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Anticipated regeneration cuts in transitional high forests of beech (*Fagus sylvatica* L.) in the Eastern Prealps: ecological and economic impacts

Natalie Piazza[1*], Antonio Tomao[1*], Pietro Piussi[2] and Giorgio Alberti[1*]

Abstract

Key message Anticipating establishment cuts in transitional high forests of beech (*Fagus sylvatica* L.) is a sustainable strategy from both ecological and economic perspectives. It could be scaled over large areas to promote structural heterogeneity while minimizing disturbances.

Context Beech forests, traditionally managed as coppices for firewood, have experienced significant changes in management practices, particularly in Southern Europe. This shift was especially noticeable in the Southern and Eastern Alps, where vast areas of coppice forests were gradually transformed into high forests, as fuelwood demand declined. However, large-scale regeneration cuts at the end of the rotation period can result in economic losses and environmental concerns.

Aims We assessed whether applying regeneration cuts at 70 years in transitional high forests can effectively accelerate the coppice-to-high-forest conversion process, relative to the conventional rotation period of 120–140 years.

Methods This study examines the possibility to implement regeneration cuts before the common rotation period in temporary high forests by applying four distinct treatments: (1) control—thinning from below; (2) shelterwood system—establishment cut; (3) clear-cut; and (4) crop tree release.

Results We found significant differences in basal area, biomass, leaf area index after tree removal, and harvesting costs/venues, with the shelterwood system being the most economically advantageous treatment. Ten years after the treatment execution, the shelterwood treatment exhibited prompt and widespread regeneration compared to other regeneration treatments, with the highest seedling abundance (12 ± 2 seedlings m^{-2}) and height of the established saplings (93 ± 6 cm).

Pietro Piussi is retired.

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*Correspondence:
Natalie Piazza
natalie.piazza@uniud.it
Antonio Tomao
antonio.tomao@uniud.it
Giorgio Alberti
giorgio.alberti@uniud.it
Full list of author information is available at the end of the article

Conclusion Our findings support the idea of implementing and gradually scaling regeneration cuts in time and space using the group shelterwood system. This approach can increase the structural heterogeneity of forest stands, maintain consistent timber production, and minimize disturbances to fauna and other ecosystem services.

Keywords Thinning from below, Group shelterwood system, Group clear-cut, Crop tree release, Temporary high forests

1 Introduction

Beech (*Fagus sylvatica* L.) is one of the most widespread and ecologically significant tree species in Europe (Houston Durrant et al. 2016), playing a key role in the structure and function of many forest ecosystems. The species thrives in temperate climates and is particularly abundant in central and southern Europe, where it forms extensive pure stands. Beech forests are found across a range of altitudes, from lowland areas to mountainous regions. According to the last Italian National Forest Inventory (Gasparini and Papitto 2022), beech forests cover 1,053,183 ha of the national territory, representing 12% of the total forest area, with 42% of this area specifically located in the Alps. From a management perspective, beech cultivation for timber production (i.e., high forest management) was not widely practiced in the past, except for some specific geographical areas (e.g., the oar woods of the Republic of Venice in the Cansiglio plateau) (Del Favero 2004). However, since beech wood was highly valued for firewood and charcoal production, coppicing was the most common form of forest management (Mairota et al. 2018). More specifically, depending on the local traditions, coppice with standards (i.e., coppice shoots growing from stumps are periodically harvested, while scattered overstory trees—the standards—are retained for longer rotations to provide timber and structural complexity) and the coppice selection system (i.e., selected individual stems or small groups are harvested periodically across the stand, without clear-cutting, to promote continuous regeneration and maintain structural diversity within the coppice) were both quite common (Nocentini 2009).

Starting around 1960, the development and widespread use of alternative low-cost energy sources combined with the depopulation of mountain areas led to significant changes in the management of beech coppices. Regardless of the management approach applied, many beech coppices were either left abandoned or actively converted into high forests to enhance timber quality and ecosystem stability (Ciancio et al. 2006; Nocentini 2009; Mariotti et al. 2017). The conversion of beech forests from coppice to high forest management has been a common practice in many European regions (Decocq et al. 2004; Van Calster et al. 2007; Baeten et al. 2009; Vild et al. 2013). In Italy, the conversion to high forest was strongly supported by the forest administration (Mairota et al. 2018) and has been carried out by reducing stand density through repeated thinnings (Ciancio and Nocentini 2004; Del Favero 2004; Ciancio et al. 2006; Nocentini 2009; Mariotti et al. 2017). The goal was to promote the growth of the best shoots while simultaneously reducing resprouting, thus to obtain a uniform transitional high forest (i.e., a stand of vegetative origin similar to a high forest). The final conversion to a high forest (i.e., stand from seedlings) should be completed through seedling establishment after a final regeneration cut. However, the regeneration stage has seldom been completed in practice due to the extended time required to finalize the conversion process (up to 120–150 years, depending on site fertility) (Nocentini 2009).

In North-East Italy, large-scale coppice-to-high-forest conversion programs were carried out over large areas between the 1960s and 1990s, resulting in monospecific, even-aged transitional high-forests that are densely packed, with trees exhibiting a high slenderness ratio and low wood quality due to their agamic origin (Del Favero 2004). The major challenge for these stands lies in implementing thinning operations that enhance their productive potential, eventually leading to a regeneration cut (Wolynski 2002). Traditionally, both pure seed-origin beech forests and those derived from coppice have been managed using either a uniform shelterwood system (Del Favero et al. 1998) or group selection cuts (Hoffman 1991) typically based on a rotation period of 120–140 years and a regeneration phase lasting around 20 years. However, given the large spatial extent of transitional stands—most of which are already over 70 years old—implementing simultaneous, large-scale and uniform regeneration cuts once they reach maturity (120–150 years) could pose significant environmental (e.g., large scale disturbances, habitat disruption) and commercial challenges (i.e., wood price decrease, logistical complexity of harvesting operations). Therefore, planned, scalar and anticipated regeneration cuts could increase landscape heterogeneity, promote structural diversification in these previously uniformly managed stands, reduce the risk of disturbances, and generate periodic economic returns for the owners (Cutini et al. 2015). Furthermore, regeneration cuts that differ from the commonly used uniform shelterwood system, such as group crop tree releases and small clear-cuts (Paci 2012), could further enhance stand diversification on a landscape scale while maintaining economic profitability.

The production of beech seeds and the successful establishment of seedlings are influenced by a complex interplay of ecological, biological, and environmental factors. Beech exhibits mast seeding, characterized by irregular intervals largely driven by weather conditions in preceding years and available storage compound availability in trees (Mund et al. 2010; Vacchiano et al. 2017; Foest et al. 2024). Seedling establishment depends on both the quality and quantity of seeds. Large seed crops can overwhelm seed predators, thereby increasing the likelihood of successful recruitment (Zwolak et al. 2016). Light availability is another critical factor: a partial canopy cover (30–70%) typically offers optimal conditions by balancing sufficient light for photosynthesis with protection against excessive soil evaporation, frost damage, and competition from light-demanding ground vegetation such as grasses and brambles (Scarascia-Mugnozza 1999). Other key determinants include soil conditions (i.e., nutrients and soil water content), interspecific competition, local microclimate, and herbivory pressure from seed and seedling predators. Given the ongoing climate change and the increasing frequency of heatwaves and droughts during the growing season (Yuan et al. 2023), it is crucial to adapt silvicultural practices to support seedling establishment. Promoting regeneration under a semi-continuous canopy cover, while avoiding large, uniform regeneration cuts, can help sustain seedling growth and vigor by mitigating hydraulic stress and buffering against climatic extremes (Wilkens and Wagner 2021; Mathes et al. 2024). In this context, management systems that emulate the natural disturbance regimes characteristic of beech forests—such as gap dynamics—can efficiently support regeneration and promote spatial heterogeneity, thereby enhancing overall biodiversity (Brang et al. 2014). Previous studies have shown that gap size in beech forests significantly influences regeneration dynamics (Kenderes et al. 2008; Diaci et al. 2012). While small gaps can be quickly closed by surrounding trees, larger gaps may favor the establishment of seedlings and saplings, but also introduce competition from other understory vegetation. The optimal gap size for beech regeneration appears to be a balance between sufficient light for growth and reduced competition, with medium-sized gaps often showing the best results (Nagel et al. 2010; Scherrer et al. 2021; Bagnato et al. 2021).

