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RESEARCH

Modeling and optimizing alpine forest management to maximize carbon sequestration

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Abstract

Forests affect the Earth's carbon cycle in different ways: by absorbing carbon into biomass and soils, by transferring carbon to the pool of harvested wood products (HWP), and by allowing some of these products to save emissions by replacing climate-intensive materials. However, management also affects the forest carbon balance in more subtle ways, such as by modifying the age structure of the forest and hence the strength of its carbon sink, and by influencing the occurrence of natural disturbances, which could reduce future sink capacity. A comprehensive estimate of the effects of forest management on climate mitigation needs to integrate all these factors, but studies that jointly take into account all this information are rare. Thus, it remains unclear what strategy maximizes climate mitigation for each forest. We couple a forest dynamic model, which simulates future forest growth, harvest and disturbance in two mountain forest catchments, to an optimisation algorithm that explores the strategy space for maximum cumulative climate mitigation up to 2100. Our optimized management generates an additional climate mitigation potential of 9.2 to 10.2 tCO_2 ha^{-1}, compared to current management. Our results consistently prioritised stand-level carbon retention, highlighting the dominant role of retaining carbon in living biomass, and the secondary benefit from HWPs and substitution when integrated judiciously. Also, the optimal mix of interventions varies among stands and forest-cover types, demonstrating that there is no one-size-fits-all solution. Altogether, the study demonstrates that coupling landscape-level forest modelling with formal optimisation provides a robust framework for evidence-based, climate-smart forest management and planning. Finally, the study proposes a comprehensive approach with the aim of including all relevant processes in the assessment of the carbon-related climate change mitigation potential of forests, with recommendations for action for all major types of alpine forests present in the study area.

Introduction

Forests have significant potential for mitigating climate change through carbon storage and sequestration. It is estimated that global forests store up to 522 Pg C (Santoro et al. 2021) and the overall sink amounts to 3.5 Pg C $year^{-1}$ (Pan et al. 2024). Alpine forests are among the most important forest ecosystems in Italy and Europe, and they are particularly sensitive to climate change: the Alps are already facing the effects of climate change (Peleg et al. 2025), leading to shifts in species' distributions, increased drought stress, and altered disturbance regimes. However, there is still ongoing debate about which management strategies are most effective in ensuring both climate change mitigation and adaptation (Ameray et al. 2021). Management practices can influence this potential, either enhancing or reducing it. Nevertheless, to understand the carbon implications of

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forest management, it is important to consider all its direct and indirect effects on climate mitigation, including changes in carbon stored in harvested wood products (HWP), substitution effects of fossil-based materials and fuels by wood products, and changes in vulnerability to emission-inducing disturbances (Leskinen et al. 2018).

The carbon stock in wood products had an estimated stock of 335Mt of CO_2eq (corresponding to 0.09 Pg C) globally in 2015 (Johnston and Radeloff 2019). Moreover, the use of wood products in place of mineral- or fossil-based products can lead to emission reductions, as wood-based products often have a lower carbon footprint than their mineral counterparts (Pingoud et al. 2012; Vizzarri et al. 2022). Both material substitution (Gustavsson et al. 2021) and bioenergy use in the alpine environment are assumed to have a role in climate change mitigation (Buonocore et al. 2019; Nikodinoska et al. 2017). These substitution effects have been extensively studied due to their significance in strategies aimed at reducing emissions from material production processes. In some cases, they may offer a greater contribution to climate change mitigation than just what is accounted for the carbon transferred from the forest pools to long-lived HWP (Nygaard et al. 2019). Substitution effects can also be generated in the energy sector: although biomass combustion is not considered carbon neutral (Adetona and Layzell 2023), the energy produced can be less carbon-intensive compared to fossil energy sources under certain conditions (e.g., cascading wood use, short carbon debt payback time, high carbon footprint of fossil energy) (Cherubini et al. 2011). Management has a primary role in HWP effects on climate mitigation, since both carbon storage and substitution effects are highly dependent on the quality and the use of HWPs (Sathre et al. 2010). To obtain timber adequate for material uses, careful management needs to be done, with thinning aimed at selecting the best stems and to reduce competition (Rossi et al. 2025).

