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# Comparison of shelterwood and clear-cut regeneration methods on morphological traits of naturally regenerated sessile oak [*Quercus petraea* (Matt.) Liebl.] seedlings

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**Abstract:** The natural regeneration of the sessile oak [*Quercus petraea* (Matt.) Liebl.] is an important aspect of sustainable forest management, especially given the ongoing global climate change and the need to maintain forest stand stability and productivity. This study aimed to evaluate the effect of various regeneration methods on the growth of naturally regenerated sessile oak in the Masaryk Forest Training Enterprise Křtiny, Czech Republic. The research was conducted in seven forest stands where regeneration felling was applied after masting in 2022 (winter 2022/2023) using clear-cut (CC) and shelterwood (S) systems. A total of 531 seedlings were collected from these seven research plots, and the following morphological traits were measured: shoot length, root collar diameter, and biomass allocation. Statistical analysis revealed significant differences ($P < 0.05$) in shoot length, main root length and total seedling length between the CC and S variants. However, there were no significant differences in root collar diameter or any of the dry-mass parameters between the clear-cut with standards (CC1) variant and the shelterwood plots. Individuals from the CC variants have a 10.3–47.0% wider root collar diameter, 22.3–91.4% more dry mass of the root system, and 51.7–90.4% more dry mass of the aboveground part than individuals in the S variants. These results indicate that the early growth of sessile oak seedlings is greatly influenced by light availability: full sunlight stimulates the development of above- and below-ground parts, whereas canopy cover restricts early growth, particularly in terms of height. The findings highlight the need to consider light and site conditions when planning silvicultural treatments aimed at establishing stable and vigorous oak stands in the face of changing climate conditions.

**Keywords:** biomass; destructive sampling; global climate change; natural regeneration; root system

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The sessile oak [*Quercus petraea* (Matt.) Liebl.] is one of the most valuable tree species in Europe due to its ecological and economic importance (Brändle, Brandl 2001; Annighöfer et al. 2015; Löf et al. 2016; Kanjevac et al. 2021; Černý et al. 2024a). There has been increasing attention paid to the condition of oak stands, the growing demand for their products, the continuity of timber production, and the effects of global climate change on their stability (Kanjevac et al. 2021). Alongside pedunculate oak (*Quercus robur* L.), this tree species is more resilient to abiotic stress factors, such as frost, prolonged drought or extreme windstorms (Jenssen 2009; Úradníček et al. 2009; Šimková et al. 2023). However, the frequency of these disturbances has increased in recent years due to climate change, placing greater demands on the stability of oak stands and necessitating adjustments of silvicultural practices (Hanewinkel et al. 2013; Kanjevac et al. 2021; Vacek et al. 2023; Bratu et al. 2025). Furthermore, oak produces high-quality timber. Combined with its ecological importance and contribution to forest biodiversity, this further emphasises the need to promote its successful regeneration (Tomczak et al. 2024).

In this context, the natural regeneration of oak forests is one of the most important topics in European forestry. The natural regeneration of sessile oak through shelterwood systems is common practice in many European countries, including France (Nicolescu et al. 2025), Germany (Von Lüpke 2008; Kuehne et al. 2020), Bulgaria (Radkov, Minkov 1963), Turkey (Nicolescu et al. 2025), Croatia (Matić 2000; Oršanić, Drvodelić 2007), and Belgium (Kohler et al. 2020). In Czech forestry, increasing emphasis is also being placed on the natural regeneration of forest stands (Vacek et al. 2010, 2015; Slanař et al. 2017), which has advantages not only from an economic perspective but also in terms of enhancing the ecological stability and species diversity of forest ecosystems (Kamler et al. 2016). However, this potential is not yet being realised fully, mainly due to strong influencing factors, such as competition from ground vegetation on nutrient-rich sites and the faster height growth of competing tree species (Poleno et al. 2009).

The most common competing tree species for sessile oak in Central and Southeastern European forests are European beech (*Fagus sylvatica L.*) and hornbeam (*Carpinus betulus L.),* (Kanjevac et al. 2021; *Černý et al. 2024b;* Fuchs et al. 2024; Modrow et al. 2025). On nutrient-poorer sites, Scots pine (*Pinus sylvestris* L.; Pretzsch et al. 2020; Brichta et al. 2023) and birch (*Betula* spp., Rock et al. 2004) often act as strong competitors. Other competing species in Central Europe include small-leaved lime (*Tilia cordata* Mill.), elm (*Ulmus* spp.), wild cherry, field maple (*Acer campestre* L.), Norway maple (*Acer platanoides* L.), common ash (*Fraxinus excelsior* L.), and *Sorbus* spp. (Vacek et al. 2018; Nicolescu et al. 2025). The seedlings of these tree species tend to outgrow oak due to their faster initial height growth, subsequently suppressing it through their higher competitive ability (Modrý et al. 2004; Kohler et al. 2020; Govedar et al. 2021). In line with this, recent observations in the Czech Republic indicated a decrease in the oak regeneration in favour of other tree species compared to the overstory (Vacek et al. 2019). Forest weeds can also be important competitors (Vacek et al. 2017; Prokůpková et al. 2021), particularly bramble (*Rubus* spp.), which can rapidly overgrow and completely suppress oak seedlings (Kuehne et al. 2020; Kanjevac et al. 2021). Higher seedling densities in the early developmental phase may positively influence overall survival rate by helping to suppress the development of competing vegetation (Annighöfer et al. 2015; Kuehne et al. 2020; Kanjevac et al. 2021).

