



Effect of an Innovative Thinning Method on the Mechanical Stability of an Artificial Black Pine (*Pinus nigra* Arn.) Stand: The Case Study of Pratomagno, Tuscany, Italy

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Abstract

Reforested and afforested areas play a key role in providing ecosystem services, contributing to the socio-economic well-being of societies. Among the forest species used for the reforestation and afforestation, black pine is one of them, and Italy is among the areas where this species has been chosen. This study aims to investigate the mechanical stability of an artificial black pine forest approximately 10 years after two different types of thinning (selective and from below). To achieve this objective, the slenderness ratio was chosen as stability parameter, as it is well suited due to its practicality of calculation and the presence of threshold values in the literature. What emerges from the study is that the slenderness ratio shows no statistically significant difference between the different thinning techniques. This lack of difference could be due to a windthrow that occurred in 2017, which acted as a “natural” thinning agent. Future research should focus on understanding the right time interval between one thinning operation and the next, also considering other aspects, such as the profitability of the timber removed during the operations and other ecosystem services, such as soil protection.

Keywords Artificial black pine forest stands · Windthrow · Slenderness ratio · Selective thinning · Ecosystem services

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Introduction

Forests provide to the people invaluable products and ecosystems services (Díaz et al. 2018), such as food, medicine, building materials, fibre, shade, recreational space, pollution filtration and flood risk reduction, and they are essential reservoirs of carbon, water and nutrients (Di Sacco et al. 2021). Historically and in the present, such ecosystem services are threatened by human activity and the intensifying effects of climate change (CC), caused by the increase of greenhouse gases. In this sense, the Intergovernmental Panel on C C highlights afforestation and reforestation as a land-based greenhouse gas mitigation strategy to limit global warming to 1.5–2 °C above preindustrial levels (Roy et al. 2018; Law et al. 2018; Arneth et al. 2019). If this strategy can act counter the CC, it is important to highlight that the planted forests, such as those established through afforestation and reforestation, are affected by global warming. In this regards, direct and indirect biophysical effects of CC will pose challenges to reforested areas in the future (Nolan et al. 2018). Specifically, maximum and minimum temperatures are expected to rise in most regions of the world, with a projected global average warming at the end of the XXI century ranging between 1.1 and 6.4 °C (Stocker 2014). According to the same author, all climate models predict variations also in global mean precipitation, with an increase in the tropical and higher latitude regions and decreases in the subtropical and mid-latitude areas. With CC extreme weather events will become more frequent and intense (Gahlawat and Lakra 2020; Marchie et al. 2018; Seneviratne et al. 2021). Extreme weather events can be defined as atmospheric phenomena that significantly differ from normal conditions in terms of intensity, duration or frequency, exceeding statistical thresholds or values considered typical for a given location and period. Examples include heat waves, floods, droughts, violent storms, tornadoes, whirlwinds and fires (Sura 2011; Radović and Iglesias 2020). The extreme climate events and their associated disturbances play a crucial role in fine scale patterning of species distribution (Reyer et al. 2013), and this can have an important influence on the long-term survival of reforested areas (Nolan et al. 2018).

In this context, it is very important to have a thorough understanding of good practices and planning strategies that can contribute to the creation and maintenance of afforested and reforested areas which have, at the same time, CC mitigation capacities and resilience characteristics towards the effects of global warming. To improve the management of new and existing afforestation and reforestation interventions, it might be useful to study degraded areas that have been reforested and managed with different strategies over the past century (Löf et al. 2019). In Europe, black pine (*Pinus nigra* Arn.) is a typical tree species used for these interventions. In fact, in accordance with Bussotti (2002), this species is commonly planted for protection purposes in Central Europe, the Balkans and Mediterranean countries. The use of black pine of the Karst region above the Gulf of Trieste from the mid XX century represents one of the first successful examples of forest restoration in barren land exposed to drought and strong winds (Kranjc 2009). In central and southern Italy, this species has been used to reforest mountains degraded by intensive use of natural resources, especially during the first and second World War (Cantiani and Chiavetta 2015). The reforestation started in the XX century at national level for limit the soil erosion (Piermattei

et al. 2012) and facilitate the natural succession toward mixed forest stands with a greater proportion of deciduous species (Cantiani et al. 2009). The commercial use of these forests was not considered relevant (Cantiani and Chiavetta 2015). Toward the end of 1970s, the mandatory requirement to reforest these areas with coniferous species was discontinued (Cantiani and Chiavetta 2015). According to the latest available data, in 2015 the area containing black pine forest with their forest subtype is about 230,351 ha (INFC 2025). In Italy, the decision to use black pine in reforestation is due to its low mortality, rapid juvenile growth, low incidence of phytosanitary problems, and ability to improve the chemical and physical characteristics of soils (Cantiani and Chiavetta 2015). More specifically, the European black pine (*P. nigra* Arn. subsp. *nigra*) was used on calcareous soils, and laricio pine (*P. nigra* subsp. *laricio* Maire) was selected for the sandstone soils (Cantiani and Chiavetta 2015). In relation to the technical characteristics, the use of this species saw a rotation period of approximately 90 years (Cantiani and Chiavetta 2015), with a plantations scheme consisting in 2500 four-year-old seedlings per hectare (2×2 m) and canopy closure at an early age, with a first pre-commercial thinning at age 15, followed by additional thinning every 15 years (Cameron 2002; Novák et al. 2017). However such interventions rarely happened (Marchi et al. 2018). Considering that the black pine forest had an average age of 50 years in 2014 (Cantiani and Chiavetta 2015), the current average age is approximately 60 years. It is therefore interesting to evaluate the development of the stand in relation to the silvicultural practices implemented, with particular focus on the mechanical stability. In fact, the stability is an indicator of the functional efficiency of the forest (Hale et al. 2004) with mechanical stable stand characterized by an equilibrium between the availability and use of resources (water, light and soil) (Hale et al. 2004). Thinning represents an essential silvicultural tool for maintaining the stability of planted stands characterized by a mixed species composition (La Marca 1983; Cameron 2002; Brüchert and Gardiner 2006; Mitchell et al. 2014). However, while existing literature provides important data on the immediate or short-term effects of such treatments (e.g., Marchi et al. 2018), there is still a significant knowledge gap regarding the evolution of mechanical stability over a longer period. In addition, while these thinning methods are well-established, their long-term monitoring in the specific context of aged black pine plantations remains under-investigated.