Management can also contribute to reducing the frequency and severity of disturbances such as wildfires and windstorms (Ascoli et al. 2023; Ostry et al. 2010), thanks to preventive interventions such as selective thinning or shortened rotations, which can reduce the emissions generated by such disturbances. As with material and energy substitution, this effect is highly context-dependent, as the amount of emissions avoided has to compensate for the missing sink following tree removal and changes in carbon sink due to the modified age structure of the forest post-harvest (Hurteau and North 2010). This, in turn depends on the disturbance regime, the growth rate of the forest, and the intensity of management operations. The trade-offs between carbon stored in living biomass, carbon in wood products, substitution effects, and avoided disturbance emissions are complex, and further impacted by climate change effects on growth and tree mortality, changes in forest dynamics, and shifts in product demand due to climate change and mitigation policies. A comprehensive assessment requires studying the trade-offs between these effects (Lin and Ge 2020; Soimakallio et al. 2021), which in turn are highly dependent on the specific context and site characteristics. These complex interactions can be successfully investigated through ecological modeling, which is an effective approach used to quantify the contribution of forests to climate change mitigation (Maréchaux et al. 2021; Vacchiano et al. 2012). Both empirical and process-based models are currently used to simulate the growth of forests. Empirical models rely on historical data and can be more site-specific since they are usually calibrated on local conditions. Nevertheless, they don't account for changing environmental variables, such as those associated with climate change. Process-based models simulate physiological processes such as photosynthesis and water use efficiency to predict forest growth under varying environmental conditions, but they can lack accuracy in simulating management (Pilli et al. 2022). A good compromise is to couple them in a hybrid framework (Cuddington et al. 2013). Also, natural disturbances can be simulated, taking into account their effects on carbon emissions, and the relationship between climate trends and their frequency and severity (Turco et al. 2017). Finally, several standards provide a guide for the assessment of carbon stored in wood products and the magnitude of substitution effects, such as those proposed by the IPCC (Pingoud et al. 2006) and various other authors (Sathre and O'Connor 2010).

Forecasting the consequences of forest management on climate mitigation by omitting to consider any one of these processes will lead to biased estimates, and can be the very reason why contrasting evidence exists in the literature, e.g., on the mitigation effectiveness of management versus strict conservation (Boukhris et al. 2025). Very few studies to date have managed to take into consideration all the consequences of forest management on the overall carbon performance of the forestry sector, analyzing the tradeoffs and synergies between these different parts of the forestry sector. As highlighted by several authors, this can lead to partial results (Nabuurs et al. 2013; Albrich et al. 2023), especially in highly heterogeneous areas like the Alps (Seild et al. 2018; Rammer et al. 2024). For this reason, an evaluation of all main processes and contributions to carbon-related climate mitigation is necessary. Once a complete picture of management impacts on carbon is gained, operational research tools such as linear programming can aid in defining site-specific management strategies (Weintraub and Romero 2006; Zhu et al. 2021) by comparing different management options and maximizing an objective function, such as overall climate mitigation impact.

The objective of this study is to investigate how to maximize the overall carbon-related climate mitigation effect obtainable by managing forests. This also means investigating the role of each mitigation effect considered, in order to assess the relative importance of each one and to find thresholds beyond which some become stronger than others.

In this study, we simulated the carbon-related mitigation effect of forest management options in two mountain communities in Northern Italy, aiming to find management practices that maximize the overall carbon-related climate mitigation potential of forests. We accounted for different management options and two climate change scenarios. We integrated in one comprehensive modeling framework all the different contributions that forests can give to the climate mitigation effect, including age-dependent carbon sink in forest pools, carbon storage in harvested wood products, energy and material substitution by wood, future climate change impacts, disturbance-related emissions and potential emission avoidance by climate-smart forestry.