Sessile oak is considered a tree species with a relatively short regeneration period and high potential for natural regeneration (Březina, Dobrovolný 2011). In the initial regeneration phase, it is partially shade-tolerant; however, its light demand significantly increases with age (Reif, Gärtner 2007). Its light requirements also increase under favourable light conditions and when competition from the forest weed and shrub layers is reduced (Kohler et al. 2020). Light conditions are a key factor in competing with other tree species, and solar irradiation below 25% leads to the dominance of more shade-tolerant tree species (Von Lüpke, Hauskeller-Bullerjahn 2004; Ligot et al. 2013; Modrow et al. 2020). These factors are also important in the context of regeneration using small-scale clear-cut patches, as they strongly influence the survival rate of naturally regenerated oak seedlings. The minimum size of such regeneration openings is generally set at 0.15–0.20 ha (Březina, Dobrovolný 2011; Modrow et al. 2020). These and other relevant findings were comprehensively summarised by Kohler et al. (2020).

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The success of natural regeneration in oak stands depends on a range of biotic and abiotic factors and their interactions, as well as the chosen regeneration method. The factors influencing the natural regeneration of oak stands are not fully understood, and this includes the size of parent tree crowns and the rate of canopy gap formation (Dobrowolska 2008; Kohler et al. 2020). Consequently, there is still uncertainty regarding the most effective silviculture practices for supporting natural regeneration (Kuehne et al. 2014).

A variety of factors affect the initial growth of oak seedlings in their early developmental stages. Light availability is one of the most important factors, playing a dominant role in seedling development and the process of natural regeneration. Sessile oak can grow in shaded conditions during the first years of development, but it requires significantly more light in later stages. Other factors that can negatively affect the success of natural regeneration include extreme air temperatures, which influence the appearance, growth, and survival rate of seedlings, thereby reducing overall regeneration success (Kuehne et al. 2020; Kanjevac et al. 2021).

The maximum height growth of sessile oak in the early developmental stages is reached at light intensities of 20–40% of full sunlight (Von Lüpke 1998; Reif, Gärtner 2007). Ligot et al. 2013 reported that, for oaks measuring 1.5–3.0 m in height, the optimal light intensity is around 20–30%. However, some studies have shown that the growth of terminal shoots in 4–7-year-old naturally regenerated oaks increased even at light intensities above 40% (Březina, Dobrovolný 2011; Modrow et al. 2020). These discrepancies may be due to the varying levels of light intensity considered in individual studies (Kohler et al. 2020). However, height increment is not a reliable indicator of seedling vitality, as crown development and branching are often better indicators, which increase with light availability (Collet et al. 1998; Nicolini et al. 2000). Seedlings growing in shade tend to produce longer lateral shoots but have lower total biomass and root-to-shoot ratios than those growing in open areas (Ammer 2003). The root-to-shoot ratio of oaks is generally significantly higher than that of European beech (Kohler et al. 2020). As light availability decreases, the root-to-shoot ratio in oaks declines markedly, which reduces their tolerance to drought and browsing. The combined effect of shading and browsing negatively affects oak growth more than that of other tree species, including beech (Harmer 1999).

Oak regeneration is the subject of much discussion in forestry practice in the context of close-to-nature silviculture. In these principles, the aim is to regenerate oak under the parent trees with the aim of not creating large open regeneration elements. However, is it appropriate to use a shelterwood system for oak regeneration? The study aimed to quantify differences in selected morphological parameters of naturally regenerated sessile oak seedlings under different regeneration felling types. Additionally, the potential of this natural regeneration process to ensure the long-term stability and productive functions of forest stands in the context of ongoing global climate change was analysed, using selected sites at the Masaryk Forest Training Enterprise (TFE) Křtiny as a case study. The aim of this work is not to discredit the shelterwood system for oak regeneration, but rather to draw attention to its limitations.

## MATERIAL AND METHODS

**Study sites.** The research was conducted in the Masaryk TFE Křtiny area (Czech Republic), which is located approximately 20 km north of Brno (Figure 1). Seven forest stands at low to middle elevations were selected for this study, all with a dominant representation of sessile oak in the upper canopy layer. All stands were situated within the second to fourth forest vegetation zones. The mean annual air temperature of the study area is 8–9 °C (Kozdasová et al. 2021), while the mean annual precipitation ranges from 550 mm to 650 mm (Kománek et al. 2024). At the studied sites, Cambisols have developed (Kadavý et al. 2024; Kománek et al. 2025) on geological substrates ranging from granodiorites to Culm sandstones and limestones (Hammond et al. 2021). All research plots covered an area of 0.2–0.3 ha and were located in stands where regeneration fellings were carried out outside the growing period (winter 2022/2023) following the mast year 2022. Three of these plots represented clear-cut regeneration elements (CC1–3), and the remaining four were characterised by shelterwood regeneration (S1–4). According to the Köppen-Geiger classification, the study area is characterised as Cfb (temperate oceanic climate; Peel et al. 2007) with an average length of the growing period of 140–160 days (Quitt 1971).