This study aims to investigate the mechanical stability of a 69-year-old planted black pine forest stand, subjected to two different types of thinning in 2015, nine years post-intervention. While these thinning methods are well-established in forest management, their application and long-term monitoring in the specific context of aged black pine plantations remain significantly under-investigated.

The goal is to provide useful information for stakeholders (e.g. policy makers, land managers, NGOs, scientific community, advisors) who are planning or managing afforestation and/or reforestation actions in areas with similar characteristics to the study site. In this regards, our study aim to inform the selection of the interventions to adopt in order to maintain and enhance the stability of forest stands and thus help ensure CC mitigation capacity, resilience to the effects of global warming and the continued provision of ecosystem services.

Materials and Methods

The experiment was conducted in Tuscany (central Italy) on the Arezzo province side of the Pratomagno Massif, in the municipality of Loro Ciuffenna (Fig. 1).

The basic structure of Pratomagno Massif is constituted by “Arenarie del Monte Falterona”. Lithologically it is characterized by quartz-feldspar sandstones alternated by siltstones and argillites. The area is situated on a slope with small “v” valleys exposed to southwest, whose slope varies from strong at the top to extreme at the bottom. The soil is generally moderately deep, with greater soil depth in some locations due to erosion-driven deposition from up close (Cantiani et al. 2015). In accordance with the same authors, the obstacle to root deepening is due to the presence of cohesive rock, the significant amount of rock fragments, gravel, pebbles and stones.

Data from the weather station in Villa Cognola (663 m a.s.l.) indicate that the climate of the area is warm-temperate, characterized by a rainy winter and dry summer. Rainfall follows the Apennines sub-mountain regime (997 mm average annual rainfall), with a maximum peak in autumn and a second in spring, while the absolute minimum precipitation occurs in July. The average annual temperature is 10.5 °C (maximum 19 °C in July and minimum of 1.5 °C in January). It is important to note that a significant windthrow occurred in the study area in 2017. Its effects were observed in the field, but not recorded by the weather station likely due to its distance from the site. For this reason, the intensity of this event is unknown.

The experimental area is located at an average altitude of 1,150 m a.s.l., with a predominant southwest exposure and an average slope of 40%. In 2015, the mono-

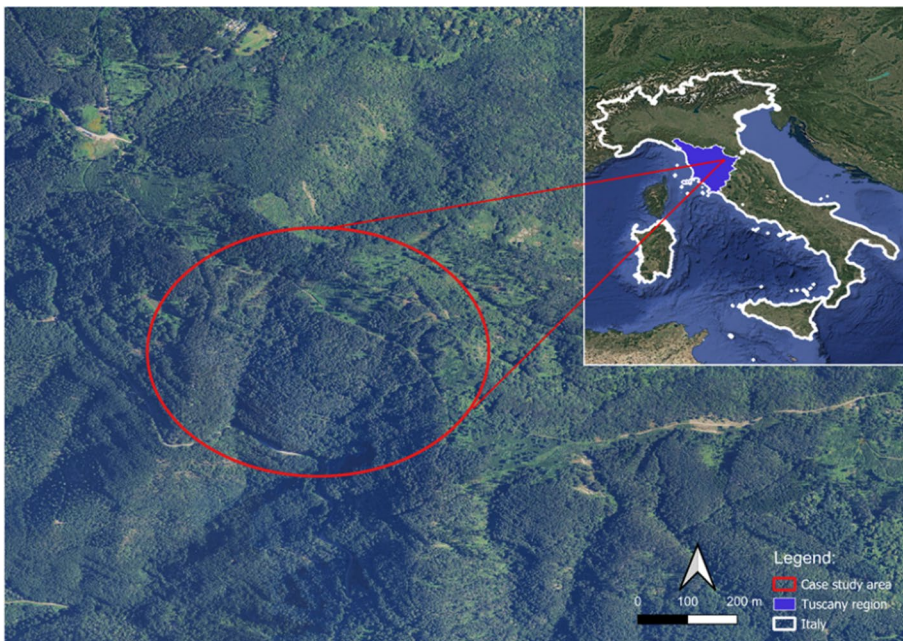


Fig. 1 Location of case study area respect to Tuscany and Italy

specific pine forest was 59 years old and belongs to the second fertility class according to the allometric model of black pine in Tuscany (Bernetti et al. 1969).

The specific composition is predominantly laricio pine with a marginal contribution from other species: the most adopted associate species was the silver fir (*Abies alba* Mill.) mostly in small groups of a few hundred square metres in the most suitable sites)) and, in areas closer to the ridge, also beech. In a few cases, sycamore maple (*Acer pseudoplatanus* L.) was also planted.

The experiment involved three different treatment scenarios: thinning from below; selective thinning and no treatment (control). Thinning from below is traditionally used in Tuscany and involves the removal of dominated trees only. The selective thinning doesn't eliminate trees of a specific category but involves a positive selection of individuals to be released and favoured through thinning (Cantiani 2016). With this thinning, 100 plants per hectare are selected, known as candidates, which are characterised by good development potential, good mechanical stability and vigour. In areas characterized by low fertility or where candidate identification is challenging, a precautionary approach was adopted by identifying a pair or trio of "contiguous candidates". This strategy ensures the maintenance of the target density of dominant trees, allowing for a final selection during subsequent management phases. This thinning involves the removal of trees that may hinder the normal development of the candidate trees. Since selective thinning can involve trees of different social classes, the proportion of material removed is generally higher than in thinning from below, as trees of equal or greater size than the candidates may be removed.

