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ORIGINAL PAPER

Enhancing ecosystem service provision through the silvicultural management of European black pine stands from afforestation and reforestation in Italy

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Abstract Afforestation and reforestation, when aligned with site-specific ecological and socioeconomic conditions, can enhance ecosystem functions and services (ESs). In the Mediterranean, European black pine is widely used in such projects. While management strategies to maximize timber yield are well studied, the economic valuation of multiple ESs and their trade-offs remains limited. This study employed a process-based forest growth model, incorporating climate, soil and stand structure, to assess the effects of thinning intensity and frequency on the provision and economic value of ESs, namely carbon sequestration, erosion control and recreational/aesthetic value, in Italian black pine stands. Results show that while intense and frequent thinning boosts growth, optimal economic outcomes were achieved with 25% basal area removal every 25 years, yielding €57,000–69000 ha^{-1}, about 30% more than high-intensity, short-rotation regimes. Non-provisioning ESs declined with heavier thinning (up to 22% loss between 15 and 35% intensity) and improved with longer thinning intervals (up to 18% gain from 10 to 25 years). Strikingly speaking, aesthetic and carbon sequestration benefits dominated total value, accounting for up to 99%, regardless of regime. These findings underscore the importance of long-term, balanced thinning strategies to optimize both wood production and broader ESs. The modeling approach offers practical guidance for multifunctional forest management, supporting more sustainable and economically viable decisions. While tailored to Italy's context, the insights are relevant to policy and practice across Mediterranean and comparable forest systems.

Keywords Forest management · Thinning · Modeling · Ecosystem services · Carbon cycle · *Pinus nigra* · *Pinus laricio*

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Introduction

Afforestation and reforestation are integral components of land management. The first refers to the direct human-induced conversion of land that has not been historically forested to forested land, essentially implying a change in land cover or land-use designation. In contrast, reforestation refers to the human-induced conversion of temporarily non-forested land to forested land, or the reversal of land that was previously forested but has been converted to non-forested land (IPCC 2000). In this paper, the terms will be paired, but their distinct definitions will always be maintained. To ensure their effectiveness, planting designs should align with the natural processes that govern the spatial establishment of forest vegetation. This involves identifying the most suitable species and intervention strategies for varying operational contexts, ensuring alignment with environmental, socioeconomic and cultural objectives and conditions. Approaches may range from fostering natural colonization, which supports the development of biologically stable and self-sustaining ecosystems, to applying silvicultural techniques aimed at establishing semi-natural forests over the long term, or even adopting intensive forest management practices typical of commercial forestry (Puettmann et al. 2015).

When afforestation and reforestation initiatives integrate the diverse eco-biological, landscape, cultural and socioeconomic characteristics of the intervention area during the planning, design and establishment phases, they can achieve substantial environmental improvements by fostering the creation of semi-natural or close-to-natural forests (Vacek et al. 2023). In Europe, and especially in Mediterranean regions, Austrian pine (*Pinus nigra* Arnold) and Corsican pine (*Pinus laricio* (Poir.) Maire), collectively known as European black pines, are some of the most frequently used tree species for afforestation and reforestation. These two species cover 4.4% of the European forest area, and they are among the most widely planted species outside their native range. European black pine plantations are mainly targeted at improving degraded landscapes. Thanks to their ability to grow in poor soil conditions and their resistance to environmental stressors such as drought and heatwaves, these species are highly suitable in different habitats and resilient to climate change (Vacek et al. 2023). In Italy, these plantations, mainly established after World War II, now cover over 120,000 ha nationwide, according to the Italian National Forest Inventory (Gasparini et al. 2022), with the majority located in central and southern parts of the peninsula.

Several studies have investigated the effects of silvicultural practices, particularly thinning operations, on forest growth and dynamics. However, fewer have considered the ecosystem functionalities, referred to as “ecosystem services” (ESs), provided by conifer forest stands originating from afforestation and reforestation, and even fewer have considered their economic value and trade-offs with wood provisioning. Recently, Başkent and Kašpar (2022) explored the long-term effects of management intensification on several ESs such as habitat for biodiversity conservation, wood production, carbon stock, cultural values, water provision and soil protection, in a Turkish forest, including black and red pine (*Pinus brutia,* Ten 1811). They found that more intense management scenarios increased harvesting levels, carbon sequestration and soil protection, at the cost of decreasing groundwater and cultural values, highlighting the critical role of forest management on key indicators of sustainability. In a subsequent study, Baskent et al. (2025) explored the long-term trade-off between carbon sequestration and timber production in forest plantations with different species, comparing four alternative management strategies. They found black pine as a better species in carbon sequestration and wood production (two well–recognized ESs), suggesting its crucial role for sustainable forest management. In both studies, authors allowed the forest area to expand through reforestation and afforestation, finding that it was the main driver for increasing ESs provisioning. However, they did not specifically consider thinning interventions (in terms of frequency and intensity of removal), but rather more general management scenarios, such as rotation length, species composition and number of planted saplings, leaving the need for future exploration. Moreover, the decision support system used to project future forest growth was driven solely by empirical allometry relations, thus lacking robust dynamics (Baskent et al. 2025). Such an approach cannot account for climate effects, which drive the majority of the main eco-physiological processes in the forest.

Thinning is a particularly relevant silvicultural practice that modifies the horizontal and vertical structure of forest stands, affects the stand’s productive and protective functions, and may increase fire resistance, thereby improving the economic viability of the stands. Thinning also influences ecological processes by modifying competition among trees and altering the availability of light, water and nutrients. As a result, it impacts elemental cycles, such as carbon assimilation and nutrient mineralization, as well as hydrological dynamics (Saponaro et al. 2025). However, thinning operations tend to have relatively high costs in conifer stands established from afforestation and reforestation, and an increase in thinning intensity does not necessarily translate into higher sequestration capacity (Dalmonech et al. 2022). On the other hand, thinning can increase the provision of various ESs in pine plantations, as noted by Simon and Ameztegui (2023).

ESs are increasingly influential in forest management decision-making and planning, as they represent the benefits ecosystems provide to human society, sustaining life on Earth and supporting human needs (Corona and Alivernini 2024). However, integrating ESs into forest management is challenging due to the trade-offs and synergies that often exist among different ESs (Croitoru 2007; Duncker et al. 2012; Wolfslehner et al. 2019; Nocentini et al. 2022). The characteristics of forest stands and management decisions can significantly influence the provision of ESs (Valentini and Miglietta 2015; Tomao et al. 2017; Corona et al. 2018; Simon and Ameztegui 2023).

Synergies and trade-offs between ESs vary depending on the region and history of the forest considered (Duncker et al. 2012), albeit most ESs analyzed have a weak trade-off with wood production, which, in contrast, is strongly positively correlated with management intensity (Biber et al. 2015). How forest management strategies can modulate the relations among ESs is tackled in literature (Duncker et al. 2012; Biber et al. 2015; Lafond et al. 2017), but the specific role of thinning interventions is under explored, despite being a crucial practice to regulate and maintain forest structure and vitality and in turn resistance and resilience to biotic and abiotic stressors. Notably, process-based forest models (PBFMs) have been rarely used for the scope of assessing synergies and trade-offs among ESs (Simon and Ameztegui 2023; Testolin et al. 2023).

In this study, we adopted a robust modeling approach to explore the effects of thinning intensity and frequency (from now on also referred to as “thinning regimes”) on the provision of ESs in European black pine stands established through afforestation and reforestation in Italy. In particular, the research questions were:

1) How do different thinning regimes influence the long-term dynamics and ES provisioning of Black pine plantations
2) What is the monetary value of ESs under different thinning regimes, and what trade-offs and synergies arise among them

To answer these questions, we utilized PBFM, a key tool for analyzing the impacts of different silvicultural management strategies on stand dynamics (Engel et al. 2021; Dalmonech et al. 2022; Vangi et al. 2024a, b). Specifically, we implemented various thinning regimes using the 3D-CMCC-FEM v 5.6 model (Collalti et al. 2018; Dalmonech et al. 2022; Testolin et al. 2023) at three different Black pine plantations. Sites were chosen along a latitudinal transect in Italy, and simulations spanned approximately 100 years. We deliberately run the model under a constant present-day climate to isolate the effect of management and stand development from the confounding effects of climate change. This approach enables a clearer attribution of observed outcomes to thinning regimes, thereby minimizing the confounding influences of climate variability or change. While this simplification limits the assessment of future climate impacts, it enables a focused evaluation of management-driven ES dynamics. Subsequently, we assessed the provision of multiple ESs, including wood production, erosion control, carbon sequestration, aesthetic/recreational value and preventing structural damage, as well as their monetary revenues through the integration of economic models. The monetary valuation of the selected ES was based on environmental appraisal methods and the concept of social (non-market) utility value (Pearce et al. 2003).

This integrated approach to evaluating ES provision under different thinning regimes offers valuable insights, informing silvicultural management of European black pine plantations, potentially not just in Italy, and supporting their long-term sustainability and multifunctional role in delivering ESs in Europe.

Materials and methods

Study area and field data collection

The analyses were conducted in three study areas of European black pine plantations in Italy: Monte Amiata and Rincine in the Tuscany region, and Varco San Mauro in the Calabria region (Fig. 1). Those sites were selected for their representativeness of the European black pine plantations in central and southern Italy, combined with the availability of multi-temporal field data needed to validate the model.

The Monte Amiata plantation is located on a southwest-facing aspect at an altitude of approximately 750 m a.s.l., with an average slope of 15%. In 2016, 27 circular plots, each with a radius of 15 m, were identified. For each tree within the plots, height and diameter at breast height (DBH) were measured, and the growing stock volume was calculated using species-specific allometric models. These measurements were taken before and after applying three experimental management protocols: thinning from below, which involved mainly removing dominated trees; selective thinning, where candidate trees were selected and their competitors’ trees were removed at the crown level, and a control (no treatment). All plots were remeasured in 2023 when the stand reached 52 years of age.

The Rincine plantation is situated at an altitude of approximately 1050 m a.s.l., with a southwest-facing aspect and an average slope of 70%. In 2008, three experimental plots, each measuring 50 m × 50 m, were established and measured using the same protocol as at Monte Amiata. These measurements were conducted both before and after implementing three experimental silvicultural treatments: thinning from below, felling carried out by opening minimal gaps to foster natural regeneration, and a control (no treatment). The stand was remeasured in 2024 when it was 51 years old.