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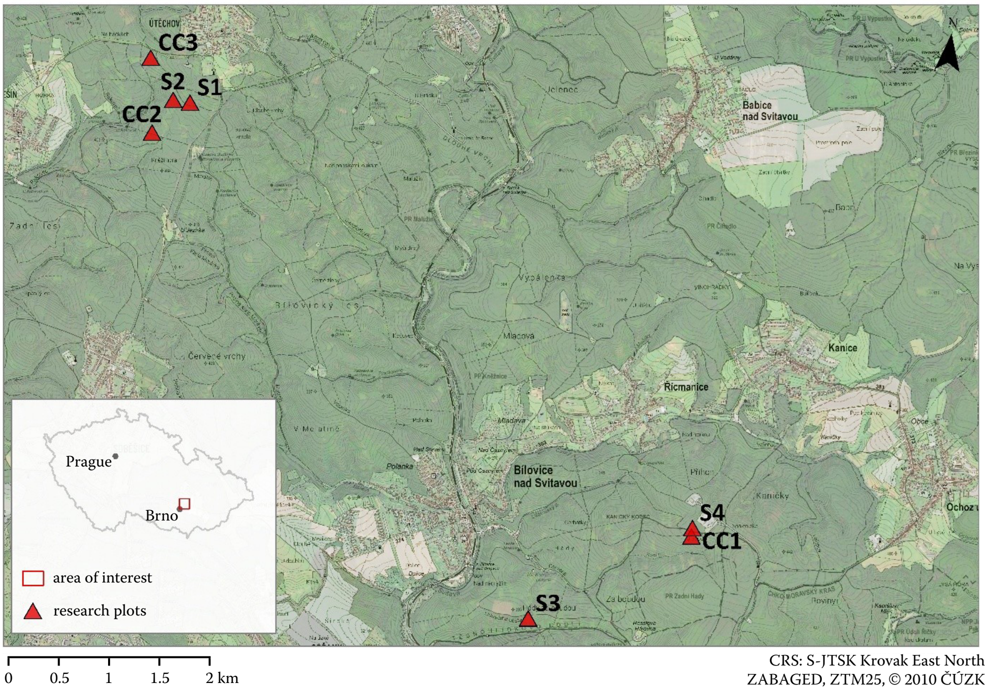


Figure 1. Location of the studied forest stands with different regeneration felling applied

CC1 – clear-cut without retained standards; CC2 – clear-cut with retained standards; CC3 – clear-cut strip with a width of 20–25 m; S1–S4 – shelterwood regeneration

The studied plots (CC1–CC3) differed in terms of regeneration felling. Plot CC1 was a clear-cut without retained standards; plot CC2 was a clear-cut with retained standards; and plot CC3 was a 20–25 m wide clear-cut stripe. The other plots (S1–S4) were located in stands that had been regenerated by shelterwood cutting, where light conditions were heterogeneous. The stocking density of the regenerated parent stand on these plots ranged from 0.3 to 0.5.

**Data collection.** Grids of sampling points were established at regular 8-m intervals on these regeneration elements, with the total number of points depending on the size of each element. At each point, with an area of 1 m$^2$, data were recorded on the abundance of naturally regenerated seedlings, their root collar diameter (measured 5 cm above the root collar) and their height. These measurements formed the basis for the subsequent targeted selection of individuals extracted from natural regeneration for destructive analysis to evaluate biomass allocation. A minimum of 24 sampling points in each studied stand was used to describe the parameters as mentioned above. The regeneration elements studied included clear-cuts and shelterwood systems, whose basic characteristics are summarised in Table 1.

Representative individuals (sample trees) of naturally regenerated sessile oak were collected within each regeneration element. On the CC1–CC3 plots, the number of sampled individuals was set at 50 and they were distributed evenly within the central part of each clear-cut area. In the shelterwood plots (S1–S4), where light conditions varied more, 100 individuals were sampled from each plot. The exception was plot S3, where only 81 samples were collected due to the overall low frequency. A total of 531 individuals were collected across all plots, comprising 150 from clear-cut plots (CC1–CC3) and 381 from the shelterwood plots (S1–S4).

Seedling samples were collected directly from the field. Each individual was carefully excavated, ensuring that the root system remained intact and taking great care to avoid damaging the main taproot. The sample seedlings were selected from average and representative individuals in each plot, as described above. Those that were evidently below average, deformed, damaged by the game, severely defoliated, exceptionally tall or potentially of a different age were excluded from the sample. Therefore, the extraction of the seedlings was carried out with utmost care to prevent mechanical damage, as any such damage could lead to biased