The experimental area covered 9 hectares, with 3 hectares for each treatment. For each of the three treatments, three monitoring areas of 1 hectare each were identified. Within each monitoring area, three circular plots with a radius of 15 m were randomly distributed for dendrometric and structural analysis of the pine forest, for a total of 27 survey plots (Fig. 2). The 27 plots were georeferenced by recording the coordinates of their centre point (Fig. 3).

The characterisation of the forest areas was carried out in early 2015, establishing a minimum threshold for individual trees with a diameter of 5 cm, followed by thinning in June 2015. In 2024, nine years after the intervention, a new survey was carried out to assess the effects of thinning at a longer interval than that achieved during the project.

The sampling intensity differed among treatments and survey years as a result of thinning operations and subsequent natural mortality. In the selective thinning plots, 634 trees were measured before thinning in 2015, 464 trees immediately after thinning, and 243 trees during the 2024 survey. In the thinning-from-below plots, 675 trees were measured before thinning in 2015, 437 trees after thinning, and 219 trees in 2024. In the control plots, 691 trees were measured in 2015 and 429 trees in 2024. These sample sizes reflect the cumulative effects of planned thinning operations and subsequent stand dynamics over time.

Tree positions were recorded using a handheld GNSS receiver. Under open-canopy conditions, positional accuracy was sub-meter, while under closed-canopy conditions the expected positional error was estimated to be within 1–2 m, which is considered acceptable for plot-level spatial analyses. Diameter at breast height (DBH, measured at 1.30 m above ground) was recorded using a diameter tape with a measurement

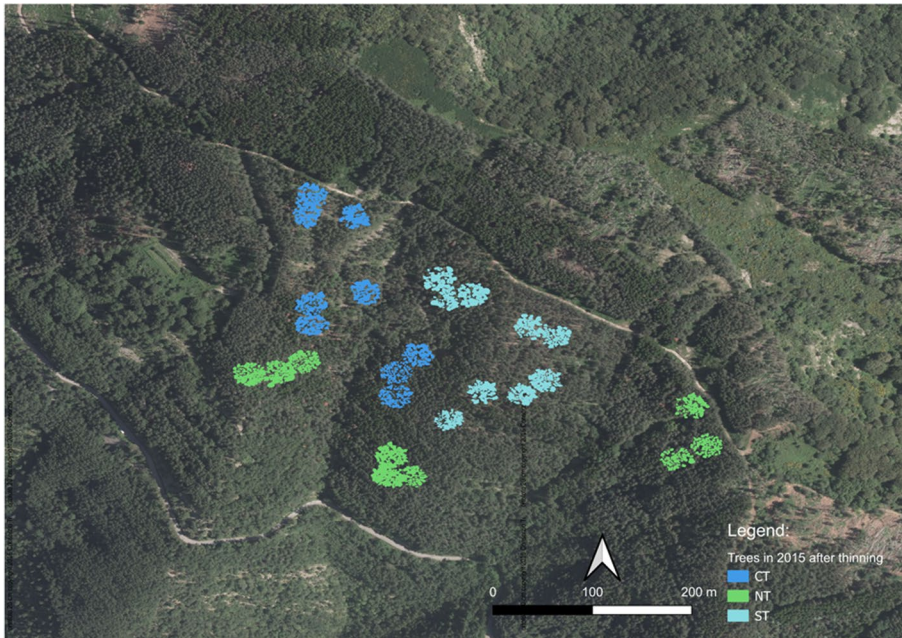


Fig. 2 Distribution of trees after thinning included in the study, where plants are represented by different colours: trees in the area subjected to thinning from below in blue (CT); control in green (NT) and trees in the area subjected to selective thinning in light blue (ST)

precision of 1 mm. Total tree height (H) and height of crown insertion were measured using a laser hypsometer; for each individual, repeated measurements were taken when necessary to minimize operator-related error. Crown radii were measured in 2015 along the four cardinal directions using measuring tapes from the stem center to the vertical projection of the crown edge on the ground. In the 2024 survey, crown projection radii were not measured.

The main average dendrometric parameters were calculated from the data collected. For the volume calculation, the estimation model for *Pinus nigra* developed by Tabacchi et al. (2011) was used.

The measurements of heights allowed the calculation of the slenderness ratio (total height of the tree/diameter at breast height) (H/DBH), one of the parameters most used to assess the mechanical stability of artificial and monospecific forest stands, such as planted black pine forests (Patacchini et al. 2020). Thinning represents a silvicultural action that substantially influences the stability of a stand by impacting tree density and, consequently, the ability of crowns to intercept light radiation, which generally increases with the expansion of the leaf area, positively affecting plant growth (Cameron 2002; Pretzsch and Schütze 2005). Literature also mentions other parameters used to assess the mechanical stability of trees in a forest stand, such as the relative crown depth, the crown area, and the eccentricity of the crown (Cantiani and Chiavetta 2015). However, the slenderness ratio is preferred for its simplicity in measuring the necessary parameters, as well as for the presence of established references and critical threshold values in the literature (Patacchini et al. 2020).