Methods

Study area

We investigated a mountain area in the Italian Alps, consisting of Valle Camonica and two northern parts of Valtellina, i.e., Valtellina di Tirano and Alta Valtellina (Fig. 1). Forests in the study area cover a surface of $62*10^3$ ha. According to the regional forest map, 39.3% of the forested area is composed of Norway spruce (*Picea abies*) forests, 36.3% of European larch (*Larix decidua*), followed of different broadleaves (2.8% Sweet chestnut, *Castanea sativa*, and 13.2% other broadleaves). The climate is mainly alpine, with cold winters and short summers. The average altitude is 1925 m, ranging from 190 m to 3824 m: this wide range highly influences temperature distribution, decreasing with altitude, but also precipitation, which is highly impacted by orography (Smith 2018). We limited our analyses to publicly owned forests, which represent 50.4% of the total and are subject to planning and active management. The type and frequency of forest management depend on forest cover type, main function and other environmental and

Fig. 1 Boundaries and forest map of the study area

administrative constraints, related, for example, to disaster risk reduction, protected areas, or accessibility.

Modeling framework

We simulated the growth of forests until the year 2100, assessed the different climate mitigation effect under multiple management and climate scenarios, and applied an optimization technique to determine optimized management portfolios able to maximize the forest carbon sequestration potential.

For each scenario, forest growth was simulated with the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3), an empirical landscape-level model widely used to simulate the carbon cycle in forests across the world (Kurz et al. 2009). The model is inventory-based, and forest growth is driven by age-volume curves entered by the user, usually parameterized from existing yield tables, which are not sensitive to future climate change. It tracks carbon transfers among the main ecosystem pools and accounts for fluxes associated with growth, harvest, and natural disturbances such as fires. CBM derives the Net Primary Production as the sum of Net Growth and turnovers, representing the carbon required to replace biomass naturally lost during the year. Carbon flows among pools are described through disturbance matrices, which determine how carbon is redistributed after different events or management actions. These matrices allocate carbon across multiple compartments, including aboveground and belowground biomass, foliage, dead organic matter, soil and harvested wood products (HWP). The model also represents soil carbon processes, capturing decomposition and transfers between soil and DOM pools over time.

The model was used to simulate forest carbon flows, as shown in Fig. 2.

To account for the direct effect of climate change (i.e., the effect of climatic variables on forest growth), we coupled CBM-CFS3 with a process-based model, 3PGmix (Physiological Processes Predicting Growth) (Landsberg and Waring 1997). We also simulated the indirect effects of climate change on the frequency and intensity of disturbances, i.e., drought and forest fires. We used future drought data as a proxy and estimated the expected frequency and intensity of each disturbance event during the simulation period. Carbon stored in living and dead biomass pools and HWP was assessed from CBM-CSF3 outputs, on top of which we added estimates of expected wood substitution benefits. Finally, we applied the optimization algorithm to model outputs under all scenarios to generate the best management scenarios.

