

Impact of silvicultural interventions on growth and survival of *Fagus sylvatica* L. saplings

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Abstract

This study aims to examine the impact of silvicultural interventions on the height and diameter growth, survival, and canopy structure of naturally regenerated European beech (*Fagus sylvatica* L.) saplings. In a field study, a system of six experimental sites was set up across three areas in the West Stara Planina region, selected according to the various types of cutting regimes within them. At each area, we chose two experimental sites – one of them with silvicultural intervention (Group selection system, Group shelterwood system and Short-term shelterwood system cuttings) and the other one – without silvicultural intervention during the last minimum twenty years (control). Biometric measurements of sapling number, height, and diameter were taken in 2018 and 2022, alongside assessments of the leaf area index (LAI). The results showed that cutting regimes influence beech regeneration growth patterns. Small canopy gaps (0.111 and 0.125 ha) in the Group selection and Short-term shelterwood systems led to similar survival and growth changes, selecting resilient individuals and increasing sapling sizes compared to controls, with no significant change in LAI. In contrast, the Group shelterwood system, with a larger canopy gap (0.555 ha), resulted in similar sapling numbers and sizes to the control but increased LAI over four years without sapling size growth. This indicates that larger gaps may have a less stimulating effect on beech regeneration compared to smaller gaps.

Key words: canopy, cutting regimes, European beech, gap, leaf area index, regeneration, silvicultural intervention, survival.

Introduction

European beech (*Fagus sylvatica* L.) is one of the main deciduous broad-leaved tree species in the Bulgarian mountains. It is widespread between 600 and 1800 m a.s.l. (Stefanov and Ganchev 1953), covering 14 % of the territory of the Bulgarian forests. The European beech is a typical

closed-stand forest tree species (Küppers 1985, Schütz et al. 2006, Matyssek et al. 2007), which becomes dominant only as late as in the final phase; when a climax microclimate has already been created (Kostov and Stipcov 2004).

Silvicultural practices significantly alter forest stand structure, leading to gaps in the forest canopy and modifications to

the light environment. Consequently, the creation of gaps triggers the regeneration processes in the understory, impacting stand dynamics (Yamamoto 2000). According to Nedyalkov (Kostov 2009), the heterogenous structure of beech stands is evident across all Bulgarian beech forests, with a more noticeable presence in areas where human intervention is minimal. Contemporary studies on the natural dynamics of beech forests confirm the notion that small-scale natural disturbances have a dominant influence on them. Within these created gaps of varying sizes, the beech regenerates successfully (Aleksandrov and Rafailova 2009). Group selection system, which mimics the prevailing natural disturbance regime, is considered a suitable method for managing beech stands (Atlegrim and Sjöberg 2004, Aleksandrov and Rafailova 2009, Hobi et al. 2015). Conversely, tree regeneration from seeds under a dense canopy may be poor (Lukyanets et al. 2022). Nevertheless, usually in potential beech habitats, beech trees typically regenerate and establish themselves effectively across a range of stand conditions resulting from various silvicultural systems. Natural regeneration process in the European beech forests is most often successful due to the ability of this species to form mono-dominated stands (Rafailov et al. 2009) where mature trees protect the saplings.

Several studies under controlled conditions suggest that beech seedlings can benefit rapidly from canopy opening (Tognetti et al. 1997, van Hees 1997, Welander and Ottosson 1997). Despite that, young European beech trees are very sensitive to late spring frost (Dittmar et al. 2003, Ammer et al. 2005) and direct sunlight (Stefanov and Ganchev 1953). Research carried out in several European beech stands found a possible 80–90 %

loss of germination capacity (Bílek et al. 2009), especially in a wet and not sufficiently cold winter. Such sensitivity risks damage for several saplings, especially few years after disturbance or forest cutting. The damage incidentally affects individuals and causes accidental nature of mortality, and therefore of natural selection at this stage of the beech forest development. Survived trees have post-stress physiological features (Dittmar et al. 2003), which remain permanent for a long time after cutting or disturbances (Wagner et al. 2010), especially in the context of climatic changes (Silva et al. 2012).