The Varco San Mauro plantation is located within the Sila Plateau Forest at an altitude of 1118 m a.s.l. on south and southwest-facing slopes. The experimental protocol involved establishing four plots, each measuring 30 m × 30 m, where two treatments were applied: selective thinning and a control (no treatment). The same measurement protocol as in the other two sites was used. Measurements were conducted in 2007, both before and after thinning, with a final survey performed in 2023, when the stand reached 63 years of age.

All field measurements were considered observations without error and used as reference data for model validation and calibration (McRoberts and Westfall 2014). In

Table 1, the number of plots for each site and the years of the first and second surveys are presented, while Table 2 displays the measurement data for both surveys.

3D-CMCC-FEM Model

The 'Three-Dimensional – Coupled Model Carbon Cycle – Forest Ecosystem Module' (3D-CMCC-FEM, v.5.6) is a biogeochemical, biophysical and process–based

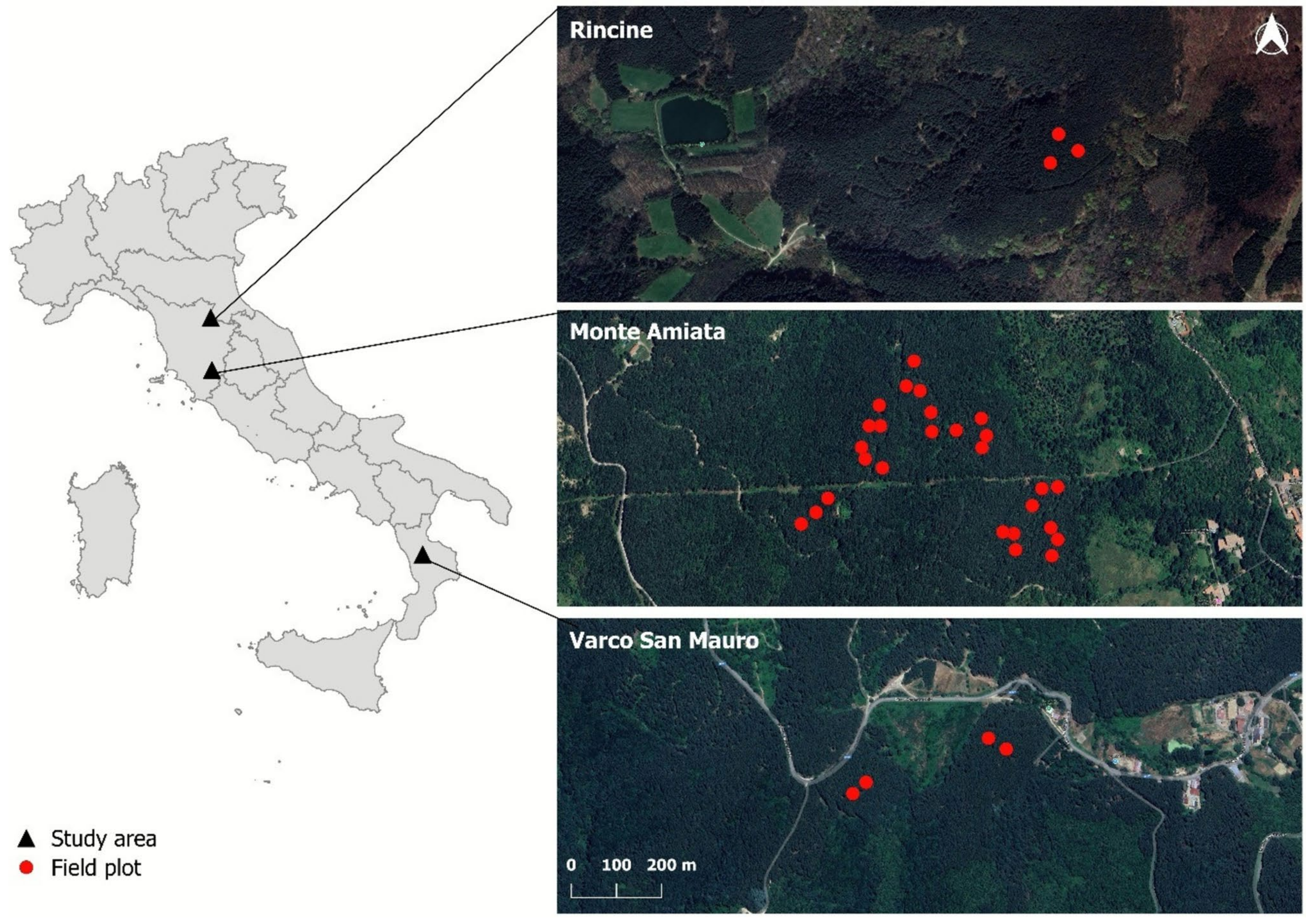

Fig. 1 Location of the study areas and distribution of experimental field plots

Table 1 Overview of the field plots in the three study sites

Sites	Number of control plots	Number of treatment plots	Total number of plots	Year of first survey	Year of the second survey
Monte Amiata	9	18	27	2016	2023
Rincine	1	2	3	2008	2024
Varco San Mauro	2	2	4	2007	2023

Table 2 Measurement data aggregated by management type (control and treatment) for consecutive surveys

Management type	First survey			Second survey		
	N	DBH (cm)	H (m)	N	DBH (cm)	H (m)
Control	1072	22.0	16.5	1032	24.0	18.2
Treatment	1028	24.2	18.6	660	28.3	20.8

model that simulates the eco-physiological processes and structural dynamics of forest stands at the ecosystem level. The time scales range from daily to decadal, depending on the process being simulated. It is specifically designed to model carbon, nitrogen, energy and water cycles in forest ecosystems. The model can simulate silvicultural interventions in pure or mixed even-aged and uneven-aged stands, including those with complex (multi-layered) structures, under present-day climate and climate change scenarios (Collalti et al. 2016, 2018; Dalmonech et al. 2022; Morichetti et al. 2024; Vangi et al. 2024a, b; Puchi et al. 2026).

Photosynthesis is modeled using the biogeochemical model developed by Farquhar, von Caemmerer and Berry (Farquhar et al. 1980), with separate calculations for light and shade leaves (de Pury and Farquhar 1997). The model accounts for the acclimation of leaf photosynthesis to temperature increases and simulates autotrophic respiration (R_A) by distinguishing between the maintenance costs of existing tissues and the synthesis costs of new tissues. Maintenance respiration is controlled by the nitrogen content in living tissues (a stochiometrically fixed fraction of carbon content) and temperature. Net Primary Productivity (NPP) is calculated as the difference between Gross Primary Productivity (GPP) and R_A. Annual NPP is allocated to various compartments, including biomass production and the non-structural carbon pool (NSC), which stores starch and sugars for use during periods of negative carbon balance (i.e., when $R_A > GPP$). Summer values of NSC below a set threshold lead to progressive crown defoliation. If NSC reserves are depleted and not replenished, the model predicts tree mortality based on McDowell et al. (2008) their carbon starvation hypothesis, one of the different routines included in the model to represent mortality (Collalti et al. 2024, for an in-depth description of the other mortality routines). The model incorporates species-specific phenological and allometric patterns as a function of stand age and biomass accumulation. It is initialized using structural data from the forest stand (e.g., mean stem diameter at breast height, mean tree height, stand age and stand density). It is driven by daily climate variables (e.g., temperature, precipitation, solar radiation and relative humidity) and annual atmospheric CO_2 concentration values (μmol mol^{-1}). Other input data include soil texture, soil depth and site elevation. More details are reported in Collalti et al. (2024).

The forest ecosystem model has been tested and evaluated over several sites in Italy and Europe showing good performances in simulating carbon fluxes and structural variables across different species, environments, climate and management scenarios, at different spatial and temporal scales (Collalti et al. 2014, 2016; Marconi et al. 2017; Dalmonech et al. 2022; 2024; Testolin et al. 2023; Morichetti et al. 2024; Vangi et al. 2024a, b), and when compared to other forest models (Engel et al. 2021; Mahnken et al. 2022; Saponaro et al. 2025).

Climate and soil data

The 3D-CMCC-FEM model requires daily climate data for the simulation period, as well as soil texture and depth. For this study, the model was driven by daily climate data derived from the ERA5 reanalysis, specifically downscaled for Italy (Raffa et al. 2023). Downscaling was performed using the regional climate model COSMO5.0_CLM9 with INT2LM 2.06 (Rockel et al. 2008), which enhanced the spatial resolution from 31 km × 31 km to 2.2 km × 2.2 km while retaining the original hourly timescale of the ERA5 data.

The meteorological variables required for model simulation included daily minimum and maximum temperatures (T-min, T-max in °C), total daily precipitation (Pr, mm d^{-1}), daily mean net surface shortwave radiation (Rg, MJ m^{-1} d^{-1}), and the relative humidity (RH, %). From the average temperature (Tav) and the dew point (Td), the daily relative humidity was calculated using the R Humidity package (Cai 2019). Hourly data were aggregated to a daily timescale by calculating the mean values, except for precipitation, for which the daily sum was computed.

All climate data required for the model were extracted for each field plot for the period 1981–2023, which, despite the low climate change signal already observable in this period, can be considered the current climate. Global annual values of atmospheric CO_2 concentration were extracted from the PROFOUND database (Reyer et al. 2020) for the same period (1981–2023).

To simulate stand growth without the influence of future climate change and thus emphasize the effect of different thinning regimes, a long climate record was created by detrending the downscaled historical climate data from 1981 to 2023 and repeating it cyclically from 1981 to 2100. The detrending process is detailed in Dalmonech et al. (2024) and Vangi et al. (2024a, 2024b). The same procedure was applied to atmospheric CO_2 concentration records. Soil depth and texture (percentages of clay, silt and sand) were obtained from the national soil database developed by the Soil Cartography Laboratory of the Italian Council for Agricultural Research and Agricultural Economics (Costantini and Dazzi 2013). This database, with a spatial resolution of 250 m, comprises four layers representing soil depth (in cm) and the percentages of clay, silt and sand within the top meter of the soil profile.