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Table 1. Basic characteristics of the regeneration elements

| Plot ID | GPS | Altitude (m a.s.l.) | Aspect | Slope (°) | Plot size (ha) | No. of measured points | Basal area ($m^2 \cdot ha^{-1}$) | Stand volume ($m^3 \cdot ha^{-1}$) | Stocking density (%) |
|---|---|---|---|---|---|---|---|---|---|
| CC1 | 49°14'51"N, 16°42'13"E | 417 | SW | 13.5 | 0.30 | 35 | 0.00 | 0.00 | 0 |
| CC2 | 49°16'41"N, 16°37'29"E | 420 | S | 1.4 | 0.25 | 28 | 5.50 | 65.74 | 12 |
| CC3 | 49°17'05"N, 16°37'25"E | 435 | S | 5.7 | 0.22 | 24 | 2.89 | 33.98 | 6 |
| S1 | 49°16'52"N, 16°37'46"E | 455 | S | 6.8 | 0.30 | 35 | 11.06 | 133.37 | 25 |
| S2 | 49°16'53"N, 16°37'38"E | 440 | W | 13.6 | 0.30 | 35 | 12.63 | 151.39 | 26 |
| S3 | 49°14'19"N, 16°40'56"E | 320 | SE | 16.7 | 0.36 | 45 | 14.89 | 153.12 | 32 |
| S4 | 49°14'54"N, 16°42'13"E | 425 | W | 4.6 | 0.25 | 28 | 24.46 | 242.71 | 50 |

CC1 – clear-cut without retained standards; CC2 – clear-cut with retained standards; CC3 – clear-cut strip with a width of 20–25 m; S1–S4 – shelterwood regeneration; GPS – central locality coordinates

results and negatively affect the accuracy of subsequent analyses.

Basic morphological parameters were measured for each excavated seedling. The total length of seedlings, taproot length, and length of the aboveground part were recorded using a wooden folding ruler with an accuracy of 0.1 cm. The diameter at the root collar was measured with a digital calliper with an accuracy of 0.1 mm. These measurements provided essential data for evaluating the morphology of the samples. Afterwards, each seedling was separated into three main fractions (leaves, stems, and roots) and carefully placed into pre-labelled paper bags. The samples were then oven-dried for 24 hours at a constant temperature in the lab. After drying, each fraction was weighed using a digital lab scale (Bel-M1203i, Helago, Czech Republic) with an accuracy of 0.001 g. Weighing the individual plant compartments sequentially provided accurate data on their dry matter content, which was essential for assessing biomass allocation. The total dry mass of each plant was then calculated as the sum of the dry masses of leaves, stems and roots. The total aboveground dry mass was derived as the sum of the dry masses of leaves and stems.

**Data analyses.** Statistical analyses were performed using TIBCO Statistica™ (Version 14.0.0, 2020) with a significance level of $\alpha = 0.05$ (95% confidence interval). Before the main analysis, data normality and homogeneity of variances were verified. Main effects and interactions were examined using analysis of variance (ANOVA) with Fisher's *F*-test. When statistically significant differences were detected, Tukey's Honest Significant Difference (HSD) post-hoc test was applied to identify pairwise differences between the groups.

## RESULTS

The greatest total length, including roots and aboveground parts, of sessile oak seedlings was recorded for plots regenerated by clear-cutting; the CC3 variant showed the highest mean values. The shelterwood plots showed substantially shorter total lengths, with statistically significant differences observed between some variants (S1 vs. S3 and S4). The shortest total lengths were recorded for plots S3 and S4 under the shelterwood system. The statistical analysis suggests that site conditions on clear-cut regeneration plots favour the overall growth of seedlings, including their below- and above-ground parts (Figure 2).

The results show that seedlings on clear-cut regeneration plots (CC1–CC3) had significantly longer aboveground parts than those growing under shelterwood conditions. The longest aboveground part was observed on the CC3 plot, followed by plots

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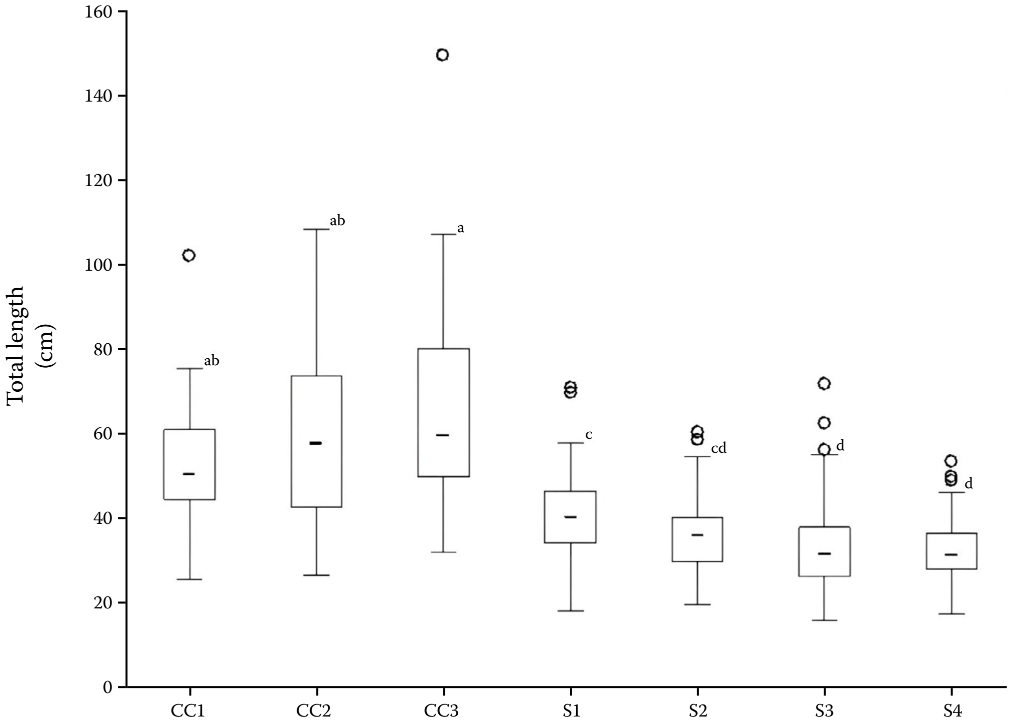