Silvicultural interventions have a significant impact on the light conditions within the understory, which are fundamental determinants of regeneration patterns in forest ecosystems (Gao et al. 2014). Competition for light and subsequent mortality are the primary processes that significantly influence the growth of young forest stands (King 1990). As the canopy closes, especially in stands generated through natural regeneration, the height of trees compared to neighbouring trees, as well as their position within the canopy, determine the amount of light accessible to their foliage (Richardson et al. 2001). Leaves possess the exclusive ability to capture energy, thereby propelling forest growth. Foliage exhibits high sensitivity to growth conditions prevailing within a stand.

Silvicultural practices that create canopy gaps influence light availability, which is crucial for beech regeneration, highlighting the need to understand how different cutting regimes affect sapling growth and survival, especially given the substantial role of microclimatic conditions in sapling survival before canopy assembly.

The aim of this research, within the context of forest management in the Bul-

garian mountains, is to investigate the effects of different silvicultural interventions altering beech regeneration. We hypothesized that differences in regeneration parameters like height and diameter growth, survival, and leaf area index of beech saplings will occur among stands managed with various cutting regimes.

Materials and Methods

Site description and field data collection

The study was carried out within the University of Forestry's Training and Experimental Forest Range 'Petrohan', located on the northeastern slopes of the Western Stara Planina Mt. The climate in this region is characterized as mountainous with a moderate continental influence. At an elevation of 1450 m, the average annual temperature is 4.8 °C, and the average annual precipitation, peaking in spring, is approximately 1080 mm. At an elevation of 700 m, the average annual temperature is 8.8 °C, and the average annual precipitation between 600 and 750 mm (Kutchuk-

ova 1983, Koleva and Peneva 1990). The soil type is identified as brown acid (eutric cambisol) developed on granite, with an average depth exceeding 80 cm (Malinova and Petrova 2019). Experimental sites were set up at different elevations ranging from 700 to 1450 m a.s.l. (Fig. 1), predominantly within European beech stands. Within the beech stands, singular occurrences of *Acer pseudoplatanus* L., *Sorbus aucuparia* L., *Acer heldreichii* Boiss, and *Carpinus betulus* L. were observed.

The experimental sites were chosen based on their varied silvicultural histories. Each study area consisted of two (ES) – with silvicultural intervention (cutting regimes – Group selection system (GSS), Group shelterwood system (GShS) and Short-term shelterwood system (StSS) (ES-O) and the other one – without silvicultural intervention during the last minimum twenty years (control) (ES-C, Table 1).

In 2011, the canopy of the ES1-O site underwent opening through the removal of all mature trees aged 120 years within a gap measuring 25 × 40 m (0.1 ha), which remained unchanged thereafter. In 2013, the canopy of the ES2-O site, consisting

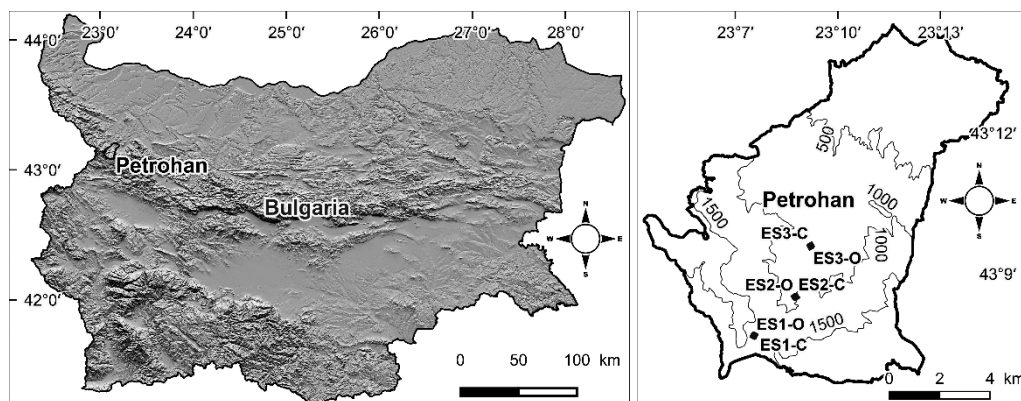


Fig. 1. Map of TEFR 'Petrohan' (left) and experimental plot location (right).

Note: Contour lines with 500 m intervals are shown on the right map.

Table 1. Properties of experimental sites.