Present-day model evaluation and long-term dynamics

To ensure that the model accurately reproduced the growth trends of the investigated stands, including the response to thinning from below, the 3D-CMCC-FEM was validated using the downscaled climate data and field measurements collected during two consecutive survey campaigns (pre- and post-intervention). The simulations were initialized with data from the first survey campaign (pre-intervention) conducted in the control plots (12 plots: nine in Monte Amiata, two in Varco San Mauro and one in Rincine), where no silvicultural interventions had been applied, and in the "thinned from below" plots (10 plots: nine in Monte Amiata and one in Rincine). The data needed for initializing the simulations were species, mean age, and structural data such as mean tree DBH, mean tree height, and the number of trees in the stand ("TREE"). A comprehensive report on the utilized data can be found in Corona et al. (2025). All simulations were stopped at the year of the second measurement. The simulation outputs for the year of the second measurement were then compared with the corresponding field-observed values for key variables, and the percentage Root Mean Squared Error (RMSE, %) and Coefficient of Determination (R^2) were computed. Figures 2 and 3 illustrate the strong agreement between the predicted and observed values, confirming the model's reliability and supporting its use in this study for both the no-management and thinning scenarios.

To evaluate stand dynamics of the 34 plots (27 at Monte Amiata, 3 at Rincine and 4 at Varco San Mauro) and the associated provision and economic quantification of ES in European black pine plantations, 20 thinning from below regimes were simulated using data collected from the experimental plots. These regimes were distinguished by thinning intensity (percentage of stand basal area to remove based on total stand basal area) and frequency (years between interventions), with combinations of thinning frequency ranging from 10 to 25 years (in 5-year increments) and thinning intensity varying from 15 to 35% of basal area (in 5% increments). In all thinning regimes, "thinning from below" was simulated by removing trees from smallest to largest until the target thinning intensity was reached. An additional non-intervention scenario was included for all plots at each site as a control, resulting in a total of 20 thinning regimes

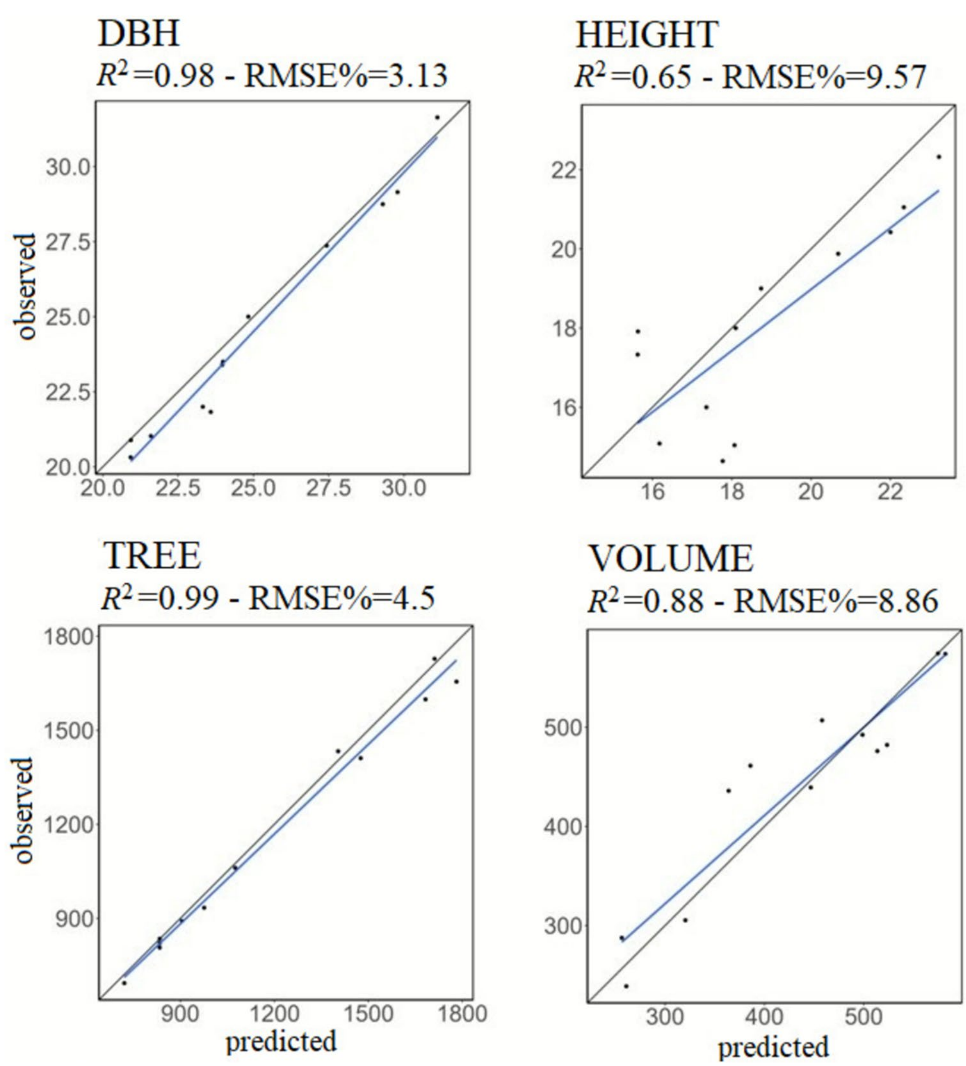

Fig. 2 Values predicted by the 3D-CMCC-FEM model (*x*-axis) vs. observed values (*y*-axis) for selected variables (DBH: mean tree diameter at breast height; HEIGHT: mean tree height; TREE: number of trees; and VOLUME: wood volume) in the control plots. Black lines represent the $y=x$ line; blue lines represent the linear regression between predicted and observed

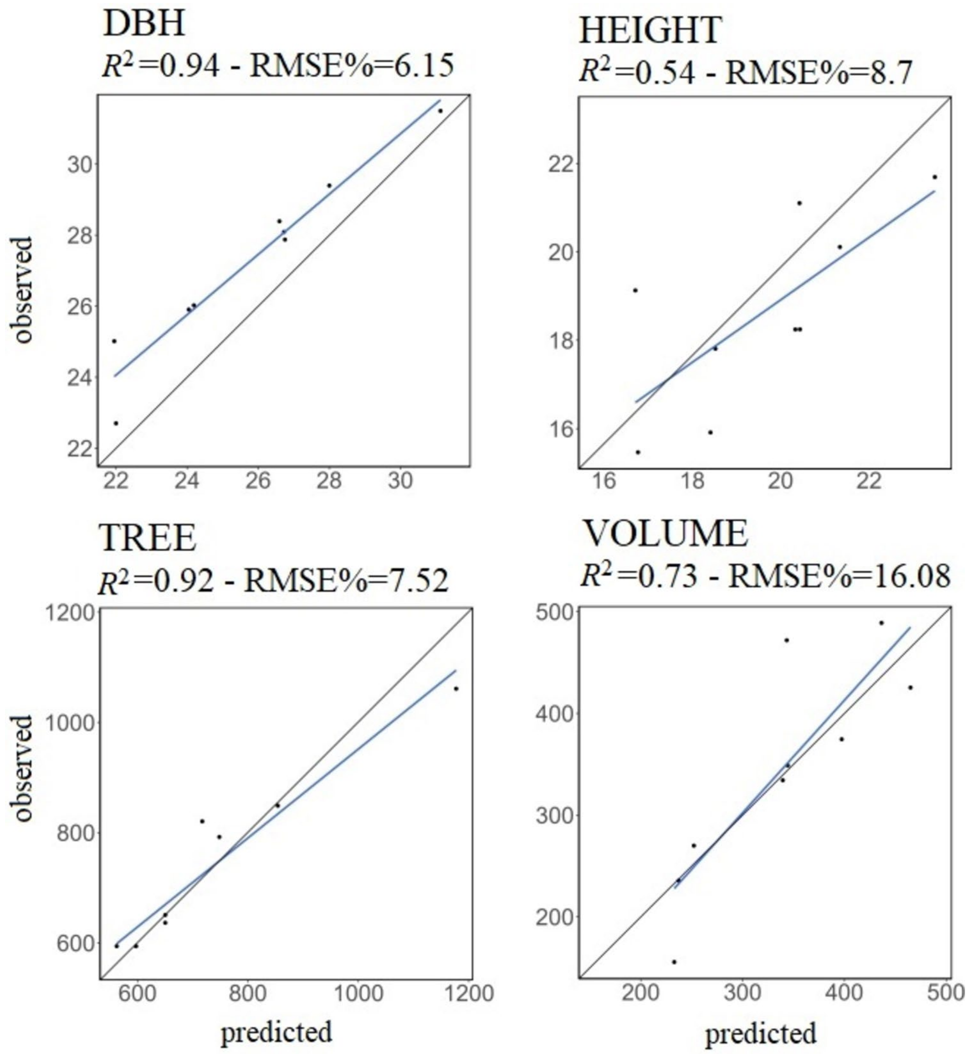

Fig. 3 Values predicted by the 3D-CMCC-FEM model (*x*-axis) vs. observed values (*y*-axis) for selected variables (DBH: mean tree diameter at breast height; HEIGHT: mean tree height; TREE: number of trees; and VOLUME: wood volume) in the thinned from below plots. Black lines represent the $y=x$ line; blue lines represent the linear regression between predicted and observed

(4 frequencies × 5 intensities) + 1 control. The focus of this assessment was to analyze the sole impact of thinning interventions on the selected ES, described in paragraph 2.5. To isolate this effect, the rotation period was set such that final harvesting was excluded from the simulation period.

For the long-term simulations, each plot was initialized using the structural variable values measured in the pre-intervention survey. Simulations were conducted using the "R3DFEM R package" (Vangi et al. 2025), which provides an R wrapper for the 3D-CMCC-FEM model. These simulations spanned the period from the year of the first survey at each study site to 2100, corresponding to a time frame of approximately 83 to 93 years, depending on the site. The key variables selected for the economic quantification of ESs included: "DBH", measured in centimeters (cm); "HEIGHT", measured in meters (m); stand basal area (B), measured in square meters per ha (m^2 ha^{-1}); aboveground carbon content (AGC), measured in mega grams of carbon per hectare (Mg ha^{-1}); canopy cover (C), expressed as a unitless proportion; harvested wood volume (HWV), measured in cubic meters per hectare per year (m^3 ha^{-1} y^{-1}).