Figure 2. Total length of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) or clear-cut (CC1–CC3) silvicultural systems

Whiskers – standard deviation ($n$ = 50; $n$ = 31 only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P$ < 0.05)

CC2 and CC1. There were statistically significant differences between these plots and all shelterwood plots (S1–S4). These results suggest that conditions on clear-cut plots promote the growth of the aboveground part in sessile oak seedlings, which could improve their chances of survival during early stages of development (Figure 3).

Oak seedlings on clear-cut regeneration plots had considerably longer taproots, with the longest taproots recorded in plot CC1, followed by plots CC2 and CC3. There were statistically significant differences between these variants and some of the shelterwood plots, particularly S4 and S2. These results suggest that the environmental conditions on clear-cut plots encourage the growth of longer main taproots, which could have a positive effect on the vitality and stability of naturally regenerated oak seedlings (Figure 4).

The highest values of root collar diameter were recorded in the clear-cut variants (CC2 and CC3), which differed significantly from all shelterwood variants (S1–S4), especially from S4, with the lowest root collar diameter observed. These results suggest that clear-cut conditions may positively influence root collar diameter, thereby contributing to higher seedling vitality and mechanical stability (Figure 5).

The highest values of root system dry weight were recorded in the clear-cut variants (CC2 and CC3), with CC3 showing the greatest mean root dry mass and differing significantly from all the other variants. In contrast, the lowest root dry mass was measured on the shelterwood plots (S1–S4), which did not differ significantly from one another. These results suggest that clear-cut conditions may promote root system development, contributing to the greater vitality and mechanical stability of sessile oak seedlings (Figure 6).

The clear-cut variants recorded the highest values aboveground dry mass, with CC3 showing the greatest dry mass and differing significantly from all the other variants. In contrast, the lowest values were measured on the shelterwood plots (S1–S4), which did not differ significantly from each other. These results suggest that clear-cut regeneration methods create more favourable conditions for the growth of oak aboveground biomass compared to shelterwood variants (Figure 7).

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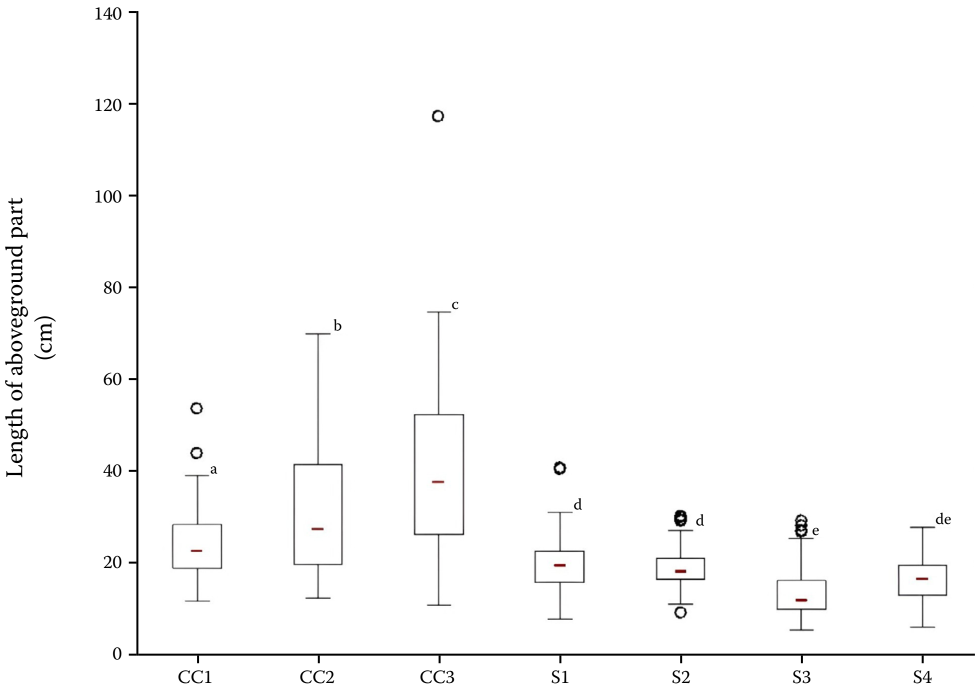


Figure 3. Average shoot length of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) or clear-cut (CC1–CC3) silvicultural systems

Whiskers – standard deviation ($n$ = 50; $n$ = 31 only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P$ < 0.05)