Experimental site	ES1-C	ES1-O	ES2-C	ES2-O	ES3-C	ES3-O
Latitude, ° ' "	43° 7' 32"	43° 7' 30"	43° 8' 22"	43° 8' 23"	43° 9' 29"	43° 9' 27"
Longitude, ° ' "	23° 7' 25"	23° 7' 23"	23° 8' 33"	23° 8' 37"	23° 9' 00"	23° 8' 59"
Elevation, m	1439	1450	970	1015	713	718
Aspect, ° from North	74.9/E	105.3/E	276.3/W	251.7/SW	323.7/NW	322.9/NW
Slope, °	15.0	10.9	24.4	28.9	8.4	6.2
Type of cutting system	-	GSS	-	GShS	-	StSS
Gap size, ha	-	0.111	-	0.555	-	0.125
Year of intervention	-	2011	-	2013	-	2011

Note: GSS – group selection system, GShS – group shelterwood system, StSS – short-term shelterwood system.

of 120-year-old trees, was opened in a circular gap with a 50 m diameter, subsequently expanded to 80 m (~0.5 ha) by 2018. The canopy of ES3-O was opened by cutting eight mature trees aged 160 years, evenly distributed across a total area of 0.1 ha. Control ES-C sites were positioned adjacent to the (ES-O) sites within the stands, remaining untouched by cutting activities for a minimum of twenty years. All control sites are situated in forests dominated by common beech, originating from seed, with a uniform structure. In ES1-C, the mature trees are 140-year-old with a canopy density of 70 %. In ES2-C, the mature trees are 160-year-old with a canopy density of 60 %. In ES3-C, the mature trees are 160-year-old with a canopy density of 70 %.

In both intervention ES and control, we assessed the number (N) of beech regeneration plants within three randomly selected sample plots (2.5 × 4.0 m). Stem height (H, cm) was measured using a tape measure, while the diameter of the stem base (D, cm) of the beech regeneration plants was measured using a calliper. QGIS 3.16 open-source software was used to calculate the LAI index. The satellite images based on which the LAI indices were calculated are from the

Sentinel-2 satellites, which, in the channels used to calculate LAI, provide the highest resolution of 10 × 10 m for one px (D'Odorico et al. 2013). These images are publicly available at earthexplorer.usgs.gov, and we've only used those for August, when it's the clearest time in the region. These measurements were conducted at the onset of the growing season in both 2018 and 2022.

Data analysis

The field-collected data, including numbers, heights, diameters, and LAI of beech saplings across various experimental sites and examined years, underwent the following statistical analyses: 1) descriptive statistical analysis and 2) Shapiro-Wilk test for evaluation of the normal distribution. Two Way ANOVA test following all pairwise multiple comparison procedures (Tukey test) was used for tests of significant differences between the means among the numbers, biometric parameters, and LAI of seedlings at experimental sites with silvicultural interventions compared to control sites, as well as between the two studied years. All statistical calculations were performed with MS Excel (Microsoft Corp., Redmond, WA)

and with specially created visual basic user-defined script.

Results and Discussion

Regeneration and survival

In ES1-O, the number of saplings remained constant throughout the study period (Fig. 2). The lack of alterations in the sapling amounts seven years after GSS cutting, for a period of four years (2018–2022) suggests that the regeneration processes following the canopy opening have already decelerated. However, upon comparing with ES1-C, it becomes evident that, unlike ES1-O, the number of saplings in ES1-C has increased since the beginning of the study period. Even in 2022, the number of saplings ES1-C was greater than those in ES1-O. The significantly higher number of beech individuals in the ES1-C compared to those in ES1-O can likely be attributed to the shelter provided to saplings within the closed canopy stand, shielding them from adverse

environmental, such as frost, prevalent at the high elevation of 1450 m, as noted by Rafailov et al. (2009) in mono-dominated beech stands. Budeanu et al. (2016), Kolář et al. (2017) also state that higher elevations (exceeding 1200 m) are not favourable to beech growth due to lower temperatures and late frosts. As Stefanov and Ganchev (1953), Dittmar et al. (2003), and Ammer et al. (2005) indicate, beech saplings are very sensitive to late spring frost and direct sunlight, and this sensitivity is particularly pronounced few years after cutting. These factors contribute to an accidental form of mortality, which consequently influences the natural selection process during this beech forest development phase (Dittmar et al. 2003). Lukyanets et al. (2022) also observe a reduction in the volume of alder stands due to poor forest site conditions. This implies that the consistent absence of an increase in the number of beech saplings at ES1-O during the study period may be interpreted as a natural selection process favouring more adaptable and thus more promising individuals.