Economic quantification of ES

The model outputs were used to estimate the provision of ES and quantify their economic value. The economic efficiency of thinning interventions was evaluated for each year of the simulation period. To underscore the role of thinning in enhancing stand stability, an assessment of avoided economic damage was conducted by comparing the outcomes with those of the non-intervention (control) scenario.

Wood production

Wood production is a key provisioning service of managed forests, directly contributing to the bioeconomy and supporting local livelihoods by sustainably supplying timber for construction and energy. The financial value of wood production is quantified by calculating the stumpage value (SV) of harvested wood volume in year *n*. The SV is a typical transformation value that is defined by the classic forestry economic-appraisal approaches, as the value of standing trees, or the difference between revenues (I) and costs (S) of the production process Eq. 1:

$$SV_n = I_n - S_n \tag{1}$$

Revenues are quantified considering both obtainable volume (predicted from the 3D-CMCC-FEM model outputs) and the average selling price of wooded assortments. The cost calculation involved an analysis of regional price lists (Tuscany and Calabria) for the reference operations. Specifically, thinning operations in coniferous forests involved cutting, debranching, extraction, clearing and site arrangement, as well as general expenses (direction costs, administrative costs and interest; Bernetti and Romano 2007). The unit of measure for revenues and costs is € m^{-3}.

The Net Present Value for provision service (NP_SV) is calculated by discounting SV with Eq. 2:

$$NP_{SV} = \sum_{n=1}^{x} \frac{SV_n}{q^n} \tag{2}$$

where, $q = 1 + r$, with r equal to the interest rate (assumed as 2.5% in this study; Sartori et al. 2014).

Aesthetic value

The aesthetic value of a forest landscape is closely tied to its ability to meet the cultural and recreational needs of the population, and it can significantly influence public perception and tourism potential. Drawing on a synthesis of extensive scientific literature on this topic, the calculation of aesthetic value is based on the work of Ribe (2009). In this study, various types of coniferous stands (mature, aged and those subject to logging) are analyzed to determine their scenic value, as perceived by a sample of respondents, using the Ratio Scenic Beauty Estimate (RSBE). The RSBE is calculated as a function of the basal area per ha (B, m^2 ha^{-1}) through the following polynomial model (Eq. 3):

$$RSBE_n = -108{,}3 + 4{,}1 \bullet B_n - 0{,}02 \bullet {B_n}^2 - 0{,}00004 \bullet {B_n}^3 \tag{3}$$

where, $RSBE_n$ indicates the value of RSBE in year n.

The model was validated in Ribe et al. (2009) for mature conifer forests and different harvest regimes. The objective was to sample in-stand scenery representative of the diversity of unharvested forests and well-controlled harvests. To achieve this objective, photographs were sampled from the Demonstration of Ecosystem Management Options (DEMO) (Aubry et al. 2004) and the Long Term Ecosystem Productivity (LTEP) databases (Homann et al. 2001). Higher RSBE values indicate better recreational suitability and vice versa. The RSBE values observed in Ribe (2009) vary in the range (+ 150, –150). These represent, respectively, upper and lower values of mean RSBEs computed in the sample forests and correspond to a scenic beauty of very high and very low qualitative perception from respondents (Ribe 2009). This dimensionless value must therefore be managed to achieve the economic value of the aesthetic function. The Benefit Transfer (BT) approach (Desvouges et al. 1998) is helpful for quickly transferring results from other case studies to areas of interest. A meta-analysis based on Contingent Valuation, Discrete Choice Experiments, and the Travel Cost Method was used, highlighting a Willingness to Pay (WTP) of 7.79 € visit y^{-1} for recreational utility in coniferous forests in the Italian context (Grilli et al. 2014). Reported WTP (7.79 € visit y^{-1}) can be cautiously considered as expressive of the maximum WTP for forests with optimal aesthetic value (RSBE = + 150). With this hypothesis, the annual WTP is quantified, weighing the potential maximum WTP on the normalized RSBE ($norm_{RSBE}$). The normalization occurred through the multicriteria approach of Compromise Programming (Romero and Rehman 2003) (Eq. 4):

$$norm_{RSBE,n} = 1 - \left(\frac{ideal_{RSBE} - RSBE_n}{ideal_{RSBE} - antiideal_{RSBE}} \right) \tag{4}$$

where, $ideal_{RSBE}$ and $antiideal_{RSBE}$ represent, respectively, the ideal (+ 150) and non-ideal (–150) RSBE values as per Ribe (2009).

The aesthetic value (AV_n) (€ ha^{-1} y^{-1}) is then calculated as Eq. 5:

$$AV_n = 7.79 \bullet norm_{RSBE} \bullet n_{visit} \tag{5}$$

where, n_{visit} is the estimated annual number of visits for the area under consideration. Given the absence of specific data in the various study areas, the value of n_{visit} was arbitrarily set to 150 for each examined stand.

The NPV for the aesthetic function (NP_AV) is quantified as Eq. 6:

$$NP_{AV} = \sum_{n=1}^{x} \frac{AV_n}{q^n} \tag{6}$$

Protection from erosion

Forests play a crucial role in stabilizing soils, particularly in erosion-prone Italian terrains characterized by steep slopes crossed by a dense river network, where vegetation cover and root systems mitigate sediment loss and sustain land productivity. The model is based on the quantification of avoided soil erosion due to forest cover in relation to the effect of atmospheric precipitation. The economic value of avoided erosion is then derived from the correlation with the price of sediment removal from potential basins located downstream of the forest area (Sacchelli et al. 2021).

The amount of erosion was calculated using the Revised Universal Soil Loss Equation (RUSLE, 2015) (Panagos et al. 2015a). The "RUSLE2015" formula estimates soil loss (E, t ha^{-1} a^{-1}), applying five input factors: rainfall erosivity (R), soil erodibility (K), forest canopy cover (C), topography factor (LS) and support practices (P) (Eq. 7):

$$E = R \bullet K \bullet LS \bullet C \bullet P \tag{7}$$

The geodata applied in the equation are freely available upon request in the European Soil Data Center (ESDAC) (https://esdac.jrc.ec.europa.eu/resource-type/soil-threats-data) (Panagos et al. 2022).

In this work, R, K, and LS factors were kept constant, given their very low variation over medium to long terms and their low influence on forest rotation. Soil erodibility (K) and topography factor (LS) can be considered relatively constant over decades corresponding to the rotation period, due to low variability in both lithological and geomorphological aspects. Rainfall erosivity (R) can vary due to climate change and pluviometric regimes. However, the high uncertainty and the difficulty in quantifying the modification of the R parameter and its impact on erosivity do not justify the variation of this factor. Future analysis should consider a sensitivity analysis on R. The P factor is excluded due to its limited application in the forestry sector (Panagos et al. 2015a).

The assessment of avoided erosion in year n is based on the difference between the factor C_n with forest and the factor C_0 in the hypothesis of absence of forest cover ($\theta_n = 0$). The value of C is quantified according to the formula reported in Panagos et al. (2015b) (Eq. 8):

$$C = C_{minLU} + \left(C_{maxLU} - C_{minLU}\right) \bullet \left(1 - \theta_n\right) \tag{8}$$

where, C_{minLU} and C_{maxLU}, respectively, the minimum and maximum values of C for forests (Panagos et al. 2015b) and θ_n fraction of canopy cover at ground level in year n.

The avoided erosion in year n is then calculated as Eq. 9:

$$E_n = R \bullet K \bullet LS \bullet \left(C_0 - C_n\right) \tag{9}$$

E_n was recalibrated with the application of the Sediment Delivery Ratio (SDR) (De Rosa et al. 2021), a coefficient allowing for quantification of actual soil debris from the basin slope to the reservoir (Eq. 10):

$$SDR = 0.4724 - A^{-0,125} \tag{10}$$

where, A corresponding to the size of the catchment area in km^2.

The SDR quantification technique developed by De Rosa et al. (2021) is tested in catchments of central Italy (Apennine area). The method computes an SDR value lower than the values reported in the scientific literature by other methods. However, it can take into account the characteristics of the basin, which in its central part has a morphological depression that acts as a trap effect for sediments (De Rosa et al. 2021), as is typical in our case studies.

The monetary value of protection from erosion (PV) is based on the unitary cost (α) of sediment removal from artificial basins or reservoirs as established in Palmieri et al. (2014) (29.29 € t^{-1}) (Eq. 11):

$$PV_n = E_n \bullet SDR \bullet \alpha \tag{11}$$

The NPV of the protective function (NP_PV) can be finally calculated as Eq. 12:

$$NP_{PV} = \sum_{n=1}^{x} \frac{PV_n}{q^n} \tag{12}$$

Carbon storage

This ES reflects the forest's capacity to act as a carbon sink and retain atmospheric CO_2, contributing to climate change mitigation and national greenhouse gas inventories. In this study, we only accounted for carbon stored in the above-ground biomass. The estimate of carbon value begins with the growing stock volume and, using wood basal density (WBD, Giordano 1980) and Biomass Expansion Factors (BEFs), leads to the calculation of above-ground biomass (AGB, m^3 ha^{-1}) (Vitullo et al. 2007; Vangi et al. 2023) (Eq. 13).

$$AGB = WBD \bullet GSV \bullet BEF \tag{13}$$

where, AGB is the above-ground biomass, WBD is the wood basal density, GSV is the growing stock volume, and BEF is the biomass expansion factor.

The total AGC is obtained by multiplying biomass by its carbon content (0.47 g of C per gram of dry matter) (Mg ha^{-1}). To obtain the mass of stored CO_2, the mass of carbon is multiplied by the β coefficient of 3.67 (Federici et al. 2008), which is the ratio between the atomic mass of C and CO_2.

The European Emission Trading System (ETS) market was applied to derive the carbon trading price (γ) (https://tradingeconomics.com/commodity/carbon). The average price in the ETS market for 2024 was selected for analysis.

The monetary annual value of the carbon storage function (CV) is given by Eq. 14 (Sacchelli 2018):

$$CV_n = \Delta AGB_n \bullet \beta \bullet \gamma \tag{14}$$

where, ΔAGB represents the variation of AGB from year n-1 to year n; the CV_n equation, a precautionary hypothesis that, for the harvesting year, the carbon contained in the removed biomass is deducted from the quantification, without knowing the final use of the woody assortments.

