31,800,580.6	9,439,851.0	15,289,912.0	143,636.8
		%	22.6	6.7	10.8	0.1
		m^3/ha	138.7	112.9	130.5	59.8
Volume increment	State forests	m^3	396,743.9	294,339.2	142,681.5	22,764.2
		%	7.3	5.5	2.6	0.4
		m^3/ha	3.4	3.3	3.4	2.8
	Private forests	m^3	764,903.4	247,483.3	390,378.4	4,767.3
		%	20.7	6.7	10.5	0.1
		m^3/ha	3.3	3.0	3.3	2.0
Origin	High stands	ha	19,600.00	44,800.00	18,000.00	/
		%	5.70	25.90	11.30	/
	Coppice stands	ha	325,600.00	128,400.00	141,600.00	10,400.00
		%	94.30	74.10	88.70	100.00
Preservation status	Well-preserved stands	ha	256,800.00	127600	134,000.00	8,000.00
		%	74.40	73.70	84.00	76.90
	Insufficiently stocked stands	ha	82,000.00	40,400.00	23,600.00	2,000.00
		%	23.80	23.30	14.80	19.30
	Devastated stands	ha	6,400.00	5,200.00	2,000.00	400.00
		%	1.80	3.00	1.20	3.80

The importance of researching oak regeneration in Europe was recognized in the early 20th century due to instances of regeneration failure (Watt 1919). Despite the fact that in some years there is abundant production of acorns and after that the appearance of oak seedlings in large numbers, successful regeneration is very rare (Watt 1919; Shaw 1968; Worell and Nixon 1991). Various reasons for unsuccessful natural regeneration have been identified, which undoubtedly affect the final outcome of this process: unfavorable environmental conditions for natural regeneration (Ovington and MacRae 1960), physiological limits of seedlings (Jarvis 1964), influence of game (Lempesi et al. 2017), influence of seed predators (Gómez et al. 2003), plant diseases (Reif and Gärtner 2007), unfavorable structure of the parent stand (Heydari et al. 2017), etc.

Regeneration of oak forests in the hilly and mountainous area of Serbia is one of the most serious and complex problems faced by forestry practice in this area.

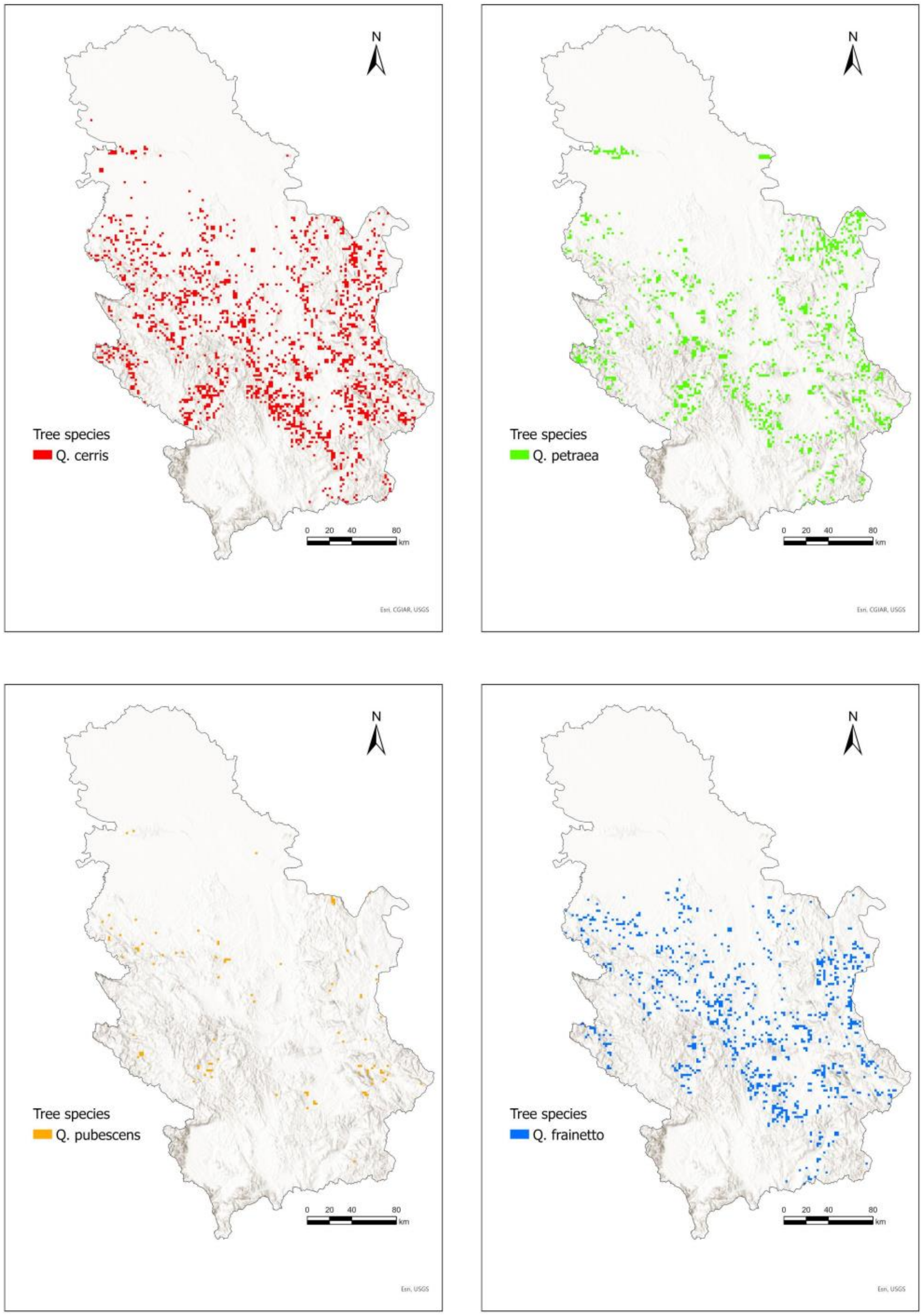

Figure 1. Distribution of *Q. cerris*, *Q. petraea*, *Q. pubescens* and *Q. frainetto* species in Serbia (Banković et al. 2009).