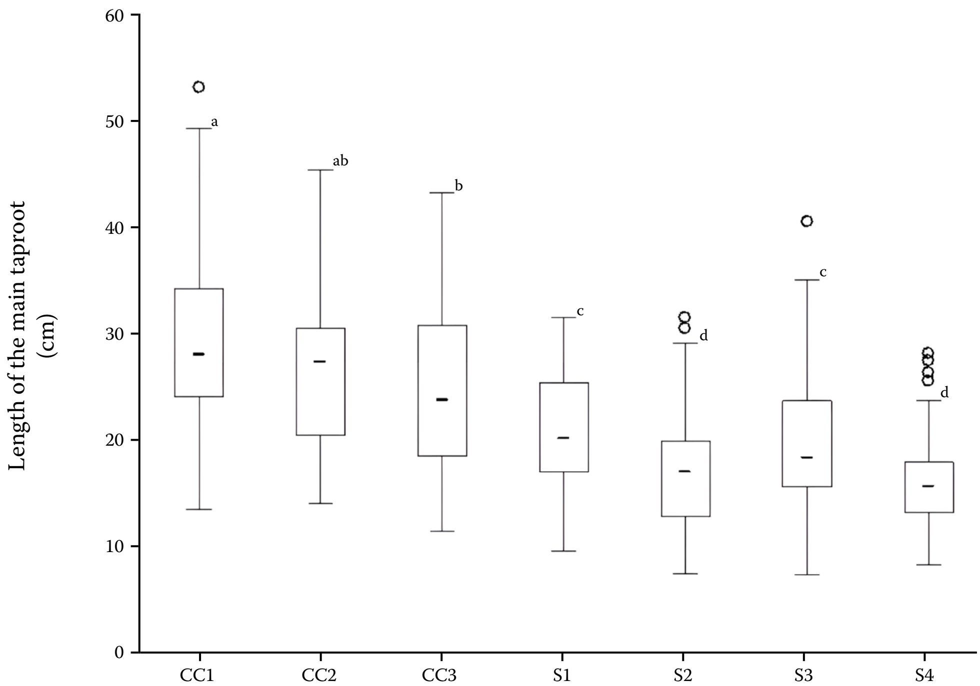


Figure 4. Length of the main taproot of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) and clear-cut (CC1–CC3) silvicultural systems

Whiskers – standard deviation ($n$ = 50; $n$ = 31 only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P$ < 0.05)

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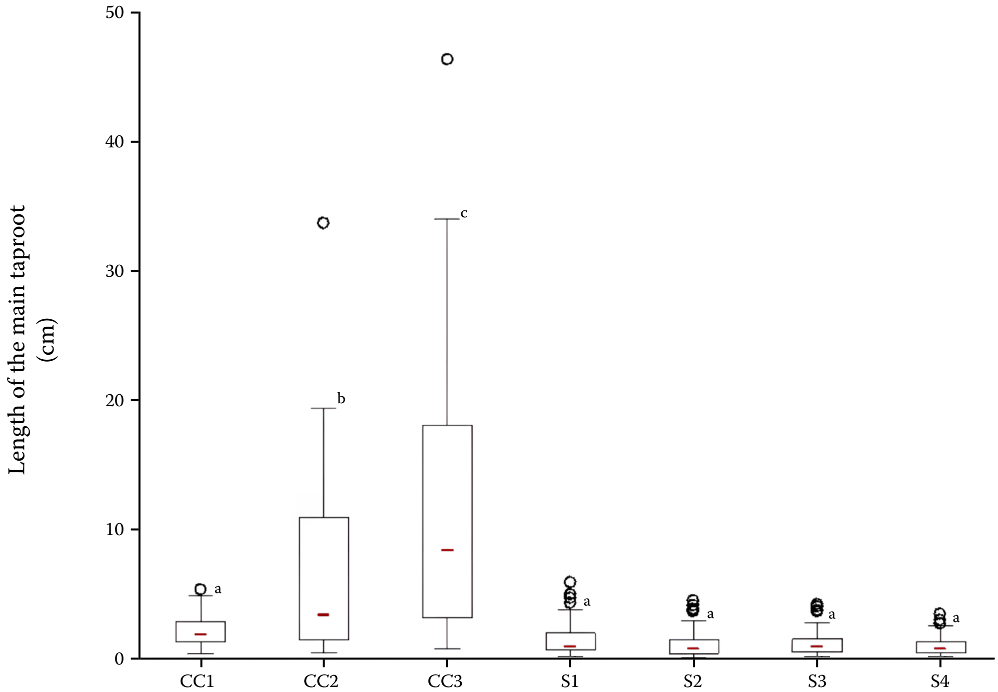


Figure 5. Average root collar diameter of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) and clear-cut (CC1–CC3) silvicultural systems

Whiskers – standard deviation ($n = 50$; $n = 31$ only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P < 0.05$)