Fig. 3 Detail of the area surveyed, with the centre point marked by a yellow-coloured wooden stake in the ground

The H/DBH ratio was determined for all trees present in each plot to compare the overall stability across all three treatments (control, thinning from below, and selective thinning). In addition, for the selective thinning treatment only, the ratio was specifically analyzed for the candidate trees (identified at a density of 100 trees per hectare) to evaluate the stability of the individuals that will constitute the forest at the end of the planned 90-year rotation length. At the time of the 2024 survey, the 68-year-old stand was in its late maturity phase, approximately two decades before the final harvest. To assess any statistically significant differences between the two thinning methods, the Shapiro–Wilk test was used preliminarily to assess the normality of the samples. The test was not satisfactory, and it was necessary to adopt the Wilcoxon–Mann–Whitney test, choosing a significance level of $\alpha=5\%$ and with the null hypothesis assuming no difference between the samples and the alternative hypothesis predicting a significant difference between the two treatments considered. This method was chosen because it is a non-parametric test that does not assume normality within the sampled populations (Wilson 2024), which is useful in our case due to the external event that certainly affected the normal distribution of the observations. The effect size was then assessed using Cohen's *d* and standard values of 0.2 (small), 0.5 (medium) and 0.8 (large) were chosen to quantify it (Cohen 2013).

The statistical analyses reported in the previous paragraph were performed using R software (version 4.3.3) (R Core Team 2024), using the `shapiro.test()` and `wilcox.test()` functions from the R base package “stats”. The `cohens_d()` function from the

‘rstatix’ package (Kassambara 2023) was used to calculate the effect size, while the ggboxplot () function from the ‘ggpubr’ package (Kassambara 2025) was used to create the boxplots.

In order to qualitatively compare land cover before and after the windthrow in the study area, orthophotos available on the Tuscany Region website for 2016 (Regione Toscana-SIPT 2025a) and 2021 (Regione Toscana-SIPT 2025b) were consulted. The open-source software QGIS Desktop (version 3.34.14) (QGIS Development Team 2025) was used for this purpose.

Results

General Results

Nine years later, it is possible to observe variations in stand levels between the three treatments under study (Table 1).

The number of trees per hectare has decreased since the first observation. In 2015, before thinning was carried out, the number of trees per hectare was 997, 1061 and 1086 for the selective thinning areas, the thinning from below areas and control areas, respectively.

With selective thinning, 26.8% (−267) of trees per hectare were removed and, with thinning from below, the reduction of trees per hectare was 35.6% (−374). Between the year of thinning and 2024, there was a significant decrease in the number of trees, equal to 47.6% (−347) and 49.9% (−343) for selective thinning and thinning from below, respectively.

This decrease in the number of trees obviously had repercussions on all other dendrometric parameters. The distribution of trees per hectare by diameter class shows a bell-shaped pattern, with a concentration of trees mainly in the central diameter classes.

When considering the diameter-class frequency distribution by treatment, the selective thinning plots showed 25 cm as the most represented diameter class in 2015,

Table 1 Main dendrometric characteristics for the three different treatment types for the year 2015 (pre- and post-thinning) and 2024

Dendrometric variables	Treatment							
	Selective			Thinning from below			Control	
	2015		2024	2015		2024	2015	2024
	PRE	POST		PRE	POST			
N	997	729	382	1061	687	344	1086	674
BA (m ² ha ^{−1})	63.76	46.94	33.19	71.08	55.64	35.09	58.95	53.08
V (m ³ ha ^{−1})	563.70	413.65	328.57	696.22	566.06	310.47	590.98	521.99
Dg (cm)	28.54	28.63	33.26	29.20	32.12	36.02	26.29	31.66
Hm (m)	18.81	18.83	20.25	19.02	19.92	21.01	18.03	19.79
Hm/Dg	65.89	65.80	60.90	65.14	62.04	58.32	68.58	62.51

N=number trees by hectare; BA=basal area; V=volume by hectare; Dg=quadratic mean diameter; Hm=mean height

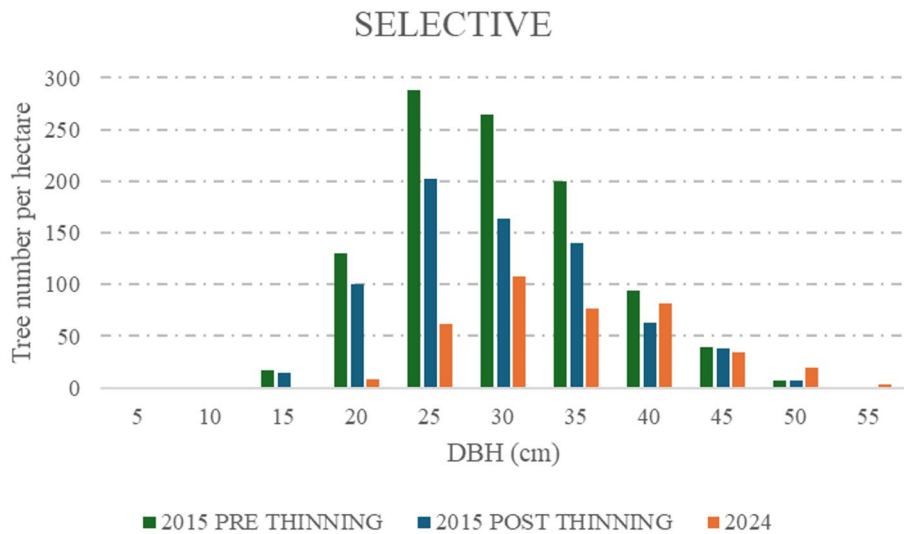


Fig. 4 Comparison of numbers of trees by diameter class for areas thinned using selective thinning, considering 2015 (pre-thinning and post-thinning) and 2024