In this study, we evaluated the effectiveness of early regeneration cuts in 70-year-old beech transitional high forests, with the dual objective of accelerating the coppice-to-high-forest conversion and exploring the potential of small-scale regeneration cuts to enhance stand structural heterogeneity at a broader scale. Specifically, we compared three treatments simulating natural gap dynamics—namely, an establishment cut following the group shelterwood system, small group clear-cuts, and crop tree releases—with the conventional management practice (no gaps) for stands of similar age, i.e., thinning from below. We assessed the impact of each treatment over a 10-year period by examining changes in leaf area index (LAI), total annual increment, seed production, seedling establishment and survival, and evaluated their economic sustainability in terms of costs and net revenue for the forest owner.

2 Materials and methods

2.1 Study area

The study area is located in the provinces of Treviso and Pordenone, located in the Pre-Alps between the Veneto Region and Friuli Venezia Giulia (north-eastern Italy) (Fig. 1A). The average annual temperature is 5.7 °C, with variations ranging from a minimum annual average of 3.6 °C in 1980 to a maximum annual average of 7.6 °C in 1992. The average temperature range is less than 20 °C, giving the climate a strong oceanic influence, which makes the entire area particularly suitable for beech. The annual precipitation totals 1824 mm (1970–2002). Generally, the highest monthly precipitation occurs during the autumn rains. The area is characterized by a calcareous substrate and widespread karst phenomena. In fact, in addition to the absence of surface hydrology, the presence of numerous underground cavities, furrows, sinkholes, caves, and swallow holes is particularly evident.

From a vegetation perspective, forests cover a total of 8974 ha. The most represented forest category is pure beech forest (3856 ha), followed by ash-oak forests and ash-oak-hornbeam forests (2294 ha), particularly along the slopes descending toward the Pordenone plain, where oak forests and chestnut stands are common (1,238 ha).

Within the study area, a total of 217 forest units were considered, covering 6409 ha, of which 3983 ha are forested. Following this analysis, we determined that around 2000 ha were converted from coppice to transitional high forests through thinning-from-below between 1960 and 1999 (Table 1), 685 ha were still managed as coppice, and 1327 ha had always been managed as high forest using a uniform shelterwood system.

2.2 Silvicultural treatments and preliminary dendrometric data collection

Within the large experimental area described above, we selected three representative forest units. All of these units were comparable in terms of species composition, year of conversion to transitional high forest (1977–1981), and number of thinning operations conducted

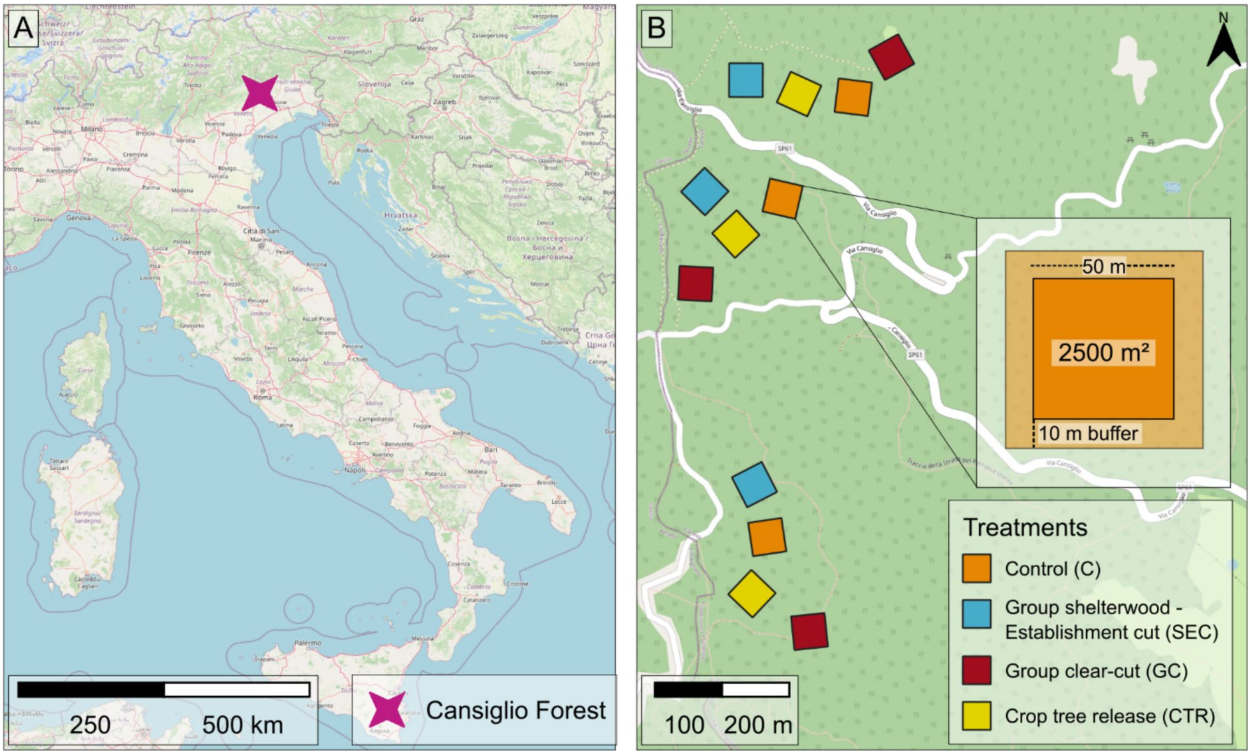

Fig. 1 Location of the study area (**A**) and the experimental plots (**B**) under the four different treatments: Control—thinning from below (C), Group shelterwood system—establishment cut (SEC), Group clear-cut (GC) and Crop tree release (CTR). Each plot was 50×50 m with a buffer of approximately 10 m. Source of the maps: OpenStreetMap contributors

Table 1 Area covered by the different forest categories and management models in the study area. For transitional high forests, the period of the first thinning (conversion) is reported

Beech pure forest	Transitional high forest	Period when the first thinning occurred (conversion)	Area (ha)
		1960–1969	520
		1970–1979	313
		1980–1989	715
		1990–1999	284
		2000–2009	70
		Not known	65
	Coppice		685
	High forest		1327
Other categories	**Conifer plantations**		658
	Not forested area		1772

since conversion (with the last thinning carried out in 1997). Additionally, the selected units were scheduled for harvesting during the 2011–2012 period. In each unit, four 50×50 m experimental plots were identified (12 in total; Fig. 1B). All stands resembled a single-layer, even-aged pure beech forest, with occasional presence of Norway spruce (*Picea abies* K.) and full canopy cover. Each unit was considered as a block consisting of four experimental plots assigned to one of the following silvicultural treatments:

i. Control (C): the conventional thinning-from-below was applied.
ii. Group shelterwood system—establishment cut (SEC) aimed to remove suppressed trees and some co-dominants, with the goal of leaving high-quality

individuals evenly distributed across the treatment area. These trees were selected to produce seed and thus facilitate regeneration.

iii. Group clear-cut (GC) involved creating a circular opening with a diameter equal to the average height of the dominant trees, within which all trees were removed. The goal was to facilitate regeneration while structuring the stand in small groups.

iv. Crop tree release (CTR) focused on 5–6 target trees of high commercial value per plot, regardless of the social position of the removed trees or the establishment of regeneration (Wolynski 2002) and their direct competitors were removed.