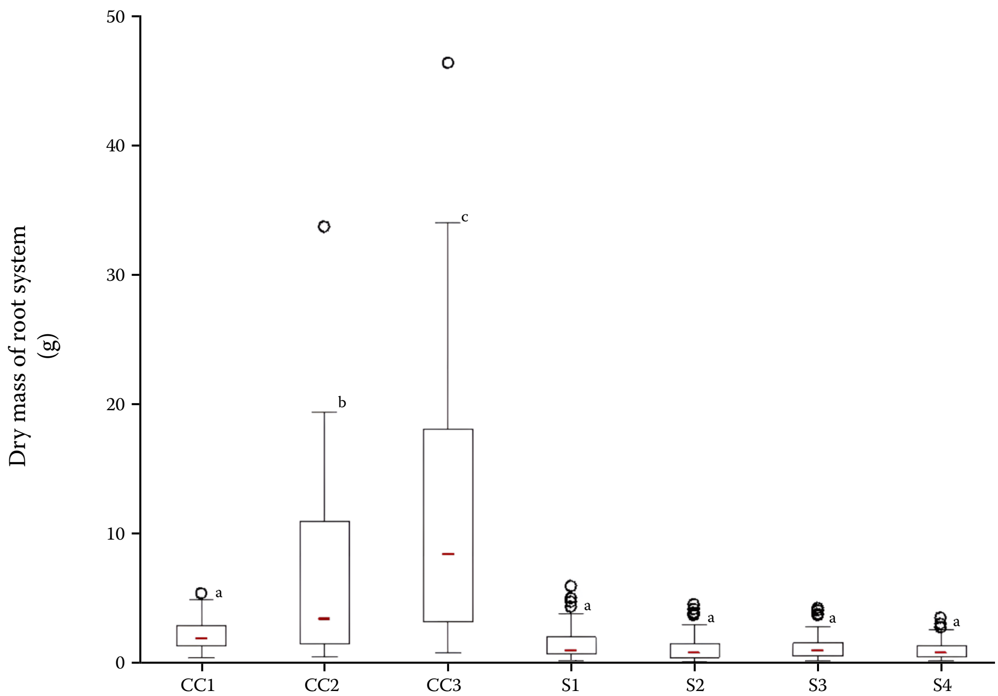


Figure 6. Dry mass of root system of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) or clear-cut (CC1–CC3) silvicultural systems

Whiskers – standard deviation ($n = 50$; $n = 31$ only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P < 0.05$)

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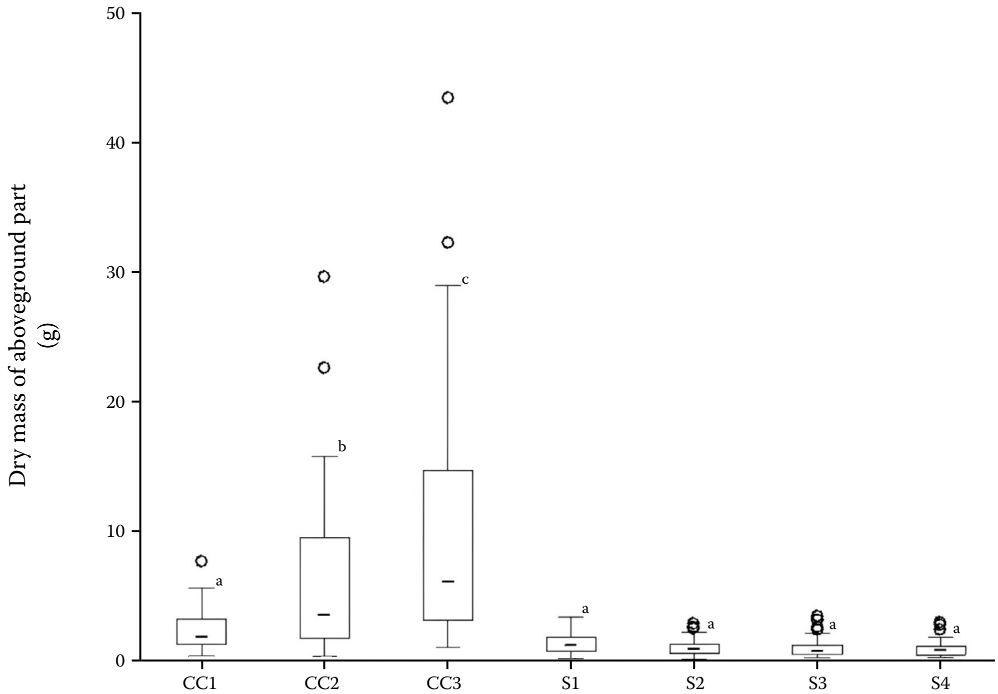


Figure 7. Differences in the dry mass of the aboveground part of naturally regenerated sessile oak seedlings under shelterwood (S1–S4) or clear-cut (CC1–CC3) silvicultural systems

Whiskers denote standard deviation ($n$ = 50; $n$ = 31 only for S3); numerical labels (1–4) distinguish different plots; different letters indicate statistically significant differences among the studied plots ($P$ < 0.05)

## DISCUSSION

The results of this study demonstrate that the selected regeneration method substantially affects the morphological characteristics, dry mass and early development of naturally regenerated sessile oak. Clear-cut plots showed a higher length of aboveground parts and main taproot, greater root collar diameters, and higher seedling dry mass than shelterwood plots. These differences confirm the pivotal role of light conditions during the early developmental stages of oak seedlings. Higher light availability allows for more intensive production of assimilates, which are then allocated more efficiently between the above- and below-ground biomass. This leads to stronger growth and better root establishment (Březina, Dobrovolný 2011; Kohler et al. 2020; Kanjevac et al. 2021).