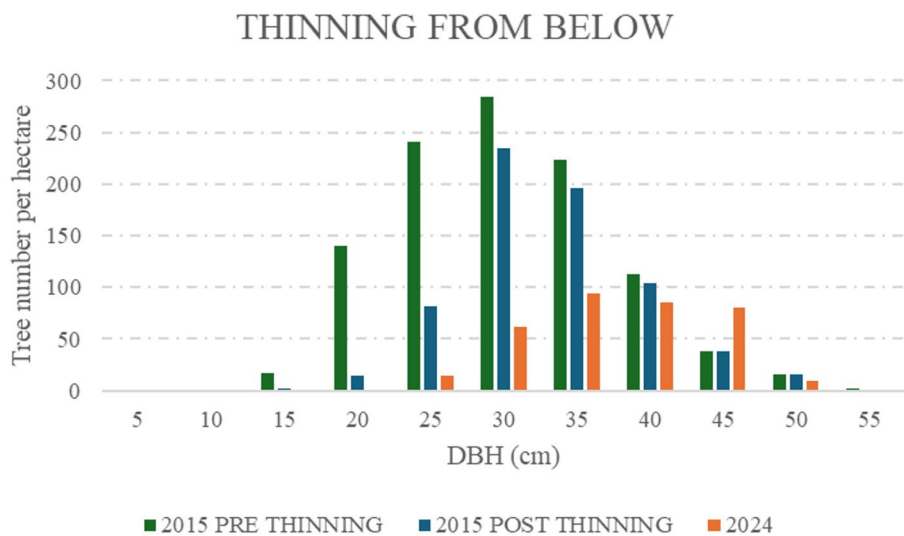


Fig. 5 Comparison of numbers of trees by diameter class for areas thinned from below, considering 2015 (pre-thinning and post-thinning) and 2024

both pre- and post-thinning. By 2024, the highest frequency was observed in the 30 cm diameter class. (Fig. 4).

Considering the diameter class distribution by treatment thinned from below, in 2015 the most represented class was 30 cm, both pre- and post-thinning. In 2024, the diameter class with the highest frequency is 35 cm (Fig. 5).

In the control, in 2015 the most represented class was 25 cm, while in 2024, the diameter class with the highest frequency corresponds to 30 cm (Fig. 6).

In 2015, the average initial basal area was $64 \text{ m}^2 \text{ ha}^{-1}$ in areas thinned with selective treatment and $71 \text{ m}^2 \text{ ha}^{-1}$ in areas treated using thinning from below. Immediately after thinning, there was a decrease of approximately 26.4% ($-17 \text{ m}^2 \text{ ha}^{-1}$) and 21.7% ($-15 \text{ m}^2 \text{ ha}^{-1}$) for selective thinning and thinning from below, respectively. The average values immediately after thinning were $47 \text{ m}^2 \text{ ha}^{-1}$ (selective thinning) and $56 \text{ m}^2 \text{ ha}^{-1}$ (low thinning). In 2024, the basal area decreased further by 29.3% ($-14 \text{ m}^2 \text{ ha}^{-1}$) and 36.9% ($-21 \text{ m}^2 \text{ ha}^{-1}$) for selective thinning and thinning from below, respectively, falling to $33 \text{ m}^2 \text{ ha}^{-1}$ and $35 \text{ m}^2 \text{ ha}^{-1}$.

In the case of average volume values, the initial situation was fairly uniform across the various treatments. The average volume values ranged between 564 and $696 \text{ m}^3 \text{ ha}^{-1}$. Thinning removed approximately 26.6% ($-150 \text{ m}^3 \text{ ha}^{-1}$) of the volume with selective thinning and 18.7% ($-130 \text{ m}^3 \text{ ha}^{-1}$) with thinning from below. After thinning, the volume values were $414 \text{ m}^3 \text{ ha}^{-1}$ (selective) and $566 \text{ m}^3 \text{ ha}^{-1}$ (from below). In 2024, both treatments underwent a reduction in values, decreasing by 20.6% ($-85 \text{ m}^3 \text{ ha}^{-1}$) and 45.2% ($-256 \text{ m}^3 \text{ ha}^{-1}$) respectively in selective and thinning from below.

The H/DBH ratio for average stand values assumes the following values: 65.8 (2015) and 60.9 (2024) in selective thinning, 62.0 (2015) and 58.3 (2024) in thinning from below, 68.6 (2015) and 62.5 (2024) in the control.

It should be clarified that the Hm/Dg ratio reported in Table 1 represents the ratio between the mean stand height (Hm) and the quadratic mean diameter (Dg), and therefore reflects an average stand-level index. In contrast, the analyses of mechanical stability presented in the following sections are based on the arithmetic mean of individual H/DBH ratios, calculated separately for each tree and then averaged at

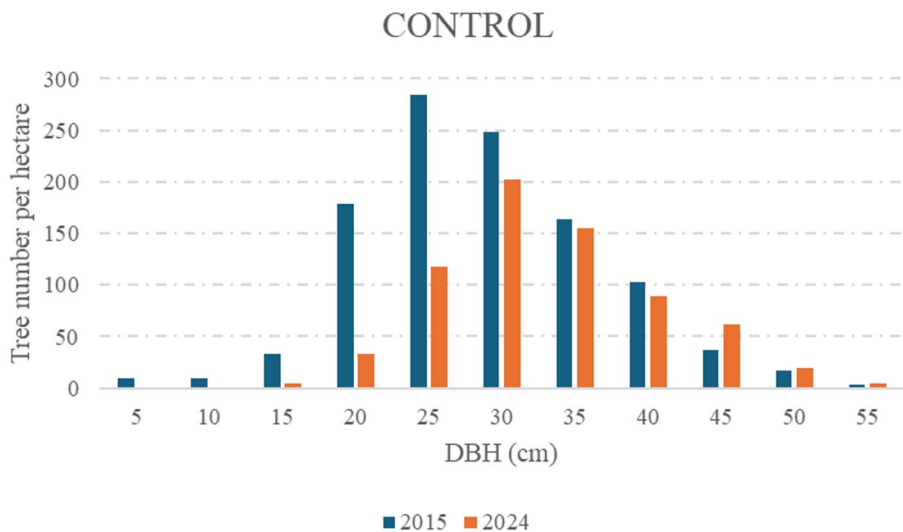


Fig. 6 Comparison of numbers of trees by diameter class for control areas, considering 2015 and 2024

plot or treatment level. These two indices therefore describe different aspects of stand structure and should not be interpreted interchangeably.