All trees within each plot with a diameter at breast height (DBH) above 7.5 cm were numbered, their species identified, and DBH measured. Total tree height was measured for a representative sample of trees in each plot (at least 33 trees per plot) to construct the corresponding height–diameter curve.

Standing tree volume (m^3 ha^{-1}) before and after treatments' application was calculated using a specific allometric equation derived from the actual volume measurements of 49 harvested trees, distributed across different diameter classes, and applying Heyer's formula (Marchi et al. 2024).

Leaf area index (LAI; m^2 m^{-2}) was measured in summer both the year before and the year after the harvest using an LAI-2200c Plant Canopy Analyzer (LICOR, Nebraska, USA). Measurements were taken along a regular 5 × 5 m grid within each plot.

The selection of trees to cut was made in August 2011, and the harvesting occurred during the winter of the same year. Each treatment was also applied outside of each study plot, extending 8–10 m to establish a buffer zone and minimize the edge effect.

Standing tree diameters were also remeasured in 2023 to calculate the total annual increment (I_V; m^3 ha^{-1} $year^{-1}$) for each silvicultural treatment, using the following equation:

$$I_V = \frac{V_{2023} - V_{2012}}{2023 - 2012}$$

where V_{2012} and V_{2023} represent the tree standing volume after the harvest in 2012 and 11 years later in 2023 (m^3ha^{-1}).

Similarly, the mean annual increment in tree diameter (I_D; cm $year^{-1}$) was also calculated:

$$I_D = \frac{D_{\mathrm{mean}2023} - D_{\mathrm{mean}2012}}{2023 - 2012}$$

where $D_{\mathrm{mean}2012}$ is the mean diameter (cm) in 2012 after the execution of the intervention and $D_{\mathrm{mean}2023}$ represents the mean diameter (cm) in 2023, 11 years after.

2.3 Evaluation of the regeneration process

Annual seed production in each plot was monitored from 2011 (prior to the harvest) to 2016 using nine circular seed traps (diameter = 45 cm) arranged along a regular 10 × 10 m grid, with a 5-m buffer from the edge. In the SEC plots, nine additional traps were placed to more effectively capture the dissemination process within the opening. These traps were positioned on three concentric circles within the harvested area. Seed production was compared with data from a chronosequence in the nearby Cansiglio high forest, established by de Simon et al. (2012), where similar seed traps have been monitored annually from 2011 to 2023 across five different age classes (42, 61, 74, 143, and 163 years old; three replicates per class).

Saplings densities (n m^{-2}) and heights (cm) were measured in October 2022 within 1 m^2 subplots arranged along a 10 × 10 m grid. Subplots located at the plot boundaries were excluded from the measurements. A total of 16 subplots per plot were sampled.

2.4 Cost and net revenue evaluation

The harvested volume was quantified through the same allometric equation built using harvested trees. Working times and hourly productivities were measured following the methodology proposed by (Berti et al. 1989), considering the following working phases:

1) Tree felling: the net felling time for each tree was measured (from the moment the directional notch was made to the moment the tree fell). Dead times (e.g., chainsaw maintenance, refueling, breaks, etc.) and the time required for the operator to move between trees were recorded separately. Times were measured in minutes and seconds (mm:ss). The standard team consisted of two workers equipped with medium and medium-light chainsaws.
2) Delimbing, debarking and bucking: the net time required to prepare each tree on the felling bed was measured, with separate timings for delimbing, debarking, and bucking, as well as for dead time. During this phase, the time required to create the bundles (loading the logs into the basket, binding the bundle, and trimming the logs) was also measured. The standard team consisted of two workers equipped with medium and medium-light chainsaws.
3) Skidding phase: the times for the tractor's round trip from the study plot to the landing, as well as the loading and unloading of the material and dead times,

were recorded. During this phase, the standard team consisted of two workers and a tractor operator.

The total cost of each harvesting operation was calculated by multiplying the labor and equipment costs (Table 2) by the hourly productivity and the net mass of the harvested wood. Additional costs, including general expenses (10%), business profit (10%), and a contingency fund (2%), were also factored in. The results for each treatment were presented as the mean per plot ± standard error ($n = 3$).

The total value of the different assortments was calculated by multiplying the total volume of wood harvested by the respective prices for each tree species: 66.07 € m^{-3} for beech and other broadleaves as firewood, and 60 € m^{-3} for spruce assortments.

The net revenue (€ ha^{-1}) was calculated as the difference of total value of assortments and the total cost for harvesting operation. This value was finally divided by the harvested volume (m^3 ha^{-1}) to get the net wood revenue (€ m^{-3}).

2.5 Data analysis

One-way ANOVA was used to analyze the following: (i) the differences between tree density, basal area, wood volume, LAI, and seed production across treatments; (ii) the tree removal effects by comparing the number, basal area, and volume of removed trees; (iii) the differences in increment between treatments; to assess differences in felling, limbing, bucking, skidding times, and felling sub-operations (actual felling, transition time, and downtime) across treatments; (iv) the total harvesting times, costs, and net revenue. The Shapiro–Wilk test was performed to check the normality of residuals from the ANOVA. Post hoc Tukey HSD tests were performed to identify pairwise differences.

A two-way ANOVA was used to evaluate the effects of treatment, year, and their interaction (treatment × year) on LAI before and after tree removal. The percentage difference in LAI between 2011 and 2012 was calculated using kriged raster data through the R package *gstat* (Pebesma 2004), retaining only positive values to avoid measurement errors (e.g., slight relocation or direct sunlight exposure after treatment). For each plot, we computed the relative change using the formula:

$$\Delta \mathrm{LAI} = \frac{\mathrm{LAI}_{2012} - \mathrm{LAI}_{2011}}{\mathrm{LAI}_{2011}} \times 100$$

We used the Kruskal–Wallis test to determine if there were any differences in seed density among treatments and the differences in sapling density and sapling height. As a post hoc analysis, we applied the Wilcoxon rank-sum test or the Dunn's post hoc test for pairwise comparisons. We performed data visualisation using the R package *ggplot2* (Wickham 2016). All statistical analyses were conducted using R version 4.4.0 (R Core Team 2024) paired with RStudio version 2024.12.0 (Posit team 2024).

3 Results

3.1 Stand and treatment characteristics

The forest stands selected for this study were characterized, before treatments' application, by high homogeneity both in terms of species composition and main dendrometric characteristics. In fact, the analysis of variance (ANOVA; Table 3) did not show any statistically significant difference ($p > 0.05$) between the treatments or between the blocks (plots) in terms of total density (n ha^{-1}), basal area (m^2 ha^{-1}), and wood volume (m^3 ha^{-1}). Similarly, no significant difference was determined in the species composition, although the experimental areas intended for the shelterwood—establishment cut showed a higher presence of Norway spruce (data not shown). On average, the examined stands had a density of 673 trees ha^{-1}, a basal area of 30.2 m^2 ha^{-1}, an average DBH of 24 cm, and a standing volume of 417 m^3 ha^{-1}.