However, in Serbia, until the 1980s, the issue of regeneration of oak forests in hilly and mountainous areas was rather neglected. In this period, according to the available literature, studies were mainly carried out with the aim to define the ecological conditions in these forests, as well as the state of these valuable forest communities in every aspect (Ilić 1948; Jovanović 1951, 1954; Gajić 1959, 1960; Vukićević 1964; Mirčevski 1972). The method of regeneration was mainly based on natural regeneration and management by shelterwood cutting, without a serious commitment to the technology of this process and the effects achieved by it. Mostly, detailed observations were related to the most favorable type of cutting that needs to be done (the size of the area and the length of the regeneration period) in *Q. petraea* forests (Radulović 1972; Miščević and Stamenković 1975; Stamenković and Miščević 1976; Milin 1974). More detailed characteristics of the process of natural regeneration, development of seedlings, micro-conditions for regeneration, as well as methods of artificial regeneration were not studied in this period.

Since the 1980s, intensive research started with the aim of defining the optimal methods of regeneration of oak forests in the hilly-mountainous area, with the greatest attention being paid to the *Q. petraea* forests. In this period, for the first time, concrete methods are recommended for the regeneration of *Q. petraea* forests, on the basis of ecological principles and with the limiting specificities of the micro-conditions of specific localities (Stojanović and Krstić 1980). In parallel with regeneration research, numerous researches have indicated decline of *Q. petraea* forests in Serbia (Marinković 1985; Popović 1987; Milin et al. 1987a, 1987b; Džomić 1987; Stojanović and Krstić 1990). Significant attention was given to the decline of *Q. petraea* forests until the late 1990s across various forestry disciplines. The general conclusion drawn was that this decline resulted from a combination of factors, including the overall health of these forests, the management practices employed, climatic conditions, and their spontaneous development (Milin et al. 1987a). This was primarily reflected in the age structure of these forests, urgent sanation and regeneration were proposed (Milin et al. 1987b), which would result in the use of 200-250% of the volume increment (Marinković and Popović 1988). Similar observations are made for the surrounding areas, also with other oaks. For example, in the territory of Romania, a strong impact of climate change on the stands of *Q. frainetto* and *Q. cerris* was recorded, which was manifested by the mass decline of *Q. frainetto* trees in the period 1989-2004, while *Q. cerris* showed much greater resistance (Bercea 2015). Increased decline of oak trees has been noted in Slovakia since 1976 (Misik et al. 2014), in Hungary since 1978 (Igmándy 1987), and in Austria since 1984 (Hämmerli and Stadler 1989).

Since *Q. petraea* forests in the hilly-mountainous oak belt of Serbia are the most preserved, and at the same time of the greatest economic interest, their regeneration has been mostly researched among the hilly-mountainous oak species. The issue of regeneration of these forests was analyzed in accordance with the specificities that distinguish them. Thus, the regeneration of monodominant high (Krstić 1989), coppice (Babić 2014), or mixed *Q. petraea* forests (Krstić et al. 2005; Krstić and Petrović 2011) was studied in detail, and especially forests with the understorey of accompanying tree species (Kanjevac 2020; Kanjevac et al. 2021). The defined methods of regeneration of these forests are based on the basic principles of shelterwood cutting, but they differ to a significant extent considering the various problems covered by the research. However, the methods developed in these forests cannot be identically applied in *Q. frainetto*, *Q. cerris* and *Q. pubescens* forests, especially since they are significantly more thermophilic and xerophilic species. The regeneration of mixed or pure oak forests in which the main tree species are *Q. frainetto*, *Q. cerris* or *Q. pubescens* has been modestly investigated, without clear indications about the regeneration of these forests in a wider context. In these forests, the regeneration process was considered together with the issue of melioration, because they are strongly degraded (Stojanović et al. 2006a, 2006b; Krstić and Spasojević 1986; Krstić et al. 2010, 2012).

Artificial regeneration in hilly-mountainous oak forests is gaining importance due to the pronounced degradation of these forests, which is manifested both at tree and stand level. There are generally few experiences related to this topic, which emphasizes the need for research and the development of new methods to enhance the effectiveness of this regeneration method. In the previous period, the possibilities of artificial regeneration of *Q. petraea* forests were mainly considered (Stojanović and Krstić 2000; Isajev et al. 2005, 2006a; Krstić et al. 2018a; Popović et al. 2019; Kanjevac 2020; Kanjevac et al. 2023), while the other oaks received far less attention (Šušić et al. 2019a, 2019b; Milanović et al. 2019; Popović et al. 2021; Devetaković et al. 2023; Jovanović et al. 2023). Most often, artificial regeneration in these forests is linked to melioration (Stojanović 1991; Krstić et al. 2006, 2010, 2012), while the introduction of other species is often proposed as a solution (Isajev et al. 2006b; Vukin and Bjelanović 2011).

The points above highlight a broad spectrum of research aimed at addressing the challenges that forestry practices encounter daily in the regeneration of these valuable forests. This includes considerations of economic, ecological, traditional, and cultural aspects. However, many questions remained open due to their complexity and specificity, which caused very dynamic changes and constant adjustment of their management. Accordingly, the aim of this paper is the synthesis of previous knowledge, the recognition of key problems, as well as suggesting future directions in natural and artificial regeneration of these forests in Serbia.

2 Materials and methods

2.1 Literature review

The literature review were performed using keywords: regeneration, restoration, Serbia, *Quercus frainetto, Quercus cerris, Quercus pubescens* and *Quercus petraea*, also as their common names Hungarian oak, Turkey oak, downy oak and sessile oak (keywords were also translated into Serbian language and searches were repeated). First, literature bases “Google Scholar”, “SCIndeks” and “DOI Serbia” were searched with a fixed set of terms. Additionally, on-line bases (E-catalogue) of the Library of the Faculty of Forestry University of Belgrade and bibliography of Šumarstvo Journal were reviewed and all papers with the mentioned topic were selected. These databases and search engines mostly comprise peer-reviewed publications of ISI-listed journals.

Relevant references, also including articles that did not completely meet the search criteria (but considered significant background knowledge) were added to the database. Sorting was done according to species type and included the most relevant information about the article, such as: ecological conditions, forest type and conditions, regeneration type and method, information about seedlings, main conclusions and remarks about the article. Total of 187 publications were selected.