The NPV of the externality (NP_CV) is obtained as Eq. 15:

$$NP_{CV} = \sum_{n=1}^{x} \frac{CV_n}{q^n} \quad (15)$$

Total Economic Value

Total Economic Value (TEV) captures the diverse benefits provided by each ES, allowing for a comprehensive assessment of trade-offs and synergies in multifunctional forest management. The Net Present TEV (NP_TEV) is derived from the sum of the discounted value of the four ecosystem utilities (Eq. 16):

$$NP_{TEV} = NP_{SV} + NP_{AV} + NP_{PV} + NP_{CV} \quad (16)$$

Analysis of avoided damage

Thinning can provide significant benefits to the structural stability of stands (Hanewinkel et al. 2013; Suliman and Ledermann 2025). Stability improvements can be quantified in both biophysical and economic terms. Within this context, assessing the potential indirect effects of thinning, such as avoided damage, is particularly relevant. Avoided damage can be evaluated by comparing the probability of adverse effects in stands without interventions (control) to those with interventions.

One of the key parameters for maintaining the structural stability of coniferous stands is the mean tree height—to—mean tree DBH ratio (H/D, Slodicak and Novak 2006). Building on the approach of Mickovski et al. (2005) and focusing specifically on wind damage, a risk trend associated with the H/D ratio can be identified. Notably, Mickovski et al. (2005) define five risk classes based on H/D ratio thresholds, ranging from < 70 to > 90. Starting from this categorization, the first step to calculate the missed damage was the quantification of the average value of the H/D ratio for each thinning regime; subsequently, to identify a stability coefficient of the stands (δ), the H/D ratio was normalized in the range 0–1 with the compromise programming technique (Romero and Rehman 2003). The ideal value was set equal to 50, while the anti-ideal value was equal, for each experimental plot, to the average H/D ratio of the non-intervention scenario. Ideal and anti-ideal values are based on work by La Marca (2005), which highlights, for conifer stands in central Apennines and at different ages, a low risk due to wind damage with an H/D ratio lower than 50. The same author also reports a higher risk in experimental plots in the case of no intervention and the absence of thinnings throughout the rotation period. Finally, the avoided damage results from the combination (joint probability), for each plot and thinning regime, between the total economic value, the probability of stability increase linked to thinning, and the probability of extreme winds (λ). The λ coefficient represents the annual probability of winds potentially causing damage to the stands, related to the reference period (μ, years). The value was extracted at the cartographic level for each plot using zonal statistics operations, starting from the geodata provided by Sacchelli et al. (2018). In particular, the lambda value is calculated based on the output from Sacchelli et al. (2018), i.e., a raster map with a 100 m × 100 m resolution. For each study area, the zonal statistics operation provides the average probability of extreme winds.

The expected avoided damage *E(AD)* in the case of thinning is therefore quantified as Eq. 17:

$$E(AD) = NP_{TEV} \bullet \lambda \bullet \mu \bullet \left(\delta_{no_{thin}} - \delta_{thin}\right) \quad (17)$$

where, δ_{no_thin} and δ_{thin} are, respectively, the stability coefficient of the stands (normalized H/D ratio) for the j-th scenario without and with intervention.

Results

Stand dynamics

The simulation outputs for varying thinning regimes applied to the 34 experimental plots of European black pine across the study areas are presented below. Figures 4 and 5 illustrate the trends in DBH and AGC over the simulation period for each combination of thinning frequency and intensity at each site.

The most significant increments in DBH and tree height were observed across all sites by the end of the simulation period, with a thinning frequency of 10 years at 35% intensity. Specifically, DBH growth reached 142, 127 and 122 cm, while tree height growth reached 24, 25 and 23 m for Monte Amiata, Varco San Mauro and Rincine, respectively. These were followed by a thinning frequency of 10 years at 30% intensity.

In contrast, AGC and basal area exhibited greater growth under a longer thinning frequency of 25 years, combined with the same 35% intensity (AGC increase of 73, 52 and 30 Mg ha^{-1} for Monte Amiata, Varco San Mauro and Rincine, respectively). Overall, heavy-intensity thinning regimes applied at short intervals yielded the highest DBH increments, with values doubling those observed under the no-management scenario, which reflects the need for light for more sustained radial growth. Those are expected results, since high-frequency, heavy-intensity

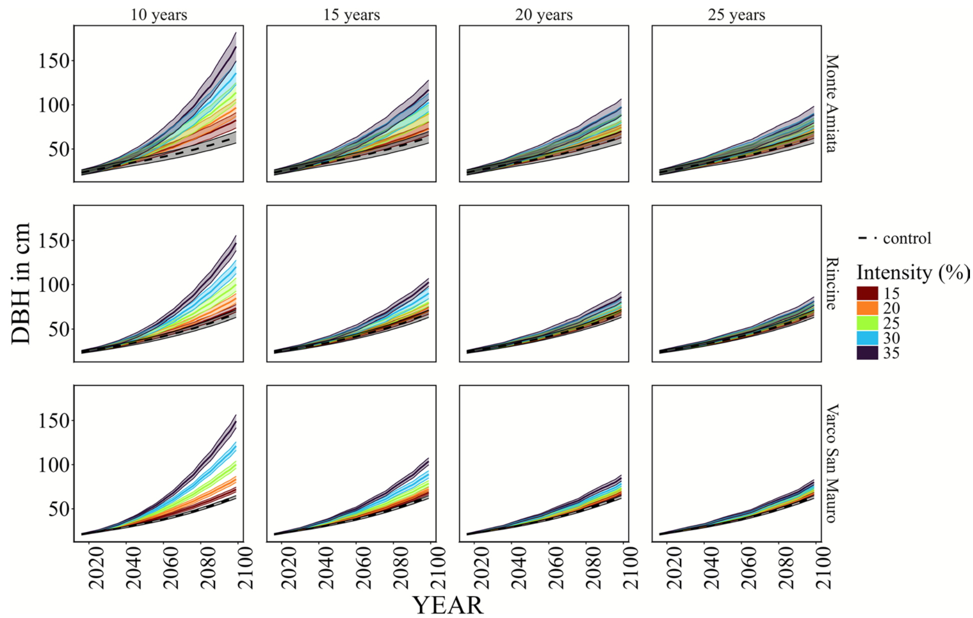

Fig. 4 Average DBH (in cm) time series for each combination of site and thinning frequency (every 10, 15, 20 and 25 years), computed from the DBH of all simulated plots. Colors map different thinning intensities (removal of 15%, 20%, 25%, 30% and 35% of basal area); the grey color is for the non-intervention (control) scenario. The shaded area represents one standard deviation from the mean value of all simulated plots

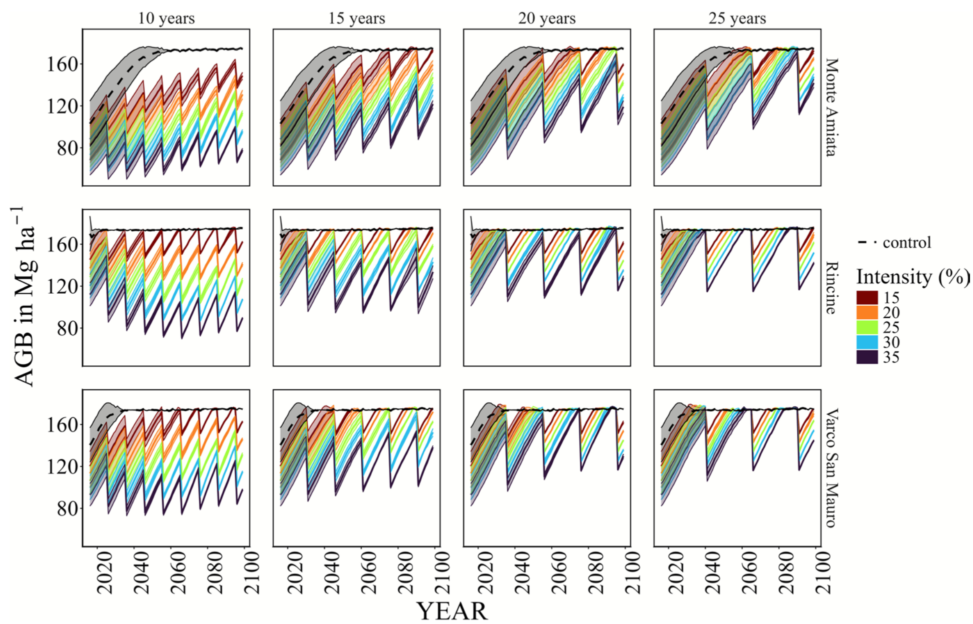

Fig. 5 Average AGC (in Mg ha^{-1}) time series for each combination of site and thinning frequency (every 10, 15, 20 and 25 years), computed from the AGC of all simulated plots. Colors map different thinning intensities (removal of 15%, 20%, 25%, 30% and 35% of basal area); the grey color is for the non-intervention (control) scenario. The shaded area represents one standard deviation from the mean value of all simulated plots

regimes resulted in substantial wood removal, leading to lower basal area and AGC values.

Consequently, the highest volume of harvested woody products across all thinning regimes was achieved with a 10-year frequency and 35% intensity, exceeding 2100, 1980 and 1680 m^3 ha^{-1} over approximately 90 years for Monte Amiata, Varco San Mauro, and Rincine, respectively. These values indicate highly productive sites, which, in combination with frequent thinning operations, can provide a stable supply of biomass. On the other hand, the lowest volume of harvested woody products (excluding the control scenario with no intervention) was expectedly recorded under the least intensive thinning regime (15%) combined with the longest frequency (25 years).

In summary, while high-intensity and frequent interventions maximize individual tree growth (DBH) and the yield of harvested woody products, they may reduce basal area and AGC accumulation. Conversely, low-intensity, less frequent interventions help sustain basal area and carbon storage, highlighting a clear trade-off between maximizing growth and preserving ecosystem carbon stocks.