Similarly, no significant difference was found in terms of LAI, either between the treatments or between the

Table 2 Unit costs of labour and equipment (Euro $hour^{-1}$). Source: National Collective Labour Contract 2023

Cost item	Number of workers or equipment	Type of workers or equipment	Unit cost (Euro $hour^{-1}$)
Felling team	2	Highly qualified worker	23.98
Delimbing, debarking and bucking team	2	Highly qualified worker	23.98
Skidding team	2	1 highly qualified + 1 not qualified workers	21.72
	1	Tractor driver (highly qualified worker)	11.99
Equipment	2	Medium and medium-light chainsaw	3.41
	1	Agricultural tractor with forestry equipment	32.50

Table 3 Forest stands prior to the implementation of the treatments and their stand characteristics: number of trees per ha, basal area per ha, wood volume per ha, mean diameter, mean height, and leaf area index (LAI). No difference was detected among the treatments (ANOVA, $p > 0.05$). Data are presented as mean ± standard error

Treatment	N trees [n ha^{-1}]	Basal area [m^2 ha^{-1}]	Volume [m^3 ha^{-1}]	Mean diamater [cm]	Mean height [m]	LAI [m^2 m^{-2}]
Control	661 ± 57	29.9 ± 1.3	384 ± 34	24 ± 0.9	20 ± 0.9	4.9 ± 0.4
Group shelterwood—Establishment cut	688 ± 68	31.9 ± 2.4	487 ± 73	24 ± 0.7	21 ± 0.9	5.0 ± 0.4
Group clear-cut	620 ± 94	29.6 ± 1.7	423 ± 50	25 ± 1.3	21 ± 0.9	4.7 ± 0.5
Crop tree release	723 ± 110	29.6 ± 1.7	372 ± 88	23 ± 2.2	20 ± 3.6	4.9 ± 0.4

blocks ($p > 0.05$). However, although there was no significant difference in the average values between the different treatments before harvesting, the distribution of LAI within each plot was not uniform. In fact, there was a clear presence of trees with expanded crowns (likely old standards), which resulted in particularly high LAI values in certain specific spots. Conversely, there were zones characterized by local and small gaps in the canopy, which led to a decrease in this index.

Significant differences were observed in the number of trees removed, basal area, and volume removed between the control and the shelterwood—establishment cut treatments. In contrast, the group clear-cut and crop tree release treatments were the most similar, showing no significant differences in the removal of trees per ha, basal area, or volume removed (Table 4; Fig. 2). The thinning from below (control) removed 27% of the basal area, the establishment cut 50%, while the crop tree release and the group clear-cut resulted in lower basal area removals (13% and 19%, respectively).

Regarding the DBH distribution, all the stands exhibited a normal distribution typical of even-aged, single-story stands before the interventions were carried out. The control mainly affected the smaller DBH classes ($d < 25$ cm), while the establishment cut eliminated all trees below 20 cm in DBH and some trees with diameters greater than 45 cm, mostly represented by Norway spruce trees that were artificially introduced in the past (Fig. 2). The group clear-cut and the crop tree release, on the other hand, affected a broader range of DBH classes.

A significant difference was found in LAI values after tree removal for treatment ($p < 0.001$), year ($p < 0.001$), and treatment × year ($p = 0.001$). Specifically, all treatments resulted in a significant reduction in LAI: control treatment caused a 40% reduction in LAI, establishment cut caused a 60% reduction, while group clear-cut and crop tree release reduced LAI by 35% and 34%, respectively. From the perspective of LAI distribution within the individual study plot after the harvest (Fig. 3), establishment cut strongly homogenized the LAI (1.8 ± 0.05 m^2 m^{-2}), while group clear-cut resulted in a noticeable decrease in the LAI only in the central part of the area, i.e., the part affected by the cut (mean LAI = 3.5 ± 0.1 m^2 m^{-2}). The crop tree release led to the release of selected individual trees, which maintained LAI values above 4 m^2 m^{-2} only locally (mean LAI = 3.8 ± 0.06 m^2 m^{-2}). In the control, the LAI distribution was more heterogeneous (mean LAI = 2.9 ± 0.05 m^2 m^{-2}), with areas exhibiting higher leaf cover compared to others.

When analysing volume increment per ha (I_V), no significant difference was found across the treatments ($p > 0.05$): 7.3, 6.8, 6.6, 7.9 m^3 ha^{-1} year^{-1} for the control, shelterwood—establishment cut, group clear-cut and crop tree release, respectively. However, when considering the diameter increment (I_D) of trees after the treatment application, the shelterwood—establishment cut showed a significantly higher increment compared to

Table 4 Number of trees, basal area, and volume extracted from the forest stands under different treatments. Significant differences are indicated by different lowercase letters. Data are presented as mean ± standard error

Treatment	N trees [n ha^{-1}]	Basal area [m^2 ha^{-1}]	Volume [m^3 ha^{-1}]
Control	295 ± 14 a	8.0 ± 0.2 a	101 ± 7 a
Group shelterwood—establishment cut	469 ± 35 b	15.9 ± 1.1 b	239 ± 25 b
Group clear-cut	120 ± 12 c	5.6 ± 0.1 c	76 ± 8 a
Crop tree release	100 ± 17 c	3.9 ± 0.7 c	49 ± 12 a

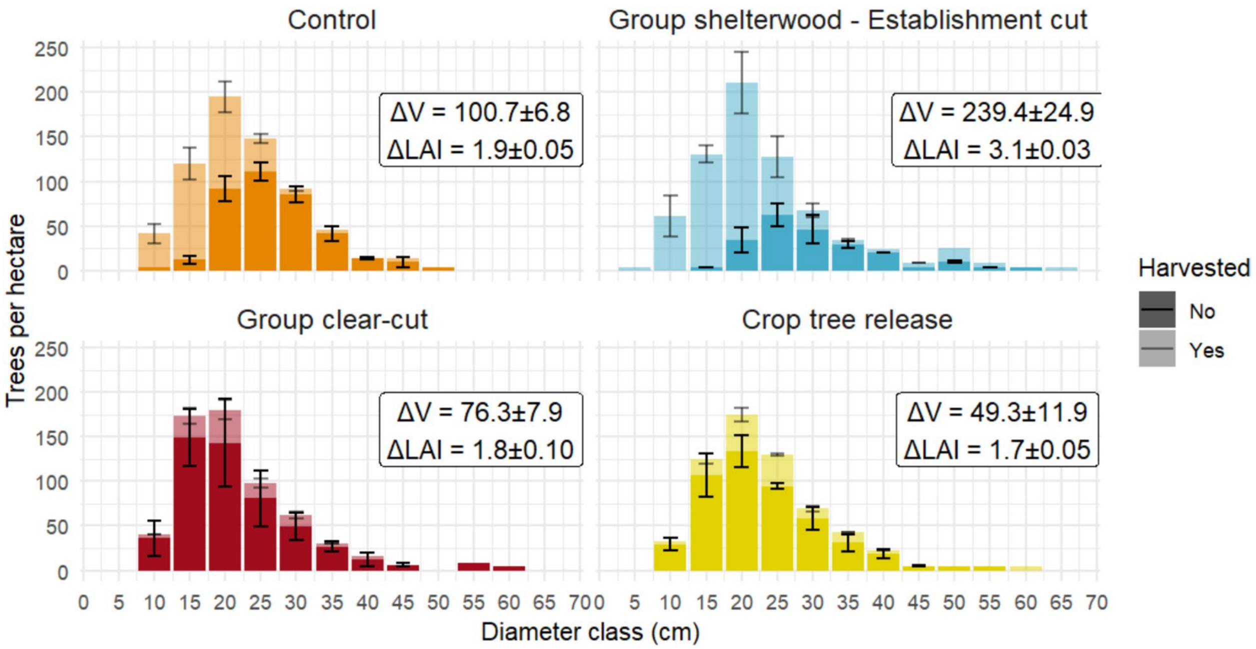

Fig. 2 Diameter distribution by treatment before and after treatment implementation. Solid colors represent retained trees, while transparent colors denote removed trees. Vertical bars indicate standard error

the other treatments ($p < 0.01$). After the tree removal in control plots, I_D was 0.30 cm year^{-1}; in SEC, it was 0.47 cm year^{-1}; and in clear-cut and crop tree release, it was 0.24 cm year^{-1}.