Stand Stability

Immediately after thinning, the average values of H/DBH calculated were 67.8 for selective thinning, 71.6 for thinning from below and 67.1 for the control. Nine years after the intervention, the average values were 65.0 for selective thinning, 63.4 for thinning from below and 68.8 for the control. Therefore, in the thinned plots, the value decreases, while in the control, there is a slight increase (Table 2). The range of variation in H/DBH is quite heterogeneous across all treatments, with values ranging from a minimum of 41.1 to a maximum of 119.4.

In 2015, H/DBH values were concentrated primarily in the 20–30 cm diameter range in both treatments. In 2024, the range expanded to 40 cm (Fig. 7).

The trend curves show a consistent decrease in the thinned plots, suggesting a tendency toward greater stability in the larger diameter classes. (Fig. 8).

The distribution of values and the trend curves suggest that thinning, regardless of the type applied, is associated with a positive effect, as a progressive reduction in the H/DBH value was observed. Over time, this appears to correspond to a shift of the most represented diameter classes towards the right (higher diameter values). This aspect is particularly interesting in relation to selective thinning: our observations suggest that the candidate trees, which will reach the end of the 90-year rotation, tend to occupy the larger diameter classes, where the trees show lower H/DBH values. What is evident in Fig. 8 is a different slope of the regression lines, which is greater in selective thinning than in thinning from below. This indicates a different allometric relationship between height and diameter across treatments; specifically, for a given diameter increment, trees in the selective thinning treatment show a more pronounced increase in total height compared to those in the thinning-from-below plots. An interesting aspect is that, for the same diameter, there is a different H/DBH value depending on whether DBH is above or below 29 cm, where the two lines meet. In fact, with values below this value, the H/DBH is higher in selective thinning, while with higher values, the opposite is true, with marked differences moving towards larger diameters.

Focusing on the effect that the windthrow had on the two types of treatment, the picture that emerges shows two different average values, with a higher H/DBH in

Table 2 Statistical parameters and variability indices by thesis in 2015 (pre- and post-thinning) and 2024 referred to the H/DBH ratio. Average (Arithmetic average), min (minimum value), max (maximum value), SD (standard deviation), Err (standard error), CV (coefficient of variation)

Statistical parameters	Selective			Thinning from below			Control	
	PRE	POST	2024	PRE	POST	2024	2015	2024
Average	64.3	67.8	65.0	71.6	69.0	63.4	67.1	68.8
Min	13.0	43.4	41.1	8.5	27.8	46.2	11.0	43.5
Max	117.3	102.6	92.6	147.7	121.1	94.8	130.9	119.4
SD	14.6	12.4	11.9	17.3	12.1	9.8	17.2	14.4
Err	0.6	0.8	1.1	0.7	0.6	1.3	0.7	1.3
CV	22.8	18.3	18.4	24.2	17.5	15.4	25.6	21.0

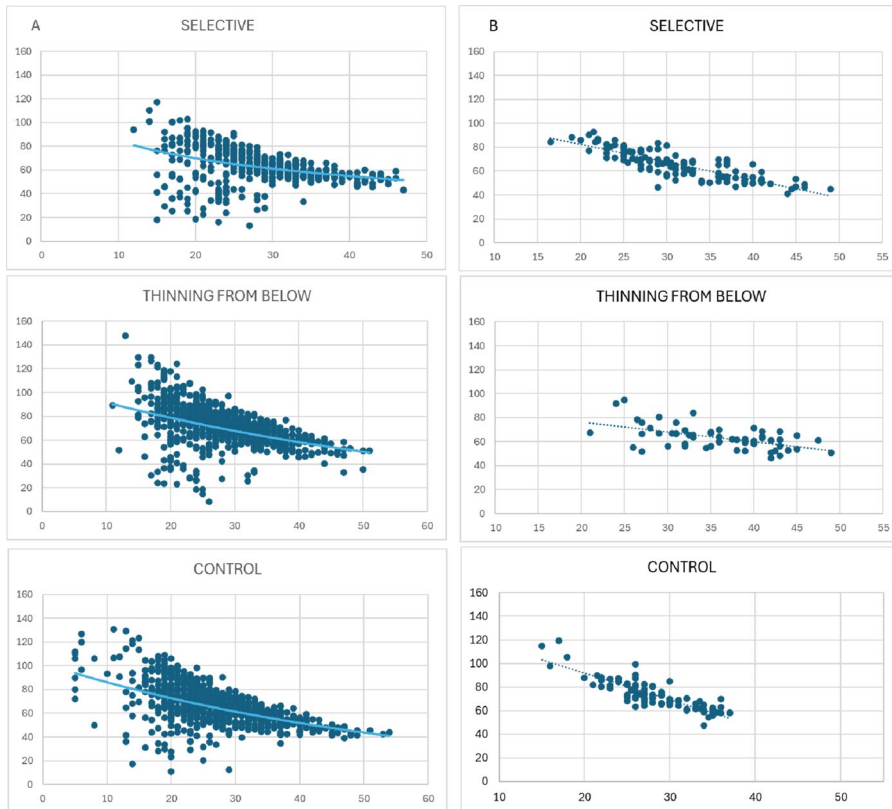


Fig. 7 Distribution of H/DBH as a function of DBH in the treatments. **A** Selective thinning in 2015 (post-thinning), thinning from below in 2015 (post-thinning), and control in 2015; **B** Selective thinning in 2024, thinning from below in 2024 and control in 2024

2024 for the forest stands subjected to selective thinning (65.0) than for the one with thinning from below (63.4), but no statistically significant difference was recorded ($W=3184.5$; p value=0.4058) and the effect size was negligible (-0.141) (Fig. 9).

Visual Analysis of Canopy Cover

A qualitative comparison of the orthophotos (Fig. 10) indicates that canopy openings caused by the 2017 windthrow were more extensive in the thinning-from-below plots. In these areas, an increased visibility of bare soil can be observed when comparing the pre-event and post-event images, suggesting that trees belonging to different social classes (dominant, co-dominant and dominated) were affected by the disturbance.