Economic quantification of ES

The results of the thinning regimes for the examined plantations indicate that NP_SV increases with both the amount of basal area removed and the length of the thinning interval (Tables 3, 4 and 5). Analyzing NP_SV in relation to thinning interval and wood removal, it was observed that, at the Monte Amiata site, NP_SV remained negative up to a removal threshold of 20% of the basal area. For higher levels of wood removal, a positive monetary value was achieved when the thinning interval was at least 15 years (Fig. 6).

The average net present values across the various thinning regimes for the case studies of Monte Amiata, Rincine and Varco San Mauro were as follows: (1) productive function: –2178, 1777 and –431 € ha^{-1}, respectively; (2) aesthetic function: 24,917, 28,199 and 27,567 € ha^{-1}; (3) erosion protection: 141, 215 and 163 € ha^{-1}; (4) carbon storage: 28,843, 36,743 and 35,138 € ha^{-1}. The Total Economic Value (TEV), averaging all ES, was therefore 51,723 € ha^{-1}, 66,934 € ha^{-1} and 62,438 € ha^{-1} for Monte Amiata, Rincine and Varco San Mauro, respectively.

The H/D ratio improved as the thinning intensity increased and the frequency decreased, with average values of 63, 66 and 66 for Monte Amiata, Rincine and Varco San Mauro, respectively. Avoided damages, depending on the thinning regime, ranged between 1037 and 7031 € ha^{-1} for Monte Amiata (2%–18% of TEV), 207 and 3948 € ha^{-1} for Rincine (0.3%–7% of TEV), and 570 and 8846 € ha^{-1} for Varco San Mauro (1%–16% of TEV).

Analysis for individual silvicultural interventions identified the minimum harvested wood volume required to achieve a positive stumpage value in each thinning regime. For example, in the case of the plantation in Varco San Mauro (Table 6), the minimum harvesting volume required for financial efficiency was approximately 160 m^3 ha^{-1}. Yield increases with stand age, reaching around 650 m^3 ha^{-1} in 60-year-old plantations (Castellani 1982), as found in the control plots in the Varco San Mauro study area.

Discussion

Black pine stands and ES dynamics under different thinning regimes

Thinning from below is one of the most used and effective practices in artificial forest stands, especially in conifer plantations, to regulate stand density, control competition, increase carbon sequestration, and control biomass allocation among different organs in trees (Jonard et al. 2006; Cantiani et al. 2015; Cabon et al. 2018). Our study examined the impact of thinning intensity and frequency from below on ES provision in European black pine plantations established in Italy for environmental improvement under a constant climate, aiming to minimize confounding effects. This is one of the few studies, to our knowledge, that exploits PBFM for the quantification and assessment of ESs under different thinning regimes, including their economic value. Previous modeling studies have evaluated the effects of forest management on ES provision. However, most have focused on a limited set of services, such as wood production and carbon storage (Bachelet et al. 2018). For example, Simon and Ameztegui (2023) used the individual-based model SORTIE-ND to simulate the effect of different thinning options on numerous ESs, but without quantifying their economic value. In Italy, within the framework of a large-scale study on the response of ESs to management, Biber et al. (2015) applied the EFISCEN model, a large-scale matrix empirical model initialized with NFI data. Unfortunately, EFISCEN does not incorporate eco-physiological processes and how they interact with climate and its effects. Moreover, the authors tested a limited number of forest management scenarios. The 3D-CMCC-FEM model used to simulate stand growth under different thinning regimes has effectively captured the effects of silvicultural interventions on stand structure and dynamics, aligning with findings from previous studies (Dalmonech et al. 2022; Testolin et al. 2023; Saponaro et al. 2025, 2026).

Our results showed that DBH growth was positively influenced by intense thinning regimes applied at short intervals, with the most significant increment occurring at a frequency of 10 years and a 35% of basal area removal. This result reflects the higher light and soil water availability post-intervention, potentially due to less competition between the remaining trees. This finding is consistent with previous studies that have shown competition to be a key driver of radial growth in black pine (Sánchez-Salguero et al. 2013; Tudoran et al. 2023). For instance, in our simulations, a 35% reduction in basal area causes the canopy cover to drop from 80% (the baseline without intervention) to approximately 67%, regardless of the frequency, compared to a drop of around 2% for the less intense regime (15% basal area reduction). These results confirm the strong short-term structural effects of intensive thinning interventions. On the contrary, thinning interventions at shorter intervals have a detrimental long-term effect on the growth response of total basal area and AGC in Rincine and Varco San Mauro. Short intervals (< 15 years) combined with high intensity (> 20% basal area removal) caused steady or negative trends in both variables at sites such as Rincine and Varco San Mauro, which are characterized by young (< 35 years) and dense stands (> 1100 ind. ha^{-1}). These conditions result in a larger number of trees being removed per intervention and, consequently, higher harvested woody volumes for the same relative basal area reduction. By contrast, low-intensity, less frequent interventions proved to be most effective in achieving

Table 3 Economic results for the plantation of Monte Amiata for each thinning regime (frequency_intensity), including the non-intervention (control) scenario

Thinning regime (years_%)	NP_SV (€ ha^{-1})	NP_AV (€ ha^{-1})	NP_PV (€ ha^{-1})	NP_CV (€ ha^{-1})	NP_TEV (€ ha^{-1})	Average H/D ratio	Norm H/D ratio	Damage thinning (€ ha^{-1})	Damage no thinning (€ ha^{-1})	Avoided damage (€ ha^{-1})	%_avoided dam TEV
10_15	–11,250	25,933	141	30,671	45,495	65	0.78	8347	10,700	2353	5
10_20	–7377	24,622	142	27,394	44,781	63	0.66	6946	10,532	3586	8
10_25	–3164	23,188	141	24,353	44,517	60	0.53	5541	10,470	4930	11
10_30	–625	21,713	140	21,472	42,700	57	0.39	3961	10,043	6082	14
10_35	1072	20,143	139	18,652	40,007	55	0.25	2378	9410	7031	18
15_15	–8224	26,803	142	33,762	52,482	67	0.87	10,742	12,344	1601	3
15_20	–5033	25,936	142	31,168	52,213	65	0.79	9707	12,280	2573	5
15_25	–1305	24,931	141	28,665	52,433	63	0.70	8673	12,332	3659	7
15_30	1313	23,824	140	26,221	51,498	61	0.60	7301	12,112	4812	9
15_35	3674	22,668	139	23,842	50,323	59	0.50	5917	11,836	5919	12
20_15	–6708	27,125	142	34,304	54,863	67	0.91	11,685	12,904	1219	2
20_20	–3795	26,511	142	32,463	55,322	66	0.85	11,092	13,012	1919	3
20_25	–1042	25,755	141	30,428	55,281	65	0.79	10,231	13,002	2771	5
20_30	1375	24,879	140	28,122	54,516	64	0.71	9124	12,822	3698	7
20_35	3768	23,972	140	26,134	54,014	62	0.63	8038	12,704	4666	9
25_15	–6402	27,275	142	35,190	56,204	68	0.92	12,183	13,219	1037	2
25_20	–4116	26,768	142	33,659	56,452	67	0.88	11,697	13,278	1581	3
25_25	–871	26,156	141	31,909	57,336	66	0.83	11,204	13,485	2281	4
25_30	1476	25,467	140	30,131	57,215	65	0.77	10,412	13,457	3045	5
25_35	3665	24,679	140	28,329	56,813	63	0.71	9443	13,362	3919	7
Control	0	28,324	143	38,142	66,609	69	1.00	15,666	15,666	0	0

Table 4 Economic results for the plantation of Rincine for each thinning regime (frequency_intensity), including the non-intervention (control) scenario

Thinning regime (years_%)	NP_SV (€ ha^{-1})	NP_AV (€ ha^{-1})	NP_PV (€ ha^{-1})	NP_CV (€ ha^{-1})	NP_TEV (€ ha^{-1})	Average H/D ratio	Norm H/D ratio	Damage thinning (€ ha^{-1})	Damage no thinning (€ ha^{-1})	Avoided damage (€ ha^{-1})	%_avoided dam TEV
10_15	–7707	29,227	217	40,020	61,757	67	0.93	6267	6744	476	1
10_20	–1793	28,335	217	36,187	62,945	65	0.83	5674	6874	1200	2
10_25	2661	27,091	215	32,442	62,409	63	0.70	4738	6815	2077	3
10_30	7404	25,661	213	28,801	62,080	60	0.55	3740	6779	3039	5
10_35	10,150	24,080	212	25,347	59,789	57	0.40	2581	6529	3948	7
15_15	–6137	29,453	217	41,516	65,049	68	0.96	6800	7103	303	0
15_20	–1690	29,106	217	39,945	67,578	67	0.92	6803	7379	576	1
15_25	2606	28,522	215	37,484	68,827	66	0.86	6482	7516	1034	2
15_30	6019	27,632	214	34,386	68,251	64	0.77	5745	7453	1708	3
15_35	10,436	26,573	213	31,539	68,761	63	0.67	5014	7509	2495	4
20_15	–5217	29,517	217	41,408	65,924	68	0.97	6965	7199	234	0
20_20	–1643	29,258	217	40,125	67,957	68	0.94	6999	7421	422	1
20_25	2025	28,891	216	38,488	69,620	67	0.91	6921	7602	682	1
20_30	5693	28,387	214	36,533	70,827	66	0.86	6683	7734	1052	1
20_35	9044	27,675	213	34,241	71,174	65	0.79	6178	7772	1595	2
25_15	–5144	29,552	217	42,038	66,663	68	0.97	7072	7280	207	0
25_20	–2414	29,325	217	40,920	68,047	68	0.95	7070	7431	361	1
25_25	420	29,007	216	39,525	69,168	67	0.93	6987	7553	566	1
25_30	3236	28,601	215	37,882	69,934	67	0.89	6812	7637	825	1
25_35	7600	28,081	214	36,030	71,925	66	0.85	6670	7854	1185	2
Control	0	29,841	218	43,466	73,525	69	1.00	8029	8029	0	0

Table 5 Economic results for the plantation of Varco San Mauro for each thinning regime (frequency_intensity), including the non-intervention (control) scenario