3.2 Regeneration process

Before treatment application (2011), a total of 68 beech seeds m^{-2} (61 g m^{-2}) were produced within the study areas. In 2012, no beech seeds were collected in any of the traps, except in one of the plots treated with crop tree release where, on average, 0.4 seeds m^{-2} were produced (0.26 g m^{-2}). When compared to the different developmental stages of the nearby Cansiglio high forest, the study areas showed production levels that were in line with those of a mature stand (77 years old; Fig. 4). In 2013, seed production in all plots was significantly higher than in 2011, followed by 2 years of almost no production, before increasing again in 2016. The seed production differed significantly between the treatments ($p < 0.05$), with the control having the highest production. Group clear-cut resulted in significantly lower production compared to control ($p < 0.01$) and crop tree release ($p < 0.05$). Examining the long-term dynamics of seed production in the nearby Cansiglio high forest (Fig. 4), the pattern was identical: 2011, 2013, 2016, and 2020 were clear mast years, while the others were "rest" years with no seed production; 2013 saw the highest production in the entire series. In the Cansiglio chronosequence, while no seed production was recorded in the pole stand, the highest production was always measured in the mature stand (147 years old) and in the stand after the establishment cut (167 years old).

Ten years after the treatment application (2022), the highest seedling density was recorded in the establishment cut (12.0 ± 1.8 plants m^{-2}; Fig. 5A), followed by the control and group clear-cut (7.3 ± 1.8 plants m^{-2} and 5.6 ± 1.9 plants m^{-2}, respectively). The crop tree release showed the lowest seedling density (3.4 ± 0.9 plants m^{-2}). While seedlings were evenly distributed in the establishment cut treated plots, they were most abundant along the edges of the small clear cut (particularly along the south-facing edge) and in the variable intensity thinning in areas where the canopy cover was interrupted. Similarly to density, seedling height was greatest in the establishment cut (93 ± 7 cm), followed by the group clear-cut and control (48 ± 11 cm and 34 ± 1 cm, respectively; Fig. 5B). Once again, the crop tree release displayed the lowest value (25 ± 3 cm).

3.3 Cost and net revenue evaluation

An exponential correlation between DBH and net felling time was observed (Fig. 6 in the Appendix). This enabled the precise recalculation of the felling time for each tree based on its actual DBH. Although establishment cut and group clear-cut treatments showed lower felling, limbing, bucking, and skidding times (minutes m^{-3}; Fig. 7A) compared to the other treatments, these differences were not statistically significant ($p > 0.05$). Similarly, no significant

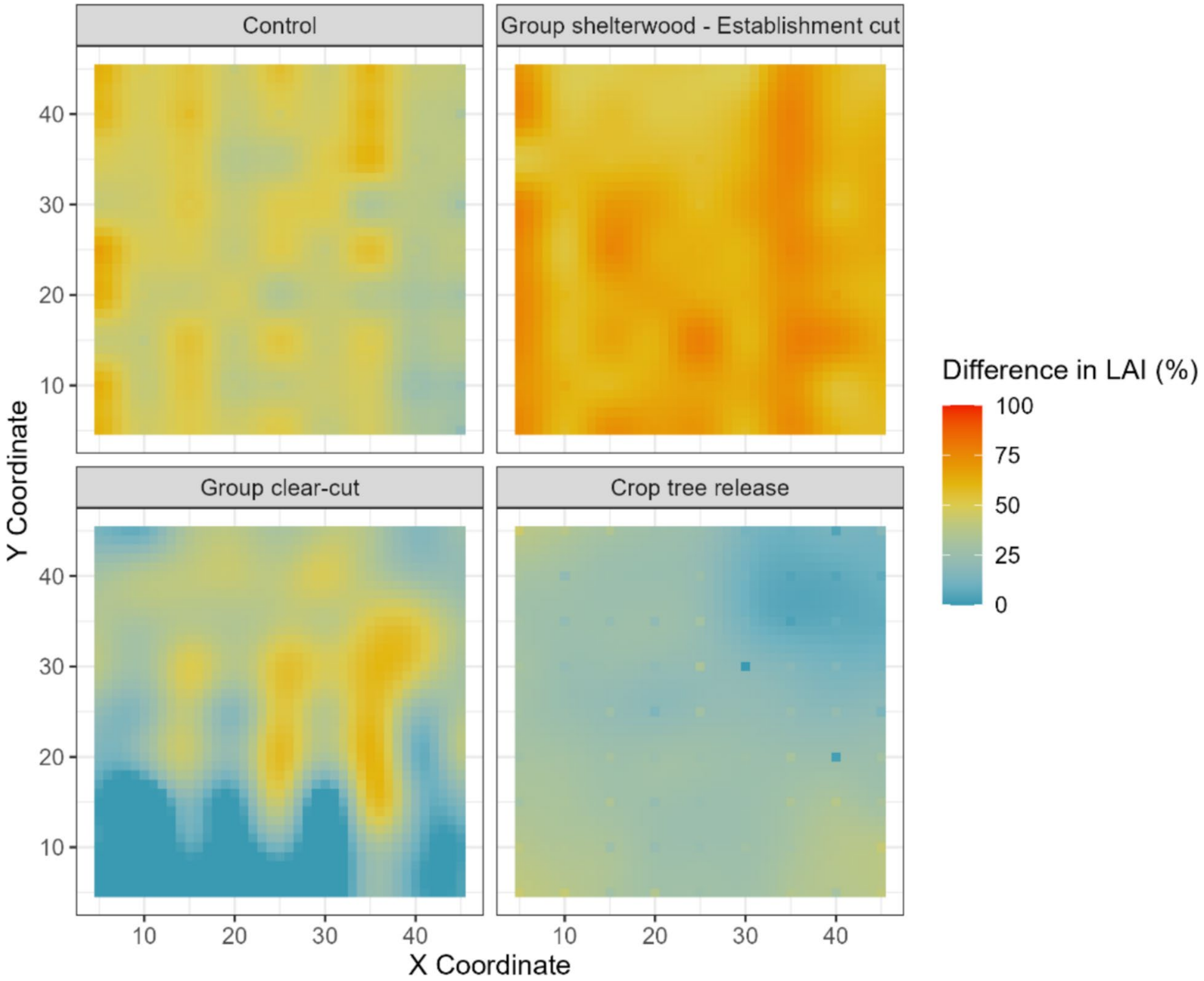

Fig. 3 The relative difference in leaf area index (LAI) is visualized using a color gradient, where darker shades of warmer colour represent higher percentage losses in leaf area. The spatial distribution of LAI differences varied across treatments, reflecting the distinct impacts of the silvicultural interventions on leaf area

differences were observed among the suboperations of felling, such as actual felling, transition time, and downtime ($p > 0.05$; Fig. 7B), even though the control and crop tree release had higher transition times between trees due to their scattered and random distribution within each plot.