2.2 Survey among practitioners

Aiming to better understand the current state and the main problems in regeneration of hilly-mountainous oaks forests in Serbia, surveys were performed among forest practitioners. Survey was addressed to six forest organizations specialized in forest management, two in each of the following categories: Public Enterprises for state forests, National Parks, and Private companies.

Survey included questions about:

- area of managed oak forests;
- types of oak forests by area;
- regenerated oak forests by area and forest type for the past 10 years;
- information about regeneration methods by area and forest type;
- information about forest reproductive material of oaks produced for the past 10 years- seed and seedlings;
- information about identification and recognition of drought in Serbia and
- opinion about main challenges and problems in regeneration of oak forests in Serbia.

Total of 4 questionnaires were completed and received back.

3 Experiences and problems

The literature base prepared during this research showed that the main focus of Serbian researchers was given to *Q. petraea* (52.45% of publications), while *Q. pubescens* was neglected from the aspect of forest regeneration (3.28%) (Figure 2). Only 16.67% of analyzed publications considered oak forests regeneration as the main topic, primarily natural (63.33%). Ecological conditions, forest type and stand structure was described in detailed in almost half of all publications (48.09%), while information about oaks' seedlings after regeneration were less represented (16.67%). Selected publications mainly belong to the period after 1980 (92.9%) which corresponds with the first information on oak decline in Serbia (Marinković 1985).

According to all available literature sources, the current state of hilly-mountainous oak forests in Serbia was primarily influenced by human activities, followed by other factors. In the past, improper treatment of these forests has caused significant degradation, leading to decreased quality, devitalization of trees, altered tree and stand origin, and regressive succession of woody species.

Considering the complexity of hilly and mountainous oak forests regeneration, it is important to systematically study the key factors affecting this process, whether positively or negatively. Also, there is currently a lack of knowledge regarding the potential synergistic or group influence of these factors. On the other hand, the opposing influence of one factors on the other is also possible.

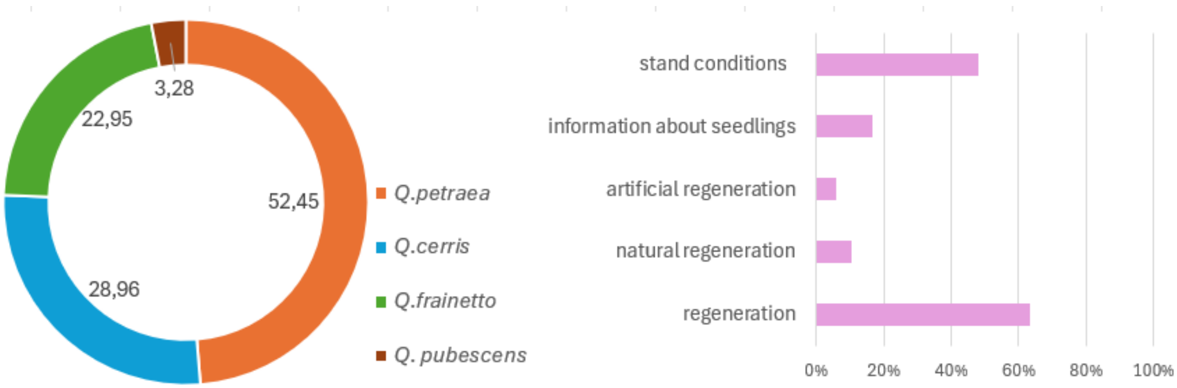

Figure 2. Publications distribution across species (left) and main topic of paper (right).

The key factors that can potentially be modified during the natural or artificial regeneration of oak forests are the canopy and microclimatic conditions in the stand (Babić et al. 2015; Kanjevac et al. 2021). In addition, the presence of seedlings of the main tree species and the accompanying ground vegetation affect the microclimate (radiation, air humidity and air movement), which is reflected in the seedlings development (Collet et al. 1998). Adapting the microclimate conditions has been identified as a major strategy to reduce the exposure of vegetation to extreme climate variables, thereby reducing vulnerability to climate change (Aussenac 2000; Vizinho et al. 2021, 2023).

The research on the influence of the canopy and modification of microclimate conditions was mostly investigated in *Q. petraea* stands (about 70% of publications). However, there is also a very modest base of literature references (26 publications). Considering other oak species, there is a clear need to study these factors in the future, especially when they can provide answers for the regeneration challenges. It is a general statement that the regeneration of oak forests in the mountainous areas of Serbia should be site-specific (e.g. Stojanović and Krstić 1980).

Canopy and microclimate changes have a strong influence on all plants in the treated area, so attention should be focused to competitive relations between oaks and other species. Competing woody vegetation can be a strong adversary to young oaks, so in many cases weed control needs to be carried out. The number of seedlings after natural or artificial regeneration is correlated with many factors. Established seedlings have many challenges to overcome even when site conditions are optimally prepared. Different biotic factors such as diseases or animals represent challenges and may require specific actions.

3.1 Oak forests canopy – the result of previous silvicultural treatments and the main driver of regeneration

The canopy in oak forests is very important for several reasons. The extent, shape, and arrangement of the canopy directly affect how light reaches the leaves, heat enters, and air circulates within the forest, as well as the internal structure and processes of the forest (Parker and Russ 2004). As a result of previous forest practices, the canopy reflects direct human influence, impacting microclimate and regeneration (Figure 3).

In oak stands, the canopy can be a barrier and a support for the regeneration process. Stands with a dense canopy can limit the development of seedlings and delay the regeneration process (e.g. in Turkey oak, Bobinac et al. 2019a). On the contrary, a too open canopy can lead to damaged seedlings caused by climate extremes, overgrowth of unwanted vegetation, and a worsened microclimate (e.g. in sessile oak, Krstić et al. 2018b). Some authors suggest that regeneration in oak stands should begin at openings in the canopy (Stajić et al. 2013). The degree of canopy openness also has a significant influence on the floristic composition of oak forests (Rakonjac et al. 2013; Novaković-Vuković and Perović 2014).