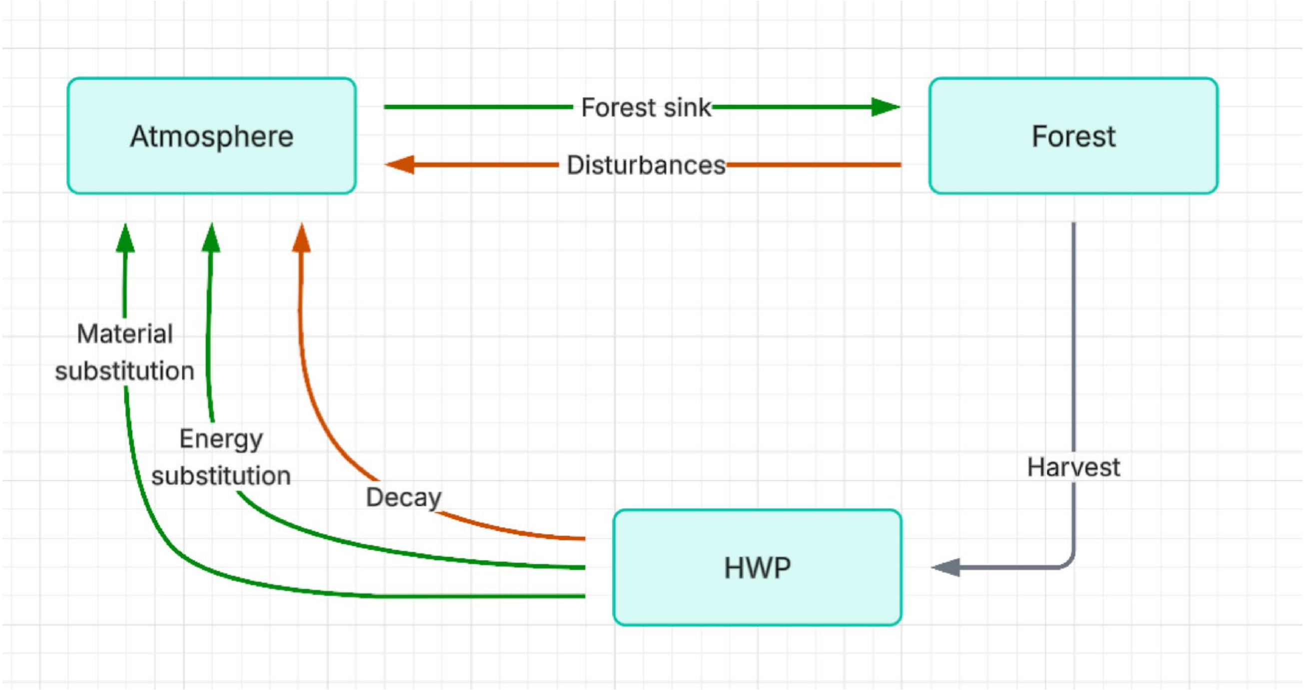


Fig. 2 Carbon flows considered in this study. The modeled stocks are forest (including aboveground biomass, belowground biomass, foliage, soil and dead organic matter), harvested wood products (HWP), and the atmosphere. Green arrows indicate net CO_2 uptake from the atmosphere or avoided emissions, whereas red arrows denote a net contribution to CO_2 emissions. The grey arrow represents the flux of carbon from Forest to HWP

Initial forest data

We used CBM to simulate forest growth in the period 2020–2100, initializing it by calculating the volume for each management unit (MU) included in existing forest management plans through a two-step remote sensing approach. We sampled the standing volume (SV) in 74 sample plots across the study area, stratified by forest types. We selected sample areas with a radius of 14 m, measuring the diameter of all trees larger than 7.5 cm, the height of 15 trees and calculated the volume of each tree through the species-specific allometric equations used in the Italian National Forest Inventory (Tabacchi et al. 2011). After that, we calibrated a linear regression model of SV (ground truth) as a function of GEDI (Global Ecosystem Dynamics Investigation) metrics (Dubayah et al. 2022), from which we extracted the volume for all the pixels contained in the GEDI product (which covered the study area only partially, since the data is produced following stripes). To produce a wall-to-wall biomass map, we subsequently acquired Sentinel-2 images (from June to September of the years 2018 to 2020) and calculated the following multispectral indices: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Normalized Difference Moisture Index (NDMI), Normalized Difference Red Edge (NDRE, three variants), Normalized Burn Ratio (NBR), and Spectral Angle Mapper Median Absolute Deviation. After that, we fitted a non-parametric random forest algorithm to model SV as a function of Sentinel-2 indices. The model was used to predict the biomass of the entire study area. Finally, we extracted the stand level per hectare for each MU (see Brocco et al. 2025 for full details).

CBM outputs provide data about carbon pools in both forest and harvested products. For this analysis, we considered the following forest carbon pools, and the fluxes between them: aboveground merchantable biomass (stems), other aboveground biomass (branches, tops, and submerchantable-size tree biomass), belowground biomass, foliage biomass, soil carbon and dead organic matter (DOM), including litter.