When expressed per ha, total harvesting times (hours ha $^{-1}$) and associated total costs (€ ha $^{-1}$) were significantly higher for the control and establishment cut treatments compared to the other two treatments. Net revenue was positive for all treatments considered, with the establishment cut showing the highest net revenue (€ ha^{-1}) compared to the other three treatments ($p < 0.01$; Fig. 8). However, these differences disappeared when recalculating the total value as net wood revenue ($p > 0.05$): 25.6, 26.1, 26.5, 25.6 € m^{-3} for control, establishment cut, group clear-cut, and crop tree release, respectively.

4 Discussion

As the forest stands considered were approximately 70 years old prior to treatment, their basal area and standing volume aligned with the silvicultural model proposed by (Del Favero 1992) for the nearby Cansiglio high forest, but were higher than those reported for beech transitional high forests in the region (Bortoli and Vanone 1983). In our experiment, the thinning from below removed 27% of the basal area, slightly exceeding the typical thinning percentage for high beech forests of the same age (i.e., 18–21%; (Del Favero et al. 1998).

Fig. 4 Beech nuts production in different developmental stages of the nearby Cansiglio high forest from 2011 to 2024. The inset shows the seed production in 2013 at our study areas after execution of the four different treatments (2013)

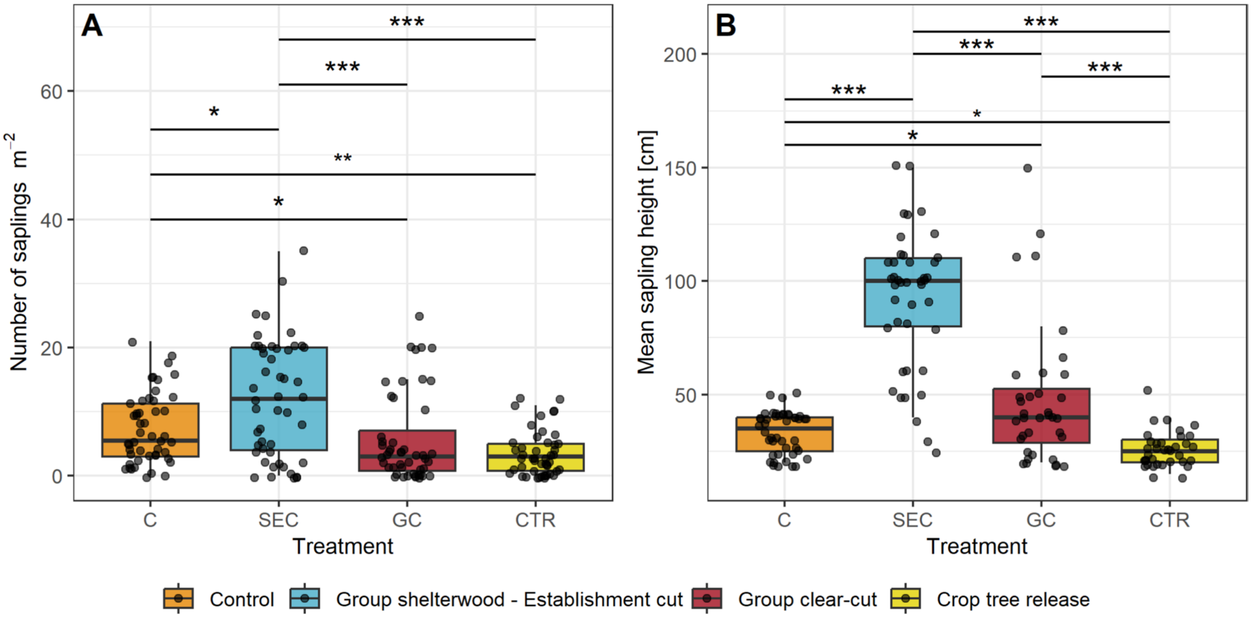

Fig. 5 Tree regeneration was measured ten years after the application of different treatments: number of saplings (n m^{-2}; **A**) and mean sapling height (cm; **B**). The different significance levels are reported as follows: $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

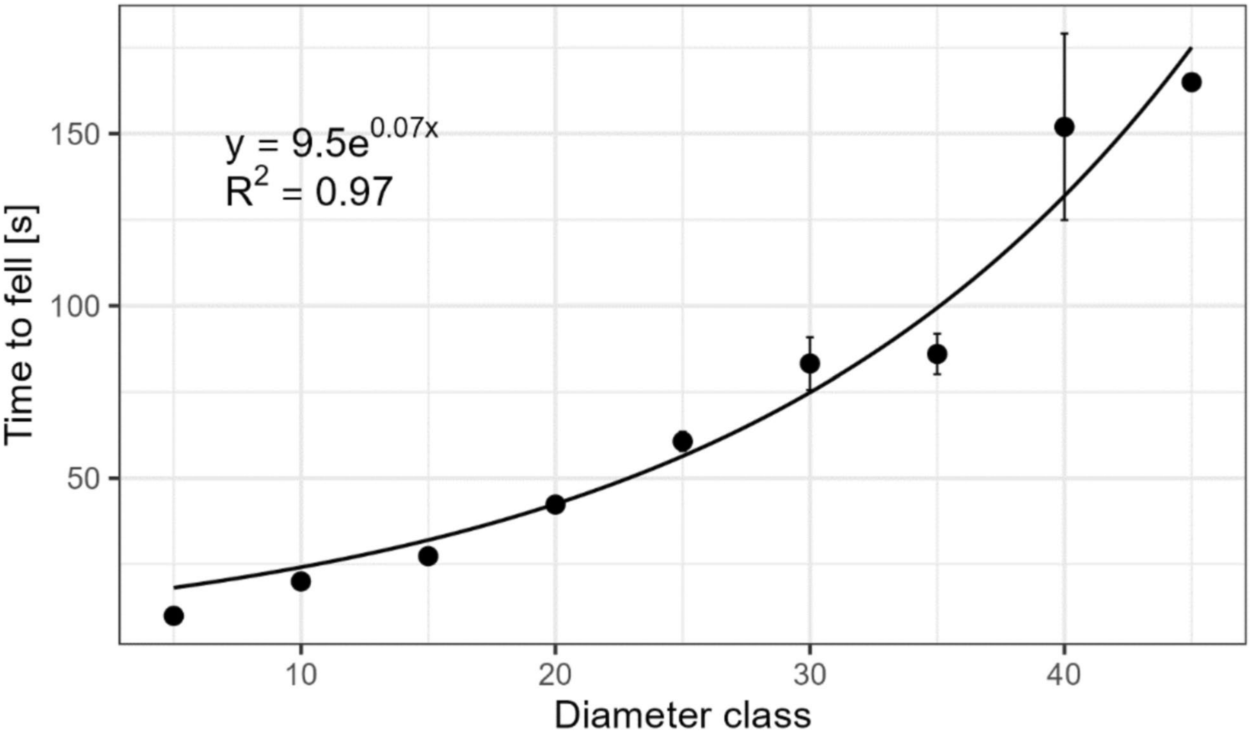

Fig. 6 Exponential relationship between diameter class and felling time (in seconds) for beech. Each point represents the mean time with standard error