Considering the unfavorable age structure of both high and coppice oak forests in Serbia, it is a very significant finding that the reactivation of increment after silvicultural treatments at the age of 140 years was noted in the stands of *Q. petraea* (Miščević and Stamenković 1975). This effect not only impacts the productivity of the stands but can also potentially be used to improve the regeneration process.

Figure 3. Comparison of the canopy before (left) and after (right) combined preparation-seed cut in *Q. petraea* forests (Kanjevac 2020).

The question of the optimal canopy openness during various stages of the regeneration process has been extensively studied in *Q. petraea* forests in Serbia. The general consensus is that stands with a canopy greater than 0.7 lack sufficient light for seedling development (Stamenković and Miščević 1976; Stojanović and Krstić 1992). Dense and high-quality seedlings appear in the canopy 0.5-0.7, depending on the type of forest (Krstić 1989; Stojanović and Krstić 1992; Krstić 1998). However, a stronger interruption of the canopy creates unfavorable conditions for regeneration. As a consequence, the disturbance of microclimatic and other ecological conditions leads to weeding and competition by hornbeam, beech, hawthorn, etc. (Stojanović and Krstić 1992). There is a common belief that providing shade is necessary during the initial phase (the first 3-4 years) for proper development, while later on, the seedlings should be gradually exposed to light (Krstić and Stojanović 2007). For the survival of the seedlings, the most important factors are light, air, and soil humidity (Krstić 1991).

In relation to the size of the area where the natural regeneration of *Q. petraea* forests is taking place, significant findings have been made. The minimum opening size at which abundant, high-quality seedlings typically appear, with a satisfactory number, is about one average height of mature trees ~25m) with the most favorable direction of the opening being southwest-northeast at a light intensity above 30% (Krstić 1989). On the other hand, there are observations that in the conditions of small regeneration gaps, *Q. petraea* seedlings exhibit single-phase growth (Bobinac et al. 2022a).

In *Q. cerris* stands with a closed canopy (light intensity about 6% of full light), one type of undisturbed height growth was observed, while on fully exposed surfaces (clear cutting), three types of height growth were observed: one-phase, two-phase, and three-phase growth (Bobinac and Vilotić 1996; Bobinac 1997). In fact, the *Q. cerris* can adapt ontogenetically in the conditions of the complete canopy, which is a very important feature in the process of natural regeneration of mixed forests where it is the dominant tree species (Bobinac et al. 2019a).

When it comes to the occurrence of multiphase growth, similar findings have been observed for the *Q. petraea* (Krstić et al. 2018a). The number and characteristics of *Q. petraea* seedling's growth significantly change depending on whether they are protected by the parent stand trees, as well as the orographic conditions that indirectly affect humidity levels (Krstić et al. 2017). In full light, *Q. frainetto* tends to have multiphase growth, which can significantly affect the success of regenerating these forests (Šušić et al. 2019b). This is especially important because *Q. frainetto* forms communities with *Q. cerris* that is considered biologically stronger species.

It is crucial to determine the length of the regeneration period, as oaks need the protection of the parent stand until they develop enough resistance to negative biotic and abiotic influences. In this context, it was observed that *Q. petraea* seedlings increases resistance with age, and the canopy can play a significant protective role when the seedlings are exposed to extremely high temperatures during the summer (Krstić et al. 2018b; Kanjevac 2020). In order to protect seedlings from extremely high temperatures, it is necessary to maintain the canopy at the beginning at 0.5-0.6, and later reduce it with a light cut to 0.3-0.4 (Kanjevac 2020; Kanjevac et al. 2021). Regarding the artificial regeneration, the presence of parent trees has a protective effect, which can significantly increase the survival rate of seedlings in the first growing season (Kanjevac et al. 2023).

3.2 Microclimate – a dynamic factor that influences the success of regeneration

The microclimate in oak forests is a variable that initiates and directs the dynamics of important processes, including regeneration. Spatial and temporal variability of microclimate is strongly influenced by forest management, so it is important to know how microclimate varies along successive gradients of managed forests and what happens to microclimate dynamics due to forest management (Máliš et al. 2023). A stable below-canopy microclimate is crucial for forest biodiversity and the preservation of ecosystem functions (Kovács et al. 2019).

As mentioned, the microclimate characteristics were mostly researched in *Q. petraea* forests. There is a limited scientific knowledge for other oak species in the hilly-mountainous areas of Serbia. Although these oaks often occur together, it is clear that the experiences from *Q. petraea* forests cannot be transferred to *Q. frainetto*, *Q. cerris*, or *Q. pubescens* forests. This is due to the clear ecological differentiation among these tree species and the communities they form.

The survival of oak seedlings mostly depends on the light regime, air and soil humidity, and the influence of temperature extremes (Figure 4) (Krstić et al. 1997, 2018b; Kanjevac 2020). These elements can be regulated in the stand by regeneration cuttings, and they largely depend on intensity, and also size, shape, and direction of seedling banks (Krstić et al. 1997; Kanjevac et al. 2023).

The light conditions in oak forests depend greatly on both orographic factors and the forest canopy. A higher light intensity is found in stands with lower canopy cover and cooler exposure than in a stand with complete canopy on the warmer southeast exposure (Babić 2010). Significant differences in air temperature and light intensity were observed in *Q. petraea* forests on Fruška Gora in relation to exposure (Babić et al. 2015). The air temperature within *Q. petraea* stands was 2.8-3.6°C lower compared to the temperature in the open space, whereas the light intensity was 36% higher on the western than on the eastern exposure (Babić et al. 2015). In relation to orographic conditions, the canopy of the stand has a stronger impact on the coefficient of light transmission than the exposure (Babić 2010). According to the same author, canopy of the stand directly impacts the light transmission to the regeneration layer, affecting the light intensity for seedling development.

In the area of Fruška Gora, it has been observed that *Q. petraea* forests with a canopy allowing an average of 9.6% light transmission and total coverage of the regeneration layer with crowns of 381.8 m^2 are conducive to the appearance and survival of numerous high-quality seedlings (Babić et al. 2019). In *Q. petraea* forests on southern exposures for abundant and good-quality seedlings, the light intensity should be 20% (1/5 of the average full daylight), on the plateau and south-western exposure, the light intensity should be about 25% (1/4), and on south-eastern exposures, the light intensity should be about 33% (1/3) (Krstić 1995).