Thinning regime (years_%)	NP_SV (€ ha^{-1})	NP_AV (€ ha^{-1})	NP_PV (€ ha^{-1})	NP_CV (€ ha^{-1})	NP_TEV (€ ha^{-1})	Average H/D ratio	Norm H/D ratio	Damage thinning (€ ha^{-1})	Damage no thinning (€ ha^{-1})	Avoided damage (€ ha^{-1})	%_avoided dam TEV
10_15	–9785	28,594	164	37,970	56,943	68	0.91	12,988	14,350	1362	2
10_20	–4871	27,635	164	34,433	57,361	66	0.80	11,541	14,455	2914	5
10_25	82	26,390	163	30,979	57,614	63	0.67	9709	14,519	4810	8
10_30	3646	25,032	161	27,716	56,555	61	0.53	7503	14,252	6749	12
10_35	7730	23,567	160	24,602	56,060	58	0.37	5281	14,127	8846	16
15_15	–8012	28,938	164	39,725	60,815	69	0.95	14,496	15,325	829	1
15_20	–3578	28,482	164	38,065	63,133	68	0.90	14,388	15,910	1521	2
15_25	300	27,805	163	35,705	63,974	67	0.84	13,520	16,121	2602	4
15_30	3559	26,909	162	33,006	63,636	65	0.75	11,991	16,036	4045	6
15_35	7701	25,828	161	30,130	63,820	63	0.64	10,291	16,083	5792	9
20_15	–6799	29,032	164	39,761	62,159	69	0.96	14,995	15,664	669	1
20_20	–3110	28,694	164	38,353	64,101	69	0.93	15,017	16,153	1137	2
20_25	161	28,242	163	36,670	65,236	68	0.89	14,669	16,440	1771	3
20_30	3420	27,654	162	34,689	65,926	67	0.84	13,960	16,613	2653	4
20_35	6596	26,940	161	32,668	66,365	66	0.77	12,930	16,724	3794	6
25_15	–6104	29,086	164	40,416	63,562	69	0.96	15,448	16,018	570	1
25_20	–3678	28,786	164	39,270	64,543	69	0.94	15,320	16,265	944	1
25_25	–1184	28,407	163	37,888	65,274	68	0.91	15,028	16,449	1421	2
25_30	1358	27,944	162	36,258	65,722	68	0.88	14,533	16,562	2029	3
25_35	3953	27,381	162	34,461	65,956	67	0.83	13,811	16,621	2809	4
Control	0	29,608	165	42,351	72,123	70	1.00	18,175	18,175	0	0

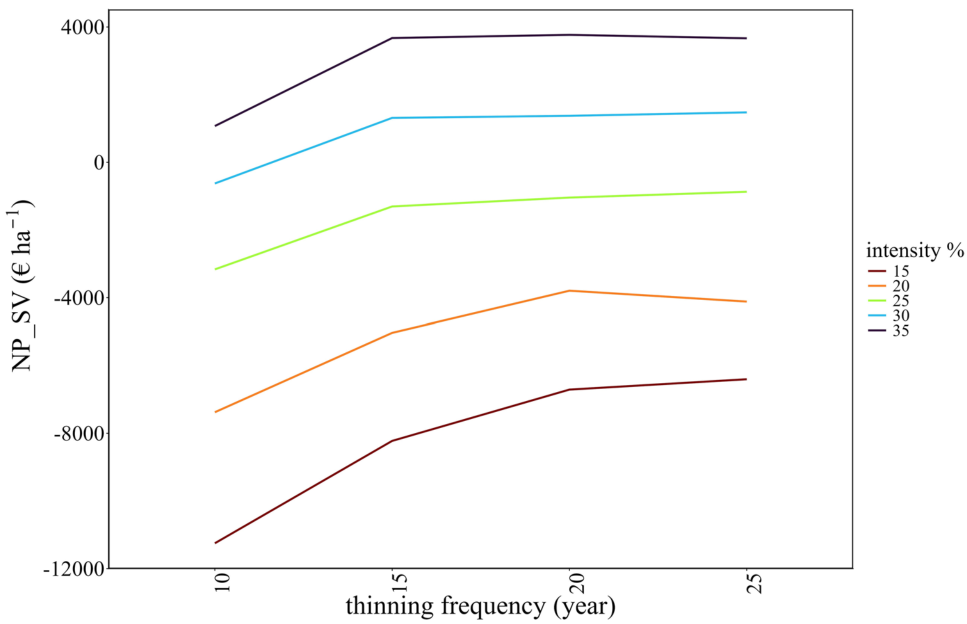

Fig. 6 Net Present Stumpage Value (NP_SV) as a function of thinning intensity (removal of 15%, 20%, 25%, 30% and 35% of basal area) and frequency (every 10, 15, 20 and 25 years). Example based on the Monte Amiata plantation

Table 6 Harvested wood volume per thinning intervention (m^3 ha^{-1}) as a function of the intervention year, thinning frequency (every 10, 15, 20 and 25 years), and thinning intensity (removal of 15%, 20%, 25%, 30% and 35% of basal area)

Thinning year	Intensity: 15%	Intensity: 20%	Intensity: 25%	Intensity: 30%	Intensity: 35%
Frequency: 10 years					
n	59*	78*	98*	118*	137*
n + 10	76*	98*	118*	135*	150*
n + 20	95*	121*	143*	161*	176
n + 30	115*	144*	170	191	208
n + 40	132*	166	195	219	237
n + 50	146*	185	217	244	258
n + 60	160	205	242	262	291
n + 70	171	223	254	293	313
n + 80	179	235	279	305	319
Frequency: 15 years					
n	59*	78*	98*	118*	137*
n + 15	91*	117*	143*	166	187
n + 30	117*	157*	192	221	249
n + 45	136*	186	233	270	301
n + 60	156*	212	275	318	357
n + 75	170	231	298	355	381
Frequency: 20 years					
n	59*	78*	98*	118*	137*
n + 20	100*	134*	167	196	223
n + 40	130*	176	225	274	317
n + 60	155*	210	268	329	394
n + 80	175	236	299	366	433
Frequency: 25 years					
n	59*	78*	98*	118*	137*
n + 25	109*	146*	183	222	258
n + 50	141*	191	243	296	355
n + 75	170	228	289	352	418

Values marked with * indicate thinnings with a negative stumpage value. Example based on the Varco San Mauro plantation higher values of stand basal area and AGC, as found in other studies (Marchi et al. 2018; Simon and Ameztegui 2023), compared to the control scenario (no intervention). As a matter of fact, longer intervals between interventions allow stands to match and exceed the final AGC compared to the control scenario, confirming the transient effect of thinning, as observed by Ameztegui et al. (2017) and del Río et al. (2008), who found that low-intensity thinning does not decrease the final basal area significantly compared to a no-intervention scenario. Corona (2024) also observed that for optimizing tree density in relation to wood volume growth, a low-intensity regime with relatively frequent thinning interventions (approximately every 10 years) proves to be the most effective. This approach involves moderate biomass removals by each intervention, typically around 15%–25% of the stand basal area. These findings are mirrored by the physiological capability of trees to allocate more assimilated carbon to new tissue and biomass rather than into the non-structural carbon pool (the reserve pool) because of maintenance respiration proportionally higher, after a reduction in stand density (Collalti et al. 2020; Pappas et al. 2020; Dalmonech et al. 2022), leading to higher harvested woody products. Shorter intervals between thinning lead to higher current annual increments (m^3 ha^{-1} y^{-1}), generally more sustained for high-intensity interventions. Beyond growth and carbon storage, thinning interventions have the benefit of decreasing the competition among trees and increasing the stand's resistance to extreme events, such as windstorms, potentially leading to a longer-lived forest, which represents a long-term biomass pool (Dalmonech et al. 2022; Testolin et al. 2023; Vangi et al. 2024a). The increased stability after thinning is also reflected in the increased H/D ratio (the tree height-to-diameter ratio), a simple yet strong proxy used for mechanical stability analyses. This holds true for every thinning regime tested in the present study.

Economic value of ESs under different thinning regimes

The modeling analyses conducted to quantify ES economically, such as timber production, aesthetic value, erosion control, and atmospheric carbon sequestration, have provided valuable insights for managing European black pine plantations considering their multifunctional role. In line with the structural responses described in the previous section, the economic value of provisioning services, particularly timber production, increases with greater basal area removals and longer thinning intervals. Net financial gain is achieved when basal area removal reaches approximately 25% with a 25-year thinning interval, highlighting the higher financial efficiency of more intensive interventions. Thresholds for harvested timber volume that yield a net financial gain are found to be around 160 m^3 ha^{-1}. These relatively high thresholds are due to the significant costs associated with harvesting operations, in particular in mountainous areas, and the need for economies of scale. In fact, over the last few decades, an increase in the unitary costs of workers and machinery, more than proportional to the revenues obtainable from wooded assortments, has been registered. Variability in net profit from stumpage value (NP_SV) among study areas can be largely attributed to site-level differences in ecological factors (e.g., soil fertility), geomorphological factors (slope, terrain roughness), and logistical factors (access to forest roads and landing sites). Such variability is consistent with patterns observed in Italian mountain forests, where operational constraints often limit the economic viability of thinning (Marchi et al. 2018).

Non-provisioning ES (erosion protection, carbon sequestration, and aesthetic/recreational value) tend to decrease with increased basal area removal but benefit from longer intervals between thinning. These results are intuitive for erosion protection and carbon sequestration; However, the aesthetic/recreational value displayed a more complex relationship with stand structure. Even if some authors defined a negative correlation between density and mood or perception (often analyzed as psychological relaxation, emotional recovery and stress reduction) (An et al. 2004; Li 2010) most of the literature highlights an improvement in the physiological status due to increased forest density (Kobayashi et al. 2019). Grilli et al. (2022) indicated that the restorative effects of forests (including conifer stands) were affected by the degree of greenness, as suggested by their correlation with electroencephalogram (EEG) trends. In addition, even if forests with lower tree density are associated with more panoramic landscapes, which can stimulate feelings of freedom, they seem to be less effective in reducing stress perception or inducing sensations of intimacy (Berman et al. 2008). Results on NP_AV seem to be, therefore, in line with outputs from scientific literature.