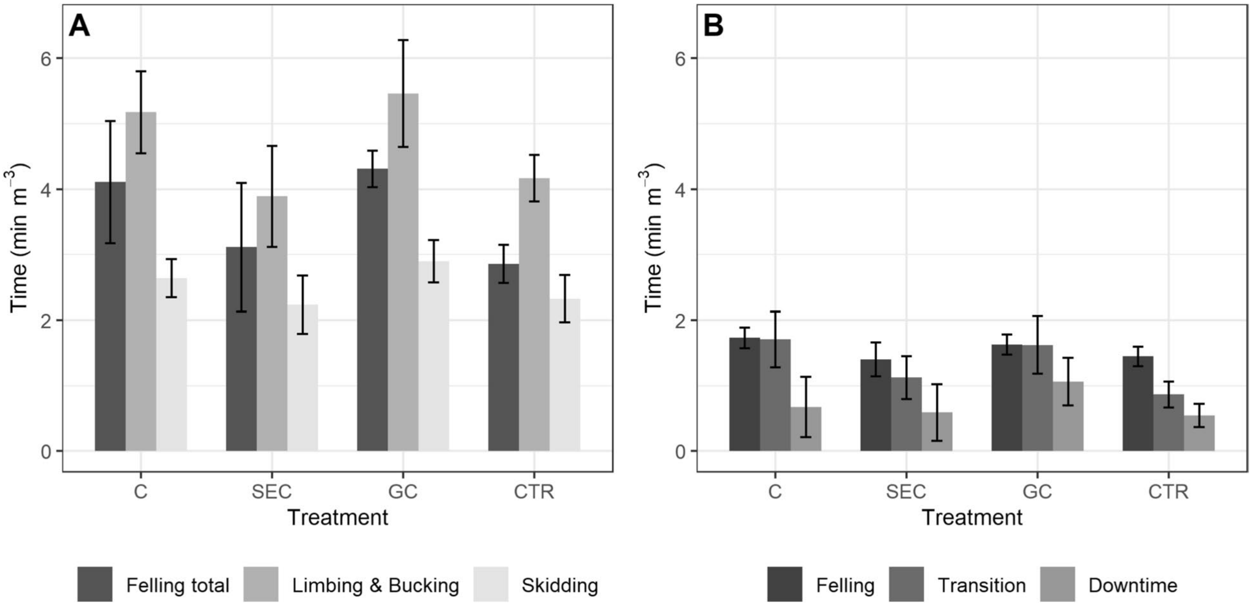

Fig. 7 Time of different harvesting operations, including felling, limbing and bucking, and skidding (**A**) and felling suboperations, such as actual felling, transition time, and downtime (**B**) per treatment. The error bars show the standard error

Similarly, the establishment cut in the group shelterwood system was somewhat more intensive than usually expected for mature high forest stands (50% compared to 40%). This difference was justified by two factors: (i) to release the older trees with larger crowns, which, due to their advanced age, are expected to produce the seed

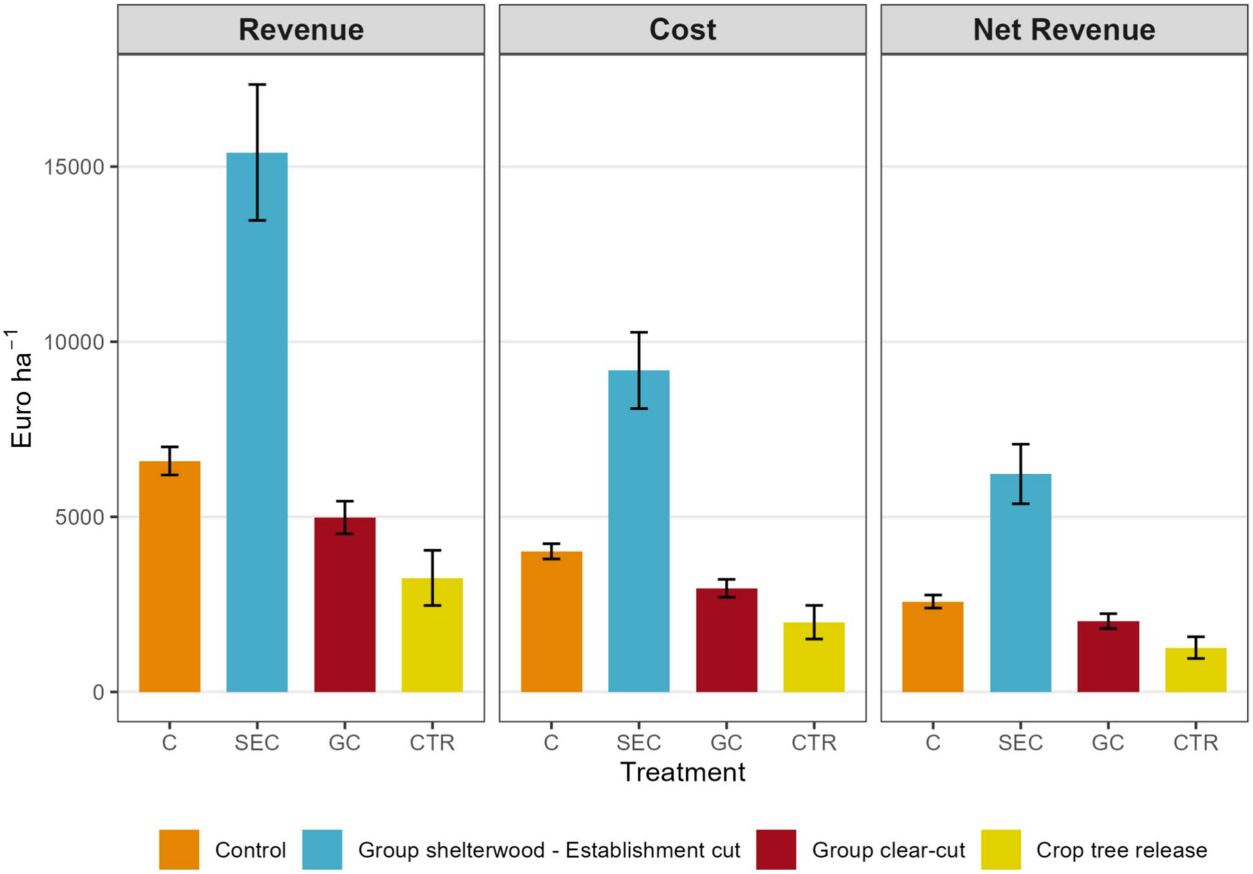

Fig. 8 Revenue, cost, and net revenue per treatment. The error bars indicate the standard errors ($n=3$)

necessary for regeneration; and (ii) to release the younger trees with narrower crowns, allowing them to develop quickly and eventually start producing seeds as well.