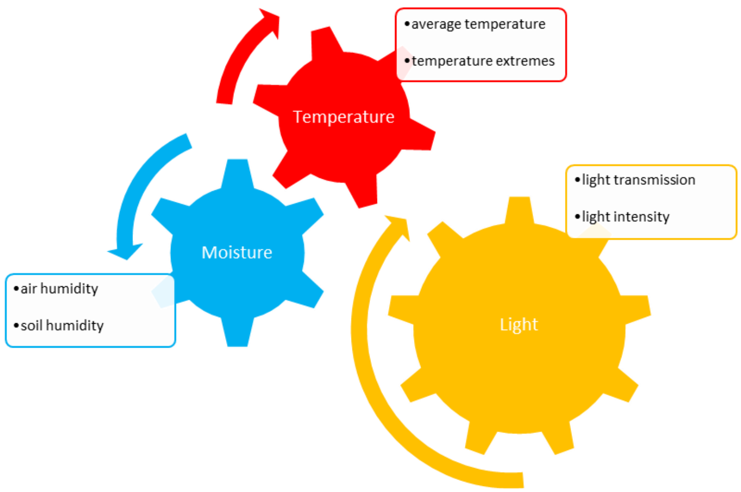

Figure 4. Dynamics of key microclimatic elements in the regeneration process.

In the context of oak regeneration, it is crucial to consider how oaks can adapt to different light conditions. *Q. cerris* demonstrates a specific growth response in the second year when exposed to increased light conditions (Bobinac 2002). *Q. petraea* belongs to a group that can survive in light above 10% of full daylight and is tolerant to shading in the initial phase of development (Krstić and Stojanović 2007). For *Q. frainetto*, it was found that it responds very well to increased light conditions, resulting in multiphase growth (Šušić et al. 2019b). For *Q. pubescens* there are no availabe information for the Serbia.

The temperature conditions in oak forests are crucial because they can either positively or negatively impact the regeneration process. For a stable and undisturbed regeneration process, it is necessary to minimize temperature fluctuations and extremes. At the lower edge of the range, the oak trees begin to leaf out in early spring, and at the upper edge they leaf out in mid-May (Krstić 1998; Kanjevac 2020), which makes them very sensitive to extreme temperatures (Krstić et al. 2018b; Kanjevac et al. 2021). The new shoots of *Q. petraea* seedlings freeze at -13°C, the normally developed root at -35°C, and the poorly developed root system at -7°C to -8°C (Krstić 1998). During the summer, the average daily temperature in *Q. petraea* forests can be up to 28.5°C, the soil temperature at a depth of 5 cm is 13-18°C, and at a depth of 50 cm it is 15°C (Krstić 1998). Major damage to *Q. petraea* seedlings was defined as the result of extremely high temperatures (over 40°C), with less severe damage occuring when the parent stand has a denser canopy and the seedlings are older (Krstić et al. 2018b).

Accordingly, the observations in the *Q. petraea* stand in the area of the "Fruška gora" National Park are also significant. In the north-western exposure, after the seed cut, the air temperature in relation to the open space has a lower value of 3.9°C, and after the light cut, a lower value of 2.6°C (Babić and Krstić 2016).

Moisture conditions in the oak forests of the hilly-mountainous area are generally favorable, considering that >50% of precipitation occurs during the growing season. However, this regularity is disrupted by dry periods in the summer, increasingly imbalanced precipitation, as well as warm exposures and steep slopes where these forests occur.

During the growing season, approximately 56% of the precipitation falls in the *Q. petraea* forests of the "Fruška gora" National Park (Babić and Krstić 2014). During August and September, the soil tends to lack moisture, while from December to April, there is an excess of water, whereby at the lower limit of the analyzed belt of *Q. petraea* forests, the surplus of water in the soil amounts to approximately 22% of the annual precipitation, and at the upper limit, it is about 25% of the annual precipitation (Babić and Krstić 2014). In the belt of *Q. frainetto* and *Q. cerris* forests, the ratio of water surplus and deficit in the soil must be considered when creating afforestation plans. This is because a significant amount of surplus water is unavailable due to surface runoff (Krstić et al. 2013).

By the end of the growing season, oak stands use all available soil moisture up to a depth of 1.8 m (Krstić 1998). The competition for water in the soil during summer droughts, in duration of 2-3 months, causes a negative impact due to all plants' great need for water. The higher the thermophilicity of the forest community, the faster degradation process are and the slower the regeneration is (Krstić et al. 2010). *Q. cerris* is more tolerant to dry periods and adapts better to climatic variations compared to other oaks (Kostić et al. 2022). *Q. frainetto* is a xerothermic species that can retain water during summer droughts (Dinić and Bobinac 2010). Drought stress directly and indirectly impacts crucial plant physiological processes essential for forest development, such as photosynthesis and respiration (Krstić et al. 2018b). Summer drought impacts CO_2 release from soil and soil microorganism presence, and in some cases, drought stress can lead to physiological stress and even death of plant (Dinić and Bobinac 2010).

During the artificial regeneration of oak forests through the transplantation of naturally regenerated seedlings, it was observed that the post-transplantation development of the seedlings was significantly influenced by ecological conditions. In areas with steep slopes, where the parent stand's canopy is broken, the organic layer is thin, and the ground vegetation is scarce, seedling survival rates are initially very high at the start of the growing season (Kanjevac et al. 2023). However, during the summer, a significant mortality rate was observed due to the lack of moisture and the negative impact of extremely high temperatures (Kanjevac et al. 2023).

3.3 Competition (ground vegetation)

During the regeneration of oak forests, it is crucial to pay special attention to the presence and dynamics of competing vegetation. The success of regenerating of hilly-mountainous oak forests largely depends on controlling this factor.

Regarding *Q. petraea*, at the canopy of 0.5-0.7, blackberry is significantly present, and should be removed by applying auxiliary measures in the regeneration phase (Krstić et al. 2017, 2018b). The same author states that seedlings survive under the blackberry until the third year, where their number decreases significantly, while in the fourth year it has a built structure and does not require maintenance. A canopy of 0.5-0.6 represents a limit value, because a more open canopy leads to greater damage (Krstić et al. 2018b), while some authors consider a stronger interruption of the canopy unfavorable conditions for regeneration (Stojanović and Krstić 1992). Auxiliary measures for *Q. petraea* seedlings, such as vegetation control, are very important (Govedar et al. 2021).