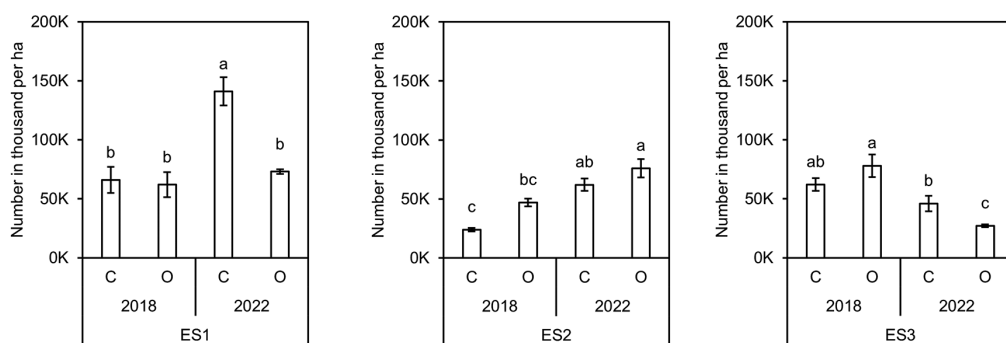


Fig. 2. Regeneration density of beech saplings within experimental sites during study period.

Note: The data represent the mean numbers of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

In ES2-O, there was a significant increase in numbers of saplings observed over the studied four-year period, beginning five years after GShS cutting. However, there were no differences in the number of saplings in ES2-O and EC2-C in the two examination years. The absence of differences in sapling numbers between ES2-O and the control group suggests that the observed sapling growth in 2022 likely stemmed from favourable environmental conditions conducive to beech regeneration in the studied area. These conditions appear to stimulate beech regeneration irrespective of the presence or absence of silvicultural intervention.

Seven years after StSS cutting (in 2018), there were no significant differences in the number of saplings between ES3-O and ES3-C, similar to that observed in the ES1 and ES2 in the same year. The consistent sapling numbers observed in the initial year of the study likely result from the transition beyond the phase of intensive sapling mortality in the early years. However, in ES1-O and ES3-O, although there were no changes in sapling numbers in 2018 compared to their respective controls, a decrease in sapling numbers was observed in 2022. The reduced number of young beech individuals in ES3-O might also be influenced by damage from an ice disturbance (heavy ice on the tree crown) in January 2021 at ES3. The absence of an increase in sapling numbers by the study's conclusion after both types of cuttings, GSC and StSS, which are characterized by small gaps in the canopy (in our study, the gap size is respectively 0.111 and 0.125 ha), resembling the regime of natural disturbances in beech forests, could be attributed to the process of natural selection leading to the occupation of the habitat from more resilient beech individuals to

the changed environmental conditions post-cutting. Collet and Chenost (2006) note that partial cutting of single trees or small gaps may result in increased beech dominance. In GShS, there was no decrease in sapling numbers in 2022. However, the gap size (0.555 ha) is approximately five times larger compared to GSS and StSS, which is likely to influence the rate of regeneration processes occurring over time. Although the highest number of saplings was found in the count site nearest to the periphery of the gap, the variation (SE) was small, indicating relative homogeneity in this measure across the individual count sites.

Biometry

In ES1, there was no difference in height between ES1-O and ES1-C in 2018 (Fig. 3), but the diameter was higher in ES1-O (Fig. 4). In 2022, there was an increase in both height and diameter in ES1-O compared to ES1-C. However, in this experimental site, the exhibited height of saplings increased over the four-year study period, while their diameter decreased.

The absence of growth in sapling diameter during the study period, compared to the increase in height are probably influenced by the increased intraspecific competition in the stand. Collet et al. (2001), Prévosto and Balandier (2007) emphasize that interspecific competition affects the diameter growth of naturally regenerated beech individuals more significantly than their height growth. In Collet et al. (2001) study diameter growth increased immediately after the gaps had been opened and showed no clear increasing trend in the following years. Conversely, height growth did not increase immediately after canopy opening and increased regularly in the fol-