In contrast, the selective thinning plots appear to maintain a more continuous canopy cover following the same event (Fig. 11). The qualitative inspection of the orthophotos (Fig. 11) suggests a different canopy response in the selective thinning

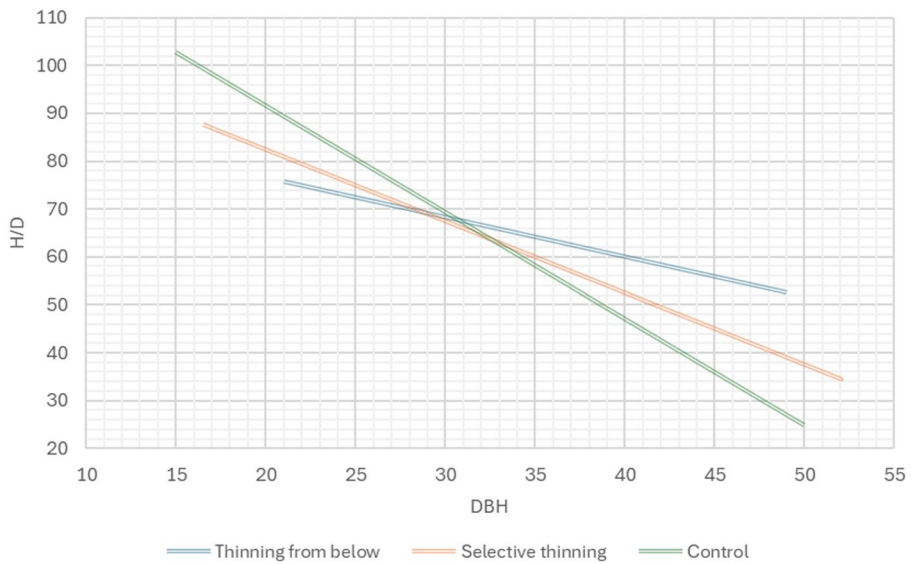


Fig. 8 Trend of H/DBH in relation to DBH in the different treatments (selective thinning, thinning from below and control) in 2024

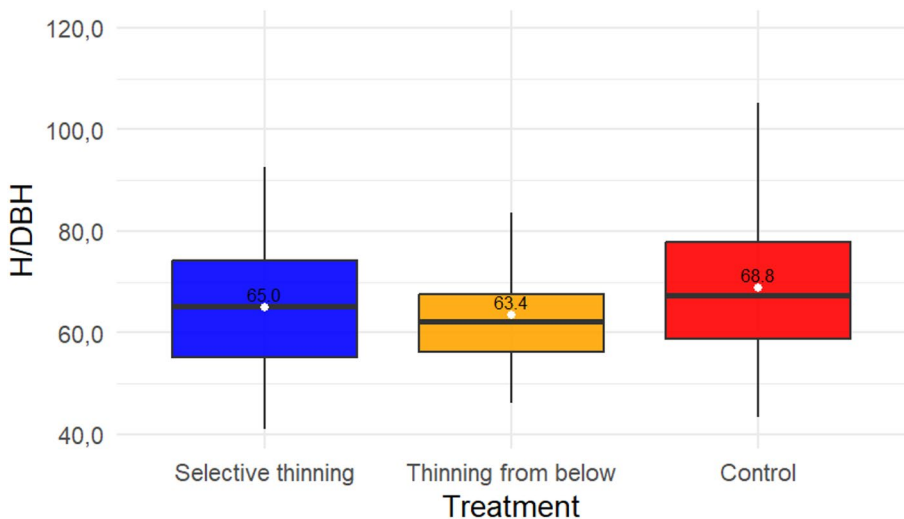


Fig. 9 Boxplot of H/DBH by treatment thesis (selective thinning and thinning from below) under study, where the black line represents the median and the white dot the mean value, which is also shown numerically in the graph

plots compared to the thinning-from-below areas, with fewer and more spatially limited canopy openings.

These observations are purely qualitative, as no quantitative photo-interpretation analysis or post-disturbance field mapping of gap surfaces was conducted. Therefore,



Fig. 10 Differences between before and after the windy event for areas thinned from below (CT), comparing orthophotos (above) and orthophotos showing the location of the plants under study (below)

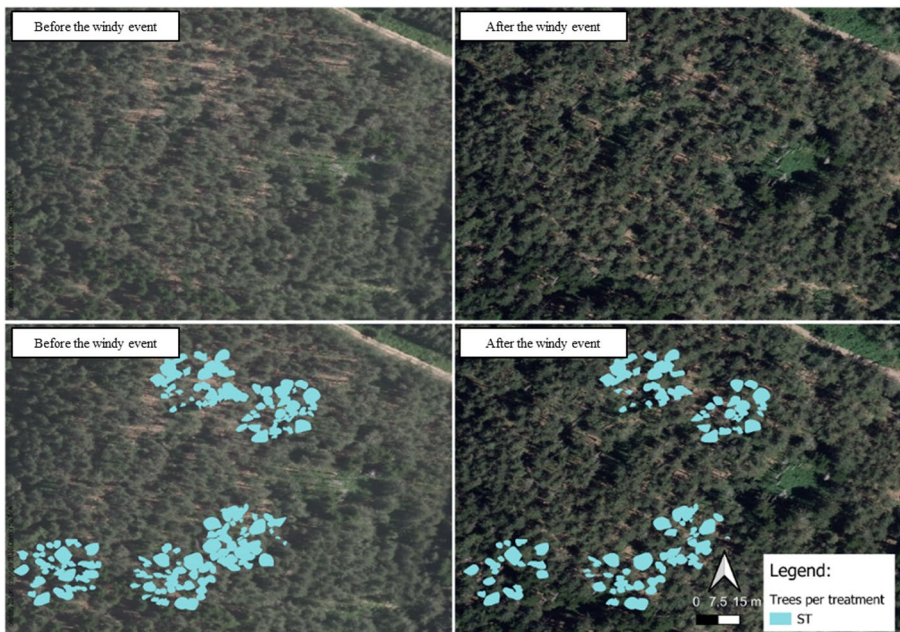


Fig. 11 Differences between before and after the windy event for areas with selective thinning (ST), comparing orthophotos (above) and orthophotos showing the location of the plants under study (below)

the visual assessment provides an indicative comparison of canopy cover dynamics rather than a definitive quantification of disturbance effects.