In sub-association *tilietosum* of the monodominant *Q. petraea* forest in northeastern Serbia, unsuccessful regeneration lead to domination of silver linden in the understorey, outcompeting *Q. petraea* (Bobinac et al. 2019b). Accordingly, the removal of old *Q. petraea* trees as part of intensive and rationalized linden thinning and stand integration was proposed as *Q. petraea* has lost the biological potential as a basis for further development (Bobinac et al. 2022b). Even in the case where seedlings come from a nursery and their height is greater than seedlings germinated in the forest, weed control is usually necessary, which was proven by the example of the artificial regeneration of the pubescent oak (Devetaković et al. 2023).

3.4 Initial number of seedlings, seedlings growth and health – a good start improves the chances of successful regeneration

The number of oak seedlings per regenerated area in Serbian forests is very divergent, and the data is mainly available for naturally regenerated *Q. petraea* forests. Successful natural regeneration implies 360,000 seedlings ha^{-1} in the first year after the mast year (Krstić et al. 2005), but in correlation with site conditions, it can vary from less than 100,000 up to 850,000 after 3 years (Krstić et al. 2017). Successful *Q. petraea* regeneration can be stopped as a consequence of different environmental factors, so Miščević and Stamenković (1975) reported good *Q. petraea* regeneration in the period 1954-1963 and later seedlings disappearance. Sessile oak seedlings are very sensitive to extreme temperatures: shoots can be strongly damaged at -13°C, strong roots at -35°C and weaker root systems at -7 to -8°C (Krstić 1998). Extreme high temperatures imply shoot damages of young seedlings (Krstić et al. 2018a), as well as drought conditions (Krstić et al. 2018b) which can reduce the height growth of *Q. petraea* seedlings considerably. The sensitivity of seedlings is directly correlated with age (Krstić et al. 2018b), so older seedlings of the same height as younger were less damaged by drought and extreme temperatures (Krstić et al. 2018a). Bobinac et al. (2022b) reported an average height for one-year-old *Q. petraea* seedlings at 9 cm with an annual height increment of 1 to 2.6 cm in the full canopy up to 9 years, and with greater annual increment (1.4 to 10.9 cm) after canopy reduction from 10 to 15 years old. *Q. petraea* seedlings in 0.5 to 0.7 canopy closure had an average height of 25.2 cm (7.7 seedlings per m^2) at 3 years old according to Kanjevac (2020), and 14 to 22 cm according to Babić et al. (2019) in the same age, 17.3 to 30.8 cm (20.3, respectively 7.4 seedlings per m^2) at 4 years old (Krstić et al. 2018a; Kanjevac 2020), 39.9 cm (15.6 seedlings m^2) at 5 years old (Krstić et al. 2018a) and 55.8 to 86.6 cm (13.4, respectively 5.6 seedlings per m^2) at 8 years old (Krstić et al. 2018a; Govedar et al. 2021).

Most authors emphasize the importance of canopy on successful establishment and growth of *Q. petraea* seedlings and recommended canopy between 0.5 (limited canopy for crucial protection from extreme insolation and temperature extremes) and 0.6 (limited canopy for satisfactory light availability) (Stojanović and Krstić 1992; Krstić et al. 1997; Krstić et al. 2018a; Govedar et al. 2021; Kanjevac et al. 2021), also as weed control (Krstić et al. 1997; Govedar et al. 2021). Aiming to promote successful seedling establishment Stamenković and Miščević (1976) recommended soil cultivation in the year before mast.

Q. cerris seedlings show the possibility for ontogenetic adaptation in low light conditions which is an important advantage in forests where it is the main tree species (Bobinac et al. 2019b), but also implicates the need for special attention in mixed forests with *Q. frainetto* because of biologically stronger *Q. cerris* (Vukin and Rakonjac 2013) and difficult regeneration of *Q. frainetto* (Aleksić et al. 2013). Although *Q. cerris* seedlings can be successfully established in low light conditions, light availability increases their growth and under full light conditions polyphase growth is expected (Bobinac and Vilotić 1996). Naturally regenerated *Q. cerris* seedlings under full canopy in *Tilio-Carpino-Quercetum robori-cerris* forest had satisfactory number per area and height around 19 cm, while in the second year more than half of seedlings showed polyphase growth with average height around 23 cm after increasing light availability. Superiority of *Q. cerris* is presented on many sites, so in the forest *Tilio-Carpino-Quercetum robori-cerris* 8 years after regeneration were 5 to 10 seedling per m² and the absence of other oaks (*Q. robur* and *Q. virgilliana*) (Bobinac 2003). Presence and natural regeneration of *Q. pubescens* were poorly described in Serbian literature, but there are some indications that this oak species appears more frequently than anticipatedand takes place in some specific situations where forest vegetation needs to be recovered after disturbances (Rakonjac et al. 2018).

Artificial regeneration of oak forests in Serbia mainly implies planting, but some areas were successfully regenerated by direct seeding. Afforestation by direct seeding was successful, performing by seeding into rows (Grujić 1949; Bobinac et al. 2001) while sowing with hoes had negative results according to a report by Grujić (1949). Krstić (1998) recommended 500-1,000 kg of *Q. petraea* acorns ha^{-1} for seeding across all area, 400 kg ha^{-1} for seeding into rows, 60-100 kg ha^{-1} for seeding into nests (1,500 nests ha^{-1} and 35-60 acorns per nest) and 180-320 kg ha^{-1} using hoes. Direct seeding across all areas in *Q. petraea* forests and under high canopy using lower quantity of acorns (300 kg ha^{-1}) resulted in seedlings density of 30,000 plants per hectare with an average height of 11.7 cm, but with very variable morphometric characteristics and survival across experimental plots (Krstić et al. 2018b). Planting of two-year-old bareroot seedlings in the same study resulted in 2,385 seedlings ha^{-1} at the age of 3 years (after the first growing period on the field). Planted seedlings have an initial advantage - height in comparison with seedlings from direct seeding or natural regeneration.