More intense management regimes lead to a higher cumulated harvested woody product, which can be seen, potentially, as a long-lasting carbon stock, depending on the end-use of the wood. Thinned stems usually do not meet the sawmills' requisites but can be used, for example, as biofuels in biomass power plants. In this sense, despite the economic value of carbon sequestration potential, the regulatory action on climate (or, in the worst case, neutral when the extracted material is converted into bioenergy) has an intrinsic value that must be considered, regardless of the carbon market. For the studied stands, the economic values of aesthetic appeal and carbon sequestration far exceed those of timber production and erosion protection, regardless of the thinning regime. Specifically, the updated values for aesthetic and carbon sequestration services are, on average, 15–20 times higher than the updated net financial gain of timber production, emphasizing the high level of trade-offs among these ES in monetary terms. Other studies in the Mediterranean area have found that timber production accounts for only a small part of the Total Economic Value of forests compared with other benefits such as carbon sequestration, watershed protection and recreation (Croitoru 2007; Bottalico et al. 2016).

The relatively modest monetary value of erosion protection is linked to two factors: (1) the good forest cover in the initial year and its exponential improvement following the first thinning intervention, and (2) the limited social cost associated with erosion compared to other hydrogeological risk regulation functions, such as flood and landslide prevention (Grilli et al. 2020). However, despite not being accounted for in this study, erosion protection, in addition to limiting maintenance costs of downstream basins, also avoids carbon loss from the soil, which translates into a direct climate benefit.

When aggregated across ESs, the TEV of the studied plantations over the simulation period (2016–2100) was approximately €60,000 ha^{-1}, even in scenarios where thinning operations generated negative stumpage values. Mechanical stability, assessed by the H/D ratio, improves post-thinning, regardless of the treatment type, although this effect diminishes over time. All thinning treatments improve height-to-diameter ratios and enhance stand stability, reducing potential damages in a range from €207 ha^{-1} to €8846 ha^{-1}. Generally, avoided damage is offset by the TEV of these stands, even when the financial outcome of thinning operations (stumpage value) is negative. This holds for basal area removal levels of at least 25% in pine plantations. These findings align with those of Marchi et al. (2018), who similarly observed in the Monte Amiata area that higher volume and basal area removal lead to increased tree stability and carbon sequestration potential, especially when considering the carbon fixed in thinned trees. Their results were preliminary due to the short observation period; however, our simulation study appears to confirm their conclusion and aligns with the literature on the same species and environment (Ruiz-Penado et al. 2013; Marchi et al. 2018; Simon and Ameztegui 2023).

Management and policy implications

Our study can complement regional guidelines that generally leave a wide margin of discretion regarding frequency and intensity of thinning operations, also allowing for overcoming the limits listed under specific authorizations. Other methods for objectively estimating thinning intensity often consider only structural parameters, such as the ratio between the potential basal area and the actual basal area, the site index, and the initial stand density (Corona et al. 2025). These methods are designed to maximize tree growth and stability. In Italy, conventional practice involves removing between 16 and 37% of the basal area at each intervention; however, the absence of clear guidance on thinning frequency may hinder the delivery of multiple ESs. In this study, we explored ESs provisioning, explicitly assessing the cost of operations to better inform forest managers and forest owners on the strategy to achieve the best synergies among ESs, to better fit in the principles of Sustainable Forest Management. Owners can infer the best frequency for thinning operations based on the wanted trade-off among the ESs investigated in this study. However, more ESs should be taken into consideration, and further investigations should be conducted to assess the transferability of this result to other climate regions and forest species.

In summary, while increased thinning intensity and frequency can reduce non-provisioning ecosystem services—such as erosion protection, carbon sequestration, and aesthetic value—longer thinning intervals help sustain these benefits. This comes at the cost of reduced individual tree growth and stability, but ultimately contributes to maximizing the TEV. The analysis of forest ES and their relationships with forest management is a complex task, especially when multiple drivers of change and a wide range of ES are considered for a more complete assessment of forest functions (Nocentini et al. 2022). To optimize the synergies between wood production and other ESs, it is essential to look for forest management approaches that go beyond maximizing a single outcome.

While the no-management scenario has been proposed in various studies as a mitigation strategy (Valade et al. 2017; Peng et al. 2023), this approach is unlikely to be realistic in many Mediterranean contexts. The assumption that harvesting cessation will not lead to a shift in emission activities is probably undesirable (Vangi et al. 2024b). Forests offer a plethora of benefits, including wood production, as well as protection, especially in coastal and mountainous areas. Managing forests for the sake of climate mitigation should not cause other cascading adverse effects, such as biodiversity loss, notch of social and recreational values, and risks associated with extreme events. For this reason, we advocate for appropriate management strategies, calibrated to meet a broader array of specific goals, rather than focusing solely on wood production or carbon storage. These strategies would benefit from better payment for ES schemes, detaching management from the sole economic advantage due to the NP_SV, which is currently the primary driver guiding management choices (including thinning regimes), especially in privately owned forests.

Limitations

In our study, we focused on the relationship between forest management and ES to deliberately avoid confounding effects due to other drivers of change, such as climate change and forest fires (Morán-Ordóñez et al. 2019), and to set a baseline for further studies, where climate change and disturbances could be directly included in the model framework. However, we acknowledge that wildfire could be an extremely influential factor in this analysis, given the sensitive nature of European black pine plantations to fire, despite these long-monitored sites not experiencing any fires in the last two decades. Thinning and fire management practices are somewhat interconnected and can significantly influence each other. On the one hand, thinning can reduce fire intensity and severity by lowering fuel loads and altering forest structure (Garcia-Jimenez et al. 2017; Palmero-Iniesta et al. 2017). More frequent and intense interventions result in a noticeable reduction in dead trees. The number of dead trees in this study was observed to be more sensitive to the frequency of interventions than to their intensity.

On the other hand, fire can affect the outcomes of thinning in contrasting ways, for example, by reducing seed availability or influencing post-fire regeneration with higher resprouting vigor (Palmero-Iniesta et al. 2017). Additionally, it can impact long-term vegetation dynamics, such as species composition and biodiversity (Gao et al. 2024). We did not account for potential species change or migration as the simulated period was relatively short for such dynamics, and the study was explicitly designed to explore the effects of thinning on the provision of ESs and their economic values provided by European black pine plantations. However, such long-term dynamics could affect the conclusion of our findings, for example, by interrupting the management routine due to species changes or decreasing productivity trends resulting from climate change. Although the ESs we considered represent only a portion of the broad spectrum of benefits provided by forests, we focused on some ESs that were less investigated in previous studies, such as soil protection and the aesthetic value of the forest (Marchi et al. 2018; Nocentini et al. 2022; Simon and Ameztegui 2023).

Aside from the simulation assumption, we acknowledge that uncertainties in the model parametrization and calibration could slightly alter the result of wood volume accumulation and, consequently, the TEV estimation. Future studies will focus on the effect of these uncertainties on the final economic values of ESs, including other services not addressed in this study, which will complement the significance of the final TEV and the overall trade-off between management and ES provisioning. Moreover, future studies should investigate the interplay of climate change and management when estimating the TEV, despite the narrative behind climate change scenarios being difficult to translate into simulable management practices.

Finally, the proposed modeling approach economically evaluates multiple ES by integrating standard parameters and coefficients that are specific to the plantations in our case study. Its modular flexibility allows for the inclusion of other drivers of change and additional ES in future applications, such as fire hazard reduction, which facilitates detailed assessments and supports sensitivity analyses on variables like harvesting costs, average assortment prices, interest rates, sediment removal costs, and CO_2-eq prices. Sensitivity analyses should, in additional evaluations, outline thresholds on economic and financial gains. In particular, the estimated number of visitors set in the model represents a cautionary value due to local conditions and due to the high economic benefit quantified for NP_AV. However, future evaluations should integrate a wider range of visitors for a sensitivity analysis based on this coefficient. The transferability of the study to other species or climatic regions requires further investigation, despite the proposed model framework being highly flexible and potentially applicable to a wide range of case studies. Future research could further explore trade-offs among ES in greater detail and under different future climate scenarios.

Additionally, the sensitivity of thresholds, such as the minimum basal area or volume required to achieve a positive stumpage value, to key parameters (e.g., harvesting costs or market prices) could be investigated. Finally, operational research techniques as well as optimisation models could focus on reaching specific objective functions through thinning and silvicultural management (e.g., maximisation of TEV, minimisation of expected damage) (Rönnqvist et al. 2023). In this way, a direct relationship between biophysical dynamics and economic parameters can also be delineated.

Conclusion

This study demonstrates that, in a pine plantation managed for multiple uses, the long-term planning of thinning operations can significantly impact the achievement of management goals. The methodological novelty of the study lies in the integration of a robust process-based modeling approach with long-term field data. The key findings are that the intensity and frequency of thinning interventions have a substantial effect on the overall production of ESs in European black pine stands established through afforestation and reforestation for environmental improvement. Therefore, strategic, long-term planning of thinning operations is essential to ensure a balanced trade-off between wood production and other ESs, while maintaining the cost-effectiveness of operations. This includes better monitoring of ES supply and demand, enhanced policy integration, and the development of payment schemes for ESs. In particular, we found that lengthening the time between interventions generally leads to higher TEV, particularly when combined with heavier intensities. At the same time, shorter frequencies tend to maximize radial growth and net stumpage value (NP_SV). However, this value is generally low (often negative) due to the low cost per unit of the thinned material. We did not consider the value of the timber that could potentially be removed at the end of the rotation period; therefore, the TEV is higher in the control scenario. From a policy and economic perspective, this does not suggest that refraining from forest management is preferable. As previously discussed, and supported by other studies, forest management plays a crucial role in ensuring the provision of products and services that would be difficult to obtain in unmanaged scenarios. However, further research is needed to assess the potential impact of including final harvesting in management scenarios on the TEV.

Therefore, the proposed assessment framework generates valuable insights to inform the silvicultural management of stands established through afforestation and reforestation, providing essential information to guide management decisions, especially in the context of Sustainable Forest Management. While such decisions must be adapted to the unique characteristics of each forest stand, as well as the specific needs and demands of local markets and communities, the framework ultimately offers guidelines for forest planners and managers to ensure the sustained provision of multiple ES. This framework can also help provide evidence to support payment for ecosystem services (PES) schemes. At the national level, it can inform and guide climate and carbon policies, as well as reporting activities, in alignment with EU forest policy initiatives such as the 2030 Agenda, the LULUCF sector, and the EU Biodiversity Strategy.

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