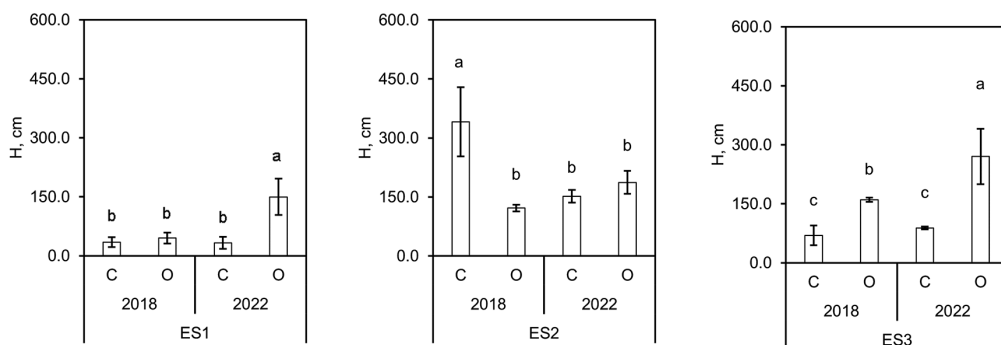


Fig. 3. Height of saplings within experimental sites during study period.

Note: The data represent the mean height of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

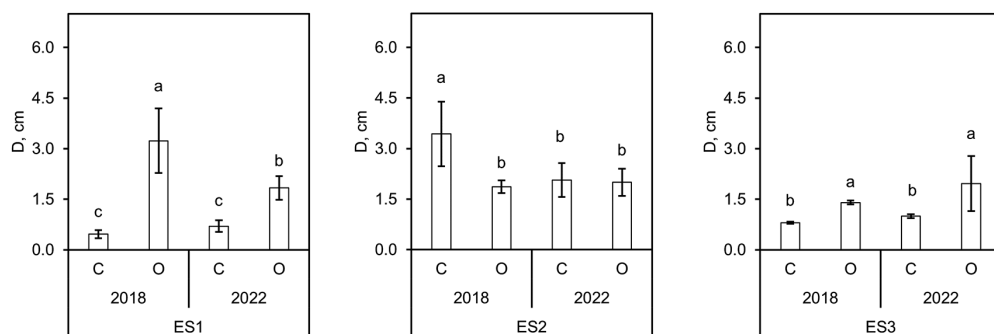


Fig. 4. Diameter of saplings within experimental sites during study period.

Note: The data represent the mean diameter of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

lowing years. Nevertheless, the decrease in overall thickness over the study period suggests that competition has yielded to the more advanced individuals.

The steady number of individuals over the study period, along with increased heights and reduced diameters in ES1-O, suggests that, as plants grow larger, they require more space. The greater space demand likely prevents an increase in the number of plants per unit area. Such an

observation indicates that, at this stage, beech individuals that exhibit greater adaptability and resilience to environmental changes persist. As highlighted by Evans et al. (2003), intra-specific competition for space, nutrients, and light arises when plants surpass the optimal limit per unit area, resulting in diminished plant growth and development, ultimately leading to a reduction in plant biomass.

In 2022, ES1 and ES3 showed similar

growth patterns, with saplings in the experimental sites using the cutting system being larger compared to those in the control site. This increase in size corresponds with a smaller number of saplings in these experimental sites for the same year. This suggests that the similar opening of the canopy resulting from these cuttings has a similar positive impact on the survival and growth processes of the saplings. The survival and growth of saplings in ES2 are characterized by the lack of significant differences in both the number of saplings and growth parameters between ES2-O and ES2-C in 2022, distinguishing it from ES1 and ES3. From 2018 to 2022, in ES2-C there was a notable reduction in the heights and diameters of saplings, due to the emergence of smaller new individuals. Additionally, no increase was evident in the growth parameters of the saplings in ES2-O throughout the four-year study period. These results suggest a less stimulating effect of canopy openings through the GShS cutting system on beech regeneration growth.

During the studied period, after a transformation into a group-selective stand, the

number of saplings remained constant, their height increased, and their diameter decreased, indicating a balance between mortality and the emergence of new individuals. In the group shelterwood system, the number of saplings increased at a rate like that in the closed canopy control, while their height and diameter remained unchanged. This suggests that some individuals died, and new ones emerged, with a rapid height growth rate. In the short-term shelterwood system, there is significant differentiation of social classes, many individuals are lost, and this process is accompanied by an increase in average height and diameter. The intense mortality in this system is likely due to the negative carbon balance of suppressed saplings.