Recommendations about planting density for oaks establishment are variable from 600-1,300 seedlings ha^{-1} to 19,200-27,800 seedlings ha^{-1}. Stilinović (1991) noticed that for greater parts of Europe favorable planting density is between 6,000 and 13,333 seedlings ha^{-1}, but there are some indications that 2,500 seedlings ha^{-1} is satisfactory for Serbian conditions (Krstić and Stojanović 2007). Despite the fact that nursery production of oaks' seedlings is viewed as efficient way of using periodically available seeds, advantage should be given to direct seeding due to greater initial density of seedlings (Isajev et al. 2006a). In this context, the production of high quality seedlings with good outplanting performance and the target seedlings concept is imperative in oaks' seedlings production. Janković (1991) highlighted the need for root pruning and recommended bareroot *Q. petraea* seedlings two-years old (1+1 for dry sites and 2+0 for moderate sites), but need for older oak bareroot seedlings (two-years or more) is evident (Isajev et al. 2006). Stojanović and Krstić (2000) recommended for *Q. petraea* planting density of 10,000 to 13-15,000 on productive sites using one or two-year old bareroot seedlings with pruning roots. More recent data (Ivetić 2015) showed that practitioners used 1+0 *Q. petraea* seedlings for melioration purposes with average survival of 88.33% and 85% after fire at the end of the first growing season, respectively 62.5% after three years. Experience with *Q. pubescens* 1+0 seedlings indicate container stocktype as an advantage in seedlings establishment, but morphological characteristics of seedlings are better in bareroot stock (Devetaković et al. 2023). There is data about positive experiences using two-year old *Q. petraea* seedlings from natural regeneration and it is observed that this process is highly affected by ecological conditions (Kanjevac et al. 2023).

Oak seedlings can be very attractive for wildlife, so injury and browsing of seedlings and saplings is expected. Gačić et al. (2006) reported moderate influence of red deer and roe deer on natural regeneration of *Q. petraea* forests in National Park "Đerdap" and highlighted damages mainly as browsing of apical and lateral shoots. After artificial regeneration by planting, the mortality of 75% *Q. petraea* seedlings was caused by wildlife (Ivetić 2015). On the contrary, damage caused by wildlife is often lower in comparison with damages caused by some other factors. Krstić et al. (2018b) noticed that only 1.3% mortality of *Q. petraea* seedlings was a consequence of wild animal influence while more than 50% was a result of negative influence of pathogens, insects, drought or their combination.

Seedlings of *Q. petraea* can be affected by a large number of insects (*A. kollarii, A. lignicolus, A. stefanii, B. pallida, C. caputmedusae, C. quercus, C. quercuscalicis, N. quercusbaccarum, N. anthracinus* etc.) and some of them implicate large harmfulness, although intensity of attack is relatively low (Dobrosavljević et al. 2018a). Behind damages at seedlings level, insects are impactful in the seed lot, especially species from genus *Curculio* and *Cydia* (Dobrosavljević et al. 2018b; Dobrosavljević et al. 2022). Kanjevac et al. (2017) presented the conclusion that only ¼ to ⅓ of the total amount of acorns fallen after fruiting could potentially germinate under natural conditions. Oak forests in Serbia are under constant threat of gypsy moth (*Lymantria dispa*r L.) which are very harmful and occures periodically (Mihajlović et al. 1998; Mihajlović et al. 2004; Tabaković-Tošić et al. 2011) with significant consequence. Intensive research of the gypsy moth began in Serbia in the 1920s because at the time it was considered, alongside the oak powdery mildew (*Microsphaera alphitoides*), to be the major factor leading to the deterioration of oak forests (Marković et al. 2011). There are some differences in resistance of different oak species and it is evident that ecological conditions can be a limiting factor for infection and spread of disease. Bobinac et al. (2019b) report high resilience of two-year old *Q. cerris* seedlings from natural regeneration under dense canopy stands.

Lower survival rates are deeply influeced by combination of biotic and abiotic factors in both artificial and natural regeneration. In order to provide successful recruitment with favourable admixture of species in a mixed forests it is necessary to combine both natural and artificial regeneration in oak forests (Isajev et al. 2005).

3.5 What does the Serbian forest practice say about this?

Managers and foresters that were included in the survey manage 139,078.65 ha of oaks' forests and have shared data about regeneration for the past 10 years. Area included in regeneration was 3,010.82 ha, from which naturally regenerated is 2,885.87 ha. According to main tree species, the greatest part of the observed area belongs to *Q. petraea*, and vegetative origin is prevailing in the total sample. Natural regeneration is dominant and assessed satisfactory for the most part of the observed area, however during this period it was necessary to assist the regeneration by appropriate measures (36.89 ha).

According to the artificial regeneration method, planting was a priority. Direct seeding was performed in total on 7.17 ha. 750 kg acorns ha^{-1} was used on 0.9 ha, and 360 kg *Q. petraea* acorns per hectare on the rest of the area. Planting was performed on 225.25 ha with planting density from 1,100 to 10,000 *Q. petraea* seedlings, 1,643 *Q. cerris* seedlings, 5,411 *Q. frainetto* seedlings and 2,777 *Q. pubescens* seedlings per hectare.

Some of the reasons for limited regeneration success are seed quality and mast year periodicity, unsatisfactory quantity of collected and stored acorns, quality of produced seedlings and manipulation during planting, competition relations on the field and inappropriate tending. Some forest practitioners consider regeneration on large areas as a potential problem and suggest regeneration on a large number of smaller areas. Low acorn yield was reported in the past 10 years at the observed area (mast year for *Q. petraea* was 2023 at one site on 2.75 ha, according to the answers from the conducted questionnaire). Oak seedlings production vary from year to year, from less than 20,000 in 2015 to more than 450,000 in 2021 and mainly belongs to bareroot stock.

Suggested ways for more successful regeneration and restoration of oaks' forests that forest practitioners mentioned are production of high quality seedlings, advanced methods for weeding, creating of a special Strategy for autochthonous oaks' forests regeneration, assessment of genetic diversity and structure of forest reproductive material and seed sources, and long term monitoring of forests' adaptations to climate changes.