No significant differences were observed in LAI before the treatment, with an average value of 4.9 ± 0.01 $m^2\ m^{-2}$. Canopy cover assessment is crucial for the regeneration process, as the ability of juvenile trees to adjust their morphological and architectural traits to varying light conditions is a key species-specific characteristic (Messier et al. 1999). Although literature on the relationship between light availability and natural regeneration in beech forests is sometimes conflicting, beech is often described in silvicultural texts as a shade-tolerant species (Bernetti 1998), with light requirements that vary depending on its age (Huss and Burschel 1972). The germination process of beech seeds can occur even under low light conditions, but light intensity can influence the development of the embryonic structures. (Fratello et al. 1994) found no natural regeneration older than 2 years when the LAI was around or above 4.5 $m^2\ m^{-2}$, and the radiation level at the forest floor was only 1–2% of full sunlight during midday. In beech forests at Abetone (Tuscany, Italy), (Bagnaresi and Pinzauti, 1995) observed regeneration when midday radiation values were no lower than 6–10% of full sunlight. However, well-established regeneration with satisfactory growth and orthotropic development was only found under radiative conditions close to full sunlight, such as in clearings or near forest edges. Once the early growth stages are overcome, well-established regeneration appears to show greater shade tolerance. In fact, even under considerable canopy cover, this regeneration maintains significant vitality (Bagnaresi and Pinzauti, 1995). It is also important to note that light conditions can influence the growth and morphology of young seedlings. In a comparative study of different tree species, (Petritan et al. 2009) showed that as light levels increased, ash and maple consistently outperformed other species in terms of length growth, while beech reached an asymptotic growth value at light levels above 35%. The same authors reported that under light conditions below about 25% of the above-canopy light, beech exhibited relatively high levels of plagiotropic growth. On the other hand, other studies have found that beech regeneration in full sunlight often produces malformed stems, compared to those grown under partial shade (Le Tacon 1983; Dupré et al. 1986). In our study, all treatments led to a significant reduction in LAI, falling below the 4.5 m^2 m^{-2} threshold (Fratello et al. 1994), particularly with the establishment cut in the group shelterwood system. However, the LAI distribution within the individual study plot after harvest varied depending on the treatment, with the establishment cut leading to a significant homogenization of the LAI across the plot. From a practical perspective, these observations support the idea that regeneration should begin with a relatively dense shelterwood, providing 5–10% above-canopy light at the forest floor. This should be followed by a gradual canopy opening, primarily through the expansion of tree groups, to ensure adequate light for necessary height growth.

In terms of growth response, no significant difference was detected in mean annual volume increment (m^3 ha^{-1} $year^{-1}$) among the treatments. In contrast, when the increment was assessed based on changes in mean diameter, a significantly higher increment was observed following the shelterwood— establishment cut treatment. This treatment more effectively stimulated the residual trees, resulting in a pronounced increase in diameter growth, which is a typical response to shelterwood cuts (Holgén et al. 2010). Higher-intensity treatments can also stimulate growth in beech stands (Andrej et al. 2007; Barna et al. 2010).

Regarding seed production, many species, including beech, exhibit a discontinuous seed production cycle that occurs in certain years known as mast years (Kelly and Sork 2002; Pearse et al. 2016). Understanding the frequency of these years is crucial for planning regeneration cuts and ensuring adequate seed production. The oldest and simplest hypothesis for masting suggests that seed production fluctuates in response to variations in weather (Bugsen 1929; Kelly 1994). A mast year is typically preceded by specific climatic conditions (Drobyshev et al. 2014; Vacchiano et al. 2017): cold, wet summer 2 years prior, followed by a dry, warm summer the year before, and finally, a warm spring during the beech mast year itself (Nussbaumer et al. 2018). (Matthews 1955) was the first to propose the biennial mast cycle of European beech, and recent research confirms this hypothesis (e.g., (Gavranović Markić et al. 2024) or for Central Europe by (Nussbaumer et al. 2016)). Our observations in the Cansiglio high forests and in our experimental plots indicated a masting frequency of every 2–3 years, with an exceptional production recorded in 2013, one year after the treatment was applied. However, no mast years have been observed since 2020, likely due to the exceptionally hot and dry summers recently recorded. This finding aligns with (Foest et al. 2024), who reported a general increase in maximum temperatures during June and July across much of the species' range, along with a widespread decline in beech masting across Europe. The temporary high forests studied here showed seed production comparable to that of mature stands (77 years old) in the nearby Cansiglio high forest, although it was much lower than that of older mature stands (147 years old) and stands after establishment cutting (167 years old). Some significant differences were observed among treatments, with group clear-cut having the lowest seed production.

The high seed production recorded in 2013, coupled with the reduced canopy cover in the group shelterwood system treated plots (establishment cut), resulted in high seedling density and sufficient height ten years later, making the seedlings well-established and ready for the final removal of the previous tree generation. The high density of bramble observed in all plots following the group clear-cut treatment (data not shown) may explain the lower seedling density, as it competes intensely with beech seedlings for light and nutrients. This, along with the heavy weight of beech seeds (gravity dispersal), may also explain the greater seedling abundance along the edges of the group clear-cut. Furthermore, the highest LAI in the crop tree release treatment could account for the lower seedling density observed in this plot.

The cost-effectiveness of forest interventions, particularly thinnings from below, is not always assured (Arnič et al. 2021). This is mainly due to rising labor costs and the fact that most of the assortments produced lack sawlog value, being suitable only for firewood, with no established market for pulpwood or wood chips. While all the applied treatments were profitable, significant differences were observed only in terms of total net revenue (€ ha^{-1}), indicating that variations in economic outcomes can be attributed primarily to differences in harvested volumes rather than harvesting times and associated total costs. In fact, when comparing total net revenue to net wood revenue (€ m^{-3}), the differences among treatments were eliminated. The measured harvesting costs (25.6 € m^{-3}) for the control—thinning from below method—were slightly higher than those reported by (Latterini et al. 2022), whereas the harvesting costs for the crop tree release were more in line with those reported by these authors.

5 Conclusion

This study highlights the potential of earlier regeneration interventions as a viable management strategy for aging coppice-origin beech forests. Over a relatively short period of 10 years, we observed promising ecological responses and practical outcomes that address broader concerns about long-term forest sustainability in the face of environmental and socio-economic change. Our results underscore the value of integrating regeneration cuts into forest planning before the traditionally applied rotation ages. By carefully applying group shelterwood cuts, forest managers can begin to reintroduce spatial diversity and dynamic structure into otherwise homogeneous stands. This approach not only facilitates regeneration but also opens opportunities to gradually reshape forest composition and stand structure in a way that enhances ecological resilience. Beyond stand-level regeneration success, our findings point toward a broader management philosophy: small-scale, adaptive interventions can serve multiple objectives without compromising forest continuity or social values. The flexibility of this method makes it suitable for landscapes where legacy management has produced structurally uniform stands, such as those prevalent across parts of the Alps and Apennines.

While we did not directly measure landscape-scale diversity outcomes, the spatial design of treatments and the potential for staggered implementation offer a practical pathway for enhancing heterogeneity across time and space. This aligns with emerging principles of forest management that emphasize resilience, multifunctionality, and stakeholder engagement.

Overall, the evidence supports a shift toward proactive, fine-scale regeneration strategies that balance ecological processes with economic and social considerations. As forest systems continue to face mounting pressures, such integrated approaches will be essential for ensuring long-term viability and public support for forest management practices.

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Authors' contributions
NP performed the statistical analysis, cured the data, visualized the data and wrote the manuscript. AT performed the analysis and wrote the manuscript. PP conceptualised the research, defined the methodology and supervised the fieldwork. GA conceptualised the research, defined the methodology, cured the data, supervised the fieldwork, wrote the manuscript and obtained the research funding.

Data availability
Piazza N, Tomao A, Piussi P, Alberti G. (2025).Anticipated regeneration cuts in transitional high forests of beech [Data set]. . Zenodo. https://doi.org/10.5281/zenodo.16995563

Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Agricultural, Food, Environmental and Animal Sciences, University of Udine, Udine, Italy. [2]Department of Agricultural, Food, Environmental and Forestry Sciences and Technologies, University of Florence, Florence, Italy.

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