Leaf area index

Beech saplings had a higher leaf area index (LAI) in ES1-O compared to ES1-C (Fig. 5). Between 2018 and 2022 in ES1-C, there is a significant increase in the number of individuals, but the LAI remains unchanged. This lack of increase in

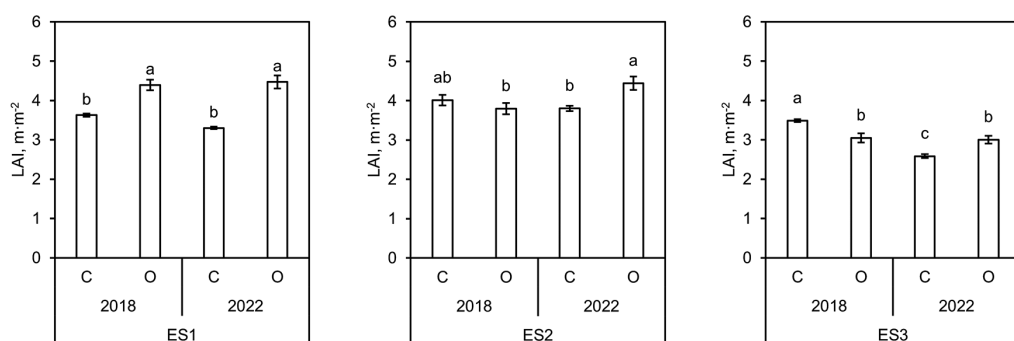


Fig. 5. Leaf area index of saplings within experimental sites during study period.

Note: The data represent the mean LAI of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

LAI, despite the rising number of saplings in this experimental site, is likely because the C-experimental sites reflect the LAI of the mother stands. When LAI remains constant during the experimental period, it suggests that the canopy of mother stand has experienced disruptions over the years. These disruptions allow more light to penetrate, stimulating regeneration and thus increasing the number of individuals in this experimental site. However, there was no observed increase in the index in ES1-O over the four-year duration of the study, which was also observed in ES3-O. The elevated index in ES1-O and ES3-O in 2022 indicates the expanded foliage of the beech saplings, likely attributed to the opening of the canopy and increased light penetration, thereby stimulating leaf production. Nevertheless, the absence of a rise in the index post-GSS and ShSS cuttings indicates that small canopy opening (gap size – 0.111 and 0.125 ha) has a limited impact on leaf production over the years.

In ES2, LAI differs only in 2022 between ES2-O and ES2-C, with predictable higher values in EC2-O due to most light. On the contrary with ES1 and ES3, while the ES1-O and ES3-O LAI showed no growth, there was an increase in the ES2-O index over the study period. This suggests a potentially stronger impact of bigger canopy opening (gap size – 0.555) due to GShS cutting on the leaf development of beech saplings, compared to the effect of five times smaller canopy opening resulting from GSS and ShSS cuttings on leaf production.

After StSS cutting, in the initial year of the study, a reduced LAI was noted in ES3-O compared to ES3-C, indicating a limited stimulating effect of that cutting on leaf production. Conversely, by the study's conclusion, the index had increased in

ES3-O relative to ES3-C. However, this augmentation was likely due to additional canopy opening resulting from damage inflicted by the heavy snow in this experimental site. Furthermore, considering the absence of an increase in the ES3-O index throughout the study period, it can be assumed that StSS cutting has a minor impact on leaf production.

The results regarding LAI align with alterations in growth parameters, as highlighted by (Givnish 1982, Niklas 1992), as leaf height increases, plants must allocate biomass disproportionately to the stem to support their weight, thereby reducing the proportion of leaf mass in the plant.

Conclusion

According to the initial results of our research, there is a correlation between the type of gap opening and the growth of beech regeneration. The eco-physiological features of European beech, in combination with a wide variation of micro-environmental factors in its distribution area, are prerequisite for a significant variation regarding growth and presence of beech saplings after cuttings. European beech successfully regenerated in all experimental sites where silvicultural interventions occurred, confirming the species' broad ecological adaptability. Nevertheless, there are different efficiencies resulting from the way the canopy is opened. The short-term shelterwood system sets the stage for intensive self-healing from an early age, which will result in more homogeneous future stand. In contrast, the other two systems maintain conditions that preserve heterogeneity in stand structure, at least during the early stages of forest development. With further research on a larger scale, these observations could be

used as indicators of young trees' regeneration dynamics and physiological stress after forest interventions.

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