4 Future challenges

The management of oak forests in Serbia and Southeast Europe is crucial due to their ecological, economic, and cultural significance, especially considering the specific habitats where they are located. However, the current condition of these forests is highly unfavorable, indicating numerous challenges and a significant disparity between potential and actual management impacts. Although there are numerous professional and scientific findings related to this topic in the territory of Serbia, it is evident that they are not sufficient, especially considering that these forests are characterized by dynamics and uncertainty regarding future perspectives.

Degradation of oak forests in Serbia primarily occurred due to human influence, leading to the dominance of coppice forests and often unfavorable relationships between principal and secondary tree species (Bobinac 2003; Krstić et al. 2012). A specific problem is represented by stands in which silvicultural treatments were carried out irregularly and inadequately, resulting in unfavorable stand structure and insufficient participation of quality trees in the upperstorey floor, necessary for successful natural regeneration. Also, the aforementioned circumstances affected the current production possibilities in these forests, which are mainly reflected in the production of firewood and energy wood, while the share of technical wood is relatively small. In general, the unfavorable condition of these forests is reflected in the following:

the canopy is often broken; the share of oak is not enough; parent trees are dominantly of vegetative origin, often of poor quality and highly influenced by numerous negative factors (pathogens, environmental factors, lower genetic diversity, inbreeding, genetic drift and bottleneck effect, etc), which is reflected in their ability to produce quality seed; the stands are at the end of the production process, where they are typically structurally even-aged. As heliophytic species, oaks enable a significant amount of light to reach the understorey, creating conditions for the appearance and development of numerous accompanying tree species and ground vegetation (Mölder et al. 2019a; Kuehne et al. 2020; Kanjevac et al. 2021). Although in an ecological sense, this phenomenon can be marked as positive, for the regeneration of these forests, the diversity and competitiveness of tree species and ground vegetation from the understorey represent an aggravating circumstance.

The climax (equilibrium) structure dominated by oak is the last step in the succession of forest vegetation and represents a stable adaptation to local ecological conditions (Bohn & Neuhäusl 2000; Saniga et al. 2014). As a consequence of the degradation of these forests, intense regressive succession is increasingly appearing where shade-tolerant species predominate (Vera 2000; Bobinac 2003; Saniga et al. 2014). This phenomenon represents a huge problem for the regeneration of oak forests, and at the same time, it can be a determinant of the qualitative performance of this process.

Establishing a high-quality and sustainable regeneration process in these forests implies improving their condition. This implies the regulation of their unfavorable age structure (Aleksić 2005; Stojanović et al. 2005; Aleksić et al. 2013), which means the definition of priority situations for regeneration in accordance with the age and condition of these forests. Also, until the moment of regeneration, the stands should be prepared for regeneration with adequate silvicultural treatments. In contemporary conditions, the regeneration of oak forests cannot be successful without human support (Vera 2000, Bobiec et al. 2011).

Deciduous oaks are the main tree species in many protected and managed forests across Europe, leading to the development of various regeneration systems in both high and low oak forests (von Lüpke 1998; Annighöfer et al. 2015; Löf et al. 2016). The mentioned issues, as well as previous experiences, point to certain directions of change in the regeneration technology of these forests. Within the context of modern silvicultural systems, oak forests in hilly and mountainous areas are regenerated on small areas, while upholding the theoretical principles of shelterwood cutting (Březina and Dobrovolný 2011; Tinya et al. 2020; Kanjevac et al. 2021). Given the complex regeneration process in these forests, which occurs under intense understoty competition and the potential threat of harmful biotic and abiotic effects, regeneration on smaller areas could allow for tighter control of the process and, consequently, better outcomes (Kanjevac 2020; Tinya et al. 2020). In addition, the time and method of carrying out regeneration cutting must be temporally and spatially compatible with the regeneration dynamics and the measures that are carried out in order to achieve satisfactory success (Kanjevac et al. 2021). Such small-scale reproduction methods are often considered closer to nature, in the context of imitating natural processes (Bauhus et al. 2013). However, it should be noted that the surface should not be too small, as it can also be ineffective (Krstić 1989; Tobisch 2010).

To preserve habitats with old oaks, which are the basis of the conservation and protection of species diversity, proposals are to manage coppice oak stands in harmony with historical silvicultural systems, such as coppice forests with standards (Löf et al. 2016; Mölder et al. 2019b).

In such circumstances, artificial regeneration can play a very significant role and stop further degradation of these forest ecosystems (Isajev et al. 2005). As it is clear that the mentioned circumstances led to a significant reduction in the possibilities for natural regeneration, it is necessary to develop and successively apply the regeneration process which will be adapted to the current conditions in these forests and represent a combination of natural and artificial regeneration. The future composition and origin of these forests can be influenced by artificial regeneration, while natural regeneration ensures the maintenance of biodiversity and ecological balance. Artificial regeneration should be conducted within the parent stand, following the principles of natural regeneration through shelterwood cutting (Krstić et al. 2018a). Also, a great potential for the regeneration of oak forests occurs within artificially established pine stands (Bobiec et al. 2018), which were established in the second half of the 20th century for the purpose of melioration of oak forests in Serbia. In such pine stands, there are very favorable ecological conditions for the artificial regeneration and establishment of oak stands.

One of the most delicate aspects of forestry in the context of climate change is the process of forest regeneration. Consequently, the regeneration of oak forests implies the influence of additional factors that burden this process, such as drought stress, effects of extreme temperatures, increased insolation, increased transpiration, etc. (Thomas and Gausling 2000; Raftoyannis and Radoglou 2002; Lloret et al. 2004; Pietras et al. 2016). Main conclusion of this review is that insufficient data about regeneration of hilly-mountainous oak forest is not only common for oak forests in Serbia, but also for the entire Sutheastern Europe region, highlighting the need for developing specific strategies for regeneration and restoration of native oak forest as one of the most complex forest ecosystems of Europe. Artificial regeneration is emphasized as crucial for influencing the future composition and origin of these forests. Reforestation programs should consider climate change projections. Long-term guidelines should include site-species matching, provenance selection, and genetic diversity and structure. Also, the selection of suitable strategies and methods to reach regeneration objectives should integrate knowledge of the biological traits of the target species with local environmental conditions and predictions of climate change (Ivetić and Devetaković 2016). This underscores the importance of researching future modified regeneration systems in these forests, taking into account the current factors that impede this process.

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