A key finding of this study is that oak seedlings on clear-cut regeneration plots (CC1–CC3) exhibited greater above-ground growth, a more developed main taproot, and higher below-ground dry mass. This confirms that sufficient light amount stimulates not only photosynthetic uptake, but also investment in root development, which is essential for accessing water and nutrients, thereby increasing resistance to stress factors, particularly drought (Staszel et al. 2022). Previous studies have reported that sessile oak individuals growing in open areas have a higher belowground-to-aboveground dry mass ratio, enhancing their ecological stability and competitiveness with other species in later growth stages (Ammer 2003; Kanjevac et al. 2021).

In contrast, shelterwood systems offer seedlings protection from extreme weather conditions and maintain more stable microclimatic conditions. However, lower light availability can be a significant limiting factor in their early growth and vitality. Consequently, seedlings show slower height and taproot growth, as well as lower total dry mass, as was observed in this study. These findings are consistent with previous research demonstrating the reduced success of the natural regeneration of sessile oak under the canopy of the parent stand, due to limited light availability and strong competition from other tree species and ground vegetation (forest weed and shrubs; Modrý et al. 2004; Govedar et al. 2021).

The effect of competing vegetation also plays an important role in the natural regeneration dy-

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namics of sessile oak. Tree species, such as European beech, hornbeam and various maples and limes, tend to outgrow and suppress oak seedlings due to their faster initial growth (Kohler et al. 2020; Modrow et al. 2025; Nicolescu et al. 2025). The herbaceous layer, particularly brambles, can also play a significant role in preventing successful natural regeneration (Kuehne et al. 2020; Modrow et al. 2020). These findings confirm that successful regeneration of sessile oak under a canopy requires active removal of competing vegetation, for instance, through the mechanical or chemical control of ground vegetation and gradual thinning treatments application in the parent stand canopy (Kanjevac et al. 2021).

From a practical perspective, it is necessary to consider that, while clear-cut regeneration methods promote seedling growth, they also pose certain risks. For instance, open areas may increase exposure to extreme climatic conditions, such as droughts or frosts, which can threaten the long-term stability of forest stands (Kuehne et al. 2020; Nicolescu et al. 2025).

The spatial arrangement of regeneration elements also deserves attention. Studies have demonstrated that a mosaic structure comprising smaller clear-cut patches (0.15–0.20 ha) strikes a balance between the rapid growth of seedlings and the microclimatic stability afforded by shelterwood elements (Von Lüpke 2008; Březina, Dobrovolný 2011). This strategy may be particularly advantageous in Central Europe, where balancing silvicultural objectives with increasing climatic stress is necessary.

The results of this study confirm the hypothesis that light conditions are a key factor in the successful natural regeneration of sessile oak (e.g. Kohler et al. 2020; Kanjevac et al. 2021). However, they also demonstrate that regeneration success depends on managing competition, maintaining favourable microclimatic conditions and adapting silvicultural measures to site-specific conditions. This coincides with the findings of Kanjevac et al. (2021). In the context of global climate change, where forest management is increasingly affected by extreme air temperatures, droughts and growing disturbance regimes, adaptive and spatially diversified regeneration strategies should be prioritised.

These findings have direct practical implications for forest management, highlighting the importance of carefully planning the size and spatial arrangement of regeneration elements, regulating competition and consistently considering the ecological requirements of the sessile oak. A combination of clear-cut and shelterwood elements designed to optimise these factors can substantially increase the likelihood of establishing stable and resilient sessile oak stands, even under changing environmental conditions.

This study is primarily limited by its short temporal scope, which may not fully capture the long-term dynamics of natural regeneration of sessile oak under varying environmental conditions. Furthermore, factors such as soil characteristics, microclimatic variability, and competition intensity were not experimentally controlled, which may have influenced the observed differences between regeneration methods. The limited plot size and number of study sites also reduce the generalizability of the results to a wider range of habitats. Therefore, future research should include long-term monitoring, a broader set of sites with differing ecological conditions, and physiological measurements to gain a more detailed understanding of seedling growth mechanisms. Additionally, this study does not evaluate the success of regeneration or the mortality rate of seedlings in shelterwood and clear-cut regeneration methods. These factors could have a significant effect on long-term stand development and should be considered in future research.

## CONCLUSION

Based on the results of this study, it can be concluded that the chosen regeneration method significantly affects the morphological characteristics of naturally regenerated sessile oak in the conditions of the Masaryk TFE Křtiny (Czech Republic). Clear-cut elements create favourable light conditions that promote intensive seedling growth, main taproot system development and biomass accumulation. In contrast, shelterwood systems provide a more stable microclimate, but often insufficient light for the optimal growth and vitality of oak seedlings. For successful natural regeneration of sessile oak, it is crucial to strike a balance between sufficient light availability, reduced competition and an appropriate spatial arrangement of regeneration elements. Therefore, a mosaic structure combining smaller clear-cut patches with shelterwood areas

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appears to be an effective compromise between maximising seedling growth potential and protecting against climatic extremes. These insights could inform the more efficient planning of silvicultural measures and sessile oak stand regeneration in Central European conditions. In the context of climate change, adaptive and spatially diversified regeneration strategies that enhance the stability and resilience of forest ecosystems must be prioritised. Therefore, the results of this study provide an important basis for forest management practices aimed at long-term sustainable sessile oak management.

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