Discussion

In 2017, the study area was affected by a windthrow event that influenced stand structure across all treatments. This disturbance altered the expected post-thinning development trajectories of the forest, making it necessary to interpret the observed patterns in mechanical stability by jointly considering both planned silvicultural interventions and unplanned extreme events. The reduction in the number of standing trees observed between 2015 (post-thinning) and 2024 across all treatments, including the control, cannot be attributed to thinning operations alone. This decline likely reflects the combined effects of natural mortality processes typical of maturing black pine plantations and the windthrow event that occurred in 2017. Although the relative contribution of these two factors cannot be quantitatively disentangled with the available data, their cumulative influence provides a plausible explanation for the observed stand dynamics.

The occurrence of wind damage across all treatments reflects the intrinsic difficulty of preventing the impacts of extreme wind events, as widely documented in the literature on forest disturbance dynamics. Such events often override management signals, especially when they occur within known periods of increased vulnerability following thinning operations, which are typically identified within a 5–10 year window after intervention. In the present case, the timing of the windthrow falls squarely within this susceptibility interval, potentially amplifying its effects on stand structure and stability.

A further critical aspect in interpreting these results is the historical management of the stand prior to 2015. Before the experimental thinning, the forest had not been subjected to regular or systematic silvicultural interventions. It is well established that early and repeated thinning during stand development can promote mechanical adaptation by inducing stronger stem architecture and more developed root systems, thereby increasing resistance to mechanical stress. The absence of such early interventions may have limited the development of adaptive traits and contributed to the observed sensitivity of the stand to wind disturbance.

The most noteworthy result of this study is the lack of statistically significant differences in individual-tree mechanical stability, expressed via the H/DBH ratio, between selective thinning and thinning from below nine years after intervention. Under undisturbed conditions, differences between thinning methods might reasonably be expected. However, the windthrow appears to have acted as a “natural thinning agent,” particularly in the thinning-from-below plots, selectively removing less stable individuals with higher H/DBH values and thereby reducing differences between treatments. This mechanism is consistent with classical silvicultural concepts suggesting that disturbances may preferentially eliminate mechanically weaker trees, resulting in residual stands with seemingly improved average stability indices.

Although the final H/DBH values in 2024 for both thinning treatments are below the critical threshold commonly reported in the literature, this apparent convergence

in mechanical stability should not be interpreted as equivalent developmental pathways. The structural conditions under which canopy development and resource redistribution occurred differed markedly between treatments over time. From a functional perspective, these differing trajectories have implications beyond stem stability alone, particularly in relation to canopy structure, soil protection, and ecosystem service provision.

In this broader context, the results of this study contribute to the growing body of evidence highlighting the need for adaptive forest management under CC. The projected increase in the frequency and intensity of extreme weather events, including windstorms, implies that future stability of reforested and afforested stands will depend not only on the choice of thinning method, but also on the capacity of management strategies to enhance resilience to unpredictable disturbances. Long-term monitoring, coupled with management approaches that prioritize structural heterogeneity and adaptive capacity, will be essential to disentangle treatment effects from disturbance-driven dynamics and to support informed decision-making in planted forest systems.

Conclusions

Both natural and artificial forests established through reforestation and afforestation are expected to play an increasingly important role in the provision of ecosystem services that underpin environmental quality and human well-being. In this context, the mechanical stability of forest stands represents a key prerequisite for ensuring CC mitigation potential, resilience to increasing disturbance regimes, and the continued delivery of multiple ecosystem services over time. Proper and continuous forest management, tailored to specific objectives and site conditions, therefore remains essential.

This study investigated the effects of two thinning methods—selective thinning and thinning from below—on the mechanical stability of an artificial black pine stand approximately nine years after intervention. The results show that, despite differences in silvicultural approach, no statistically significant differences in individual-tree stability (expressed through the H/DBH ratio) were observed between the two thinning treatments in 2024. This outcome reflects the strong influence of an unplanned windthrow event that occurred in 2017, which acted as an additional disturbance factor and contributed to shaping the present stand structure alongside the planned thinning operations.

The absence of significant differences between treatments does not imply identical developmental pathways. Rather, it highlights how extreme and stochastic events can partially or fully override expected management effects, especially in stands with a long history of limited or irregular silvicultural intervention. These findings emphasize the importance of interpreting thinning outcomes within a broader temporal framework that accounts for cumulative and interacting disturbances.

Selective thinning is designed to favor dominant trees with larger crowns, which is expected to contribute to better soil protection. However, further studies including updated crown measurements and analyses of gap-filling dynamics are needed to

quantitatively confirm this long-term benefit. From a multifunctional perspective, future research should explicitly integrate soil protection, stand stability, and other ecosystem services to better assess trade-offs and synergies among different management strategies.

Looking forward, research efforts should focus on identifying optimal thinning intervals and adaptive management regimes capable of enhancing forest resilience under increasingly variable climatic conditions. Long-term monitoring will be essential to disentangle silvicultural effects from disturbance-driven dynamics and to support evidence-based decision-making in aging artificial forest stands, particularly those expected to play a role in CC mitigation and adaptation strategies.

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Data Availability The data that support the findings of this study are available on request from the corresponding author.

Code Availability Not applicable.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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