Climate data

Simulations were carried out for two climate change scenarios, RCP4.5 and RCP8.5. For this purpose, we downscaled climate simulations at a monthly resolution produced by the MPI-ESM1.2-HR Global Climate Model, downloaded from the EU CORDEX data portal. Precipitation, minimum and maximum temperature from historic climate (period 1980–2010) and RCP scenarios were extracted from netCDF files using Climate Data Operator (CDO) (Schulzweida 2023). The downscaling was performed with the R package CSTools (Pérez-Zanón et al. 2022). The function CST_RFTemp was used to perform an orographic downscaling of temperature, by applying a correction depending on elevation, for which we used a digital elevation model with 10 m spatial resolution provided by the TINItaly project. For precipitation, we performed a stochastic downscaling using the Rainfarm function in CSTools, based on historical precipitation gridded data provided by CHELSA (Büchner and Reyer 2022) for the period 1980–2010. After downscaling, we extracted the climate time series from a grid of regular points spaced 1 km apart and averaged them to obtain a representative climate profile for the period 2020–2100 for the whole area; the same was done with the historical climatology, which we obtained for 2020–2100 by randomly reshuffling climate years in the historical data. Future time series for monthly solar radiation and CO_2 concentration were obtained for each climate change scenario, from the PVGIS online tool (Šúri et al. 2008) and from the ISIMIP repository (Büchner and Reyer 2022), respectively.

Forest growth

Each management unit starts the simulation at its current age and volume. Forest growth in CBM-CFS3 is based on yield curves expressed in volume per hectare of merchantable biomass over forest age. Curves for all the major European species have already been calibrated by Pilli et al. (2021) using regional-level inventory data, including for uneven-aged forests. Given the variability in the growing conditions of Norway spruce, the most common tree species in the study area, we refined the species' growth curves by stratifying existing stands into low-, medium-, and high-fertility classes. To define the variation of productivity of these classes, we used the Trentino regional fertility tables. Based on the provided historical productivity data, we calculated an average variation of + 20% of growth rate for high fertility stands, and of − 25% for low fertility stands (compared to the average productivity).

To make growth curves responsive to climate change, we ran the 3PGmix model on R (r3PG package) (Trotsiuk et al. 2020). 3PG is a process-based model that simulates forest growth as a result of photosynthesis and resource use. Different physiological processes are simulated and all main European species are already parameterized. Its process-based nature allows it to simulate the effect of climate variations on growth rates, even though it is not particularly suited to simulate management or disturbances at a landscape level.

The model was initialized with one virtual forest for each forest cover type, having characteristics corresponding to the average ones measured during the fieldwork (see Supplementary Materials S1 for more details). Each stand was modelled in the absence of thinning starting from its current state, with historical, RCP4.5 and RCP8.5 climate. Once the runs were performed, we compared the expected growth of each forest under each climate change scenario against growth under the historical climate. For each climate change scenario, we calculated a bias correction factor by taking the average ratio between yearly aboveground biomass under climate change and biomass under historical conditions. Subsequently, we applied this ratio to the yield curves previously calibrated for CBM-CFS3.

Disturbances

In this simulation, we considered wildfire and drought mortality, and the impact of climate change on their frequency, which we assessed using the Standardized Precipitation Evapotranspiration Index (SPEI) as a proxy for disturbance occurrence.

CBM requires specification of disturbance timing (i.e., simulation time steps), the extent of the disturbed area, and the target management units. The model then simulates carbon flows following each event through disturbance matrices, which define the proportion of carbon transferred from each pool (e.g., living biomass, litter, soil) to other pools, harvested wood products, or the atmosphere. Wildfire-induced flows move from live biomass pools to the atmosphere and to deadwood, whereas drought-related mortality transfers carbon from live biomass into deadwood, and ultimately (via decomposition) into the atmosphere in the following years.

For wildfires, we modelled the historical burned area, provided by Lombardy Region and clipped on the study region, against yearly SPEI using a GLM for the period 1997–2017, following the method by Turco et al. (2017). We calibrated the models using either SPEI3 and SPEI6 (i.e., considering the 3 and 6 months before the reference month), using all the months of the year as reference months, obtaining thus 24 models. The SPEI6 of March, representing drought in the winter period, resulted in the most predictive index (Negelkerke R^2 of 0.337).

This GLM was then used to predict future burned area using the SPEI6-March computed from each climate change scenario as a predictor. The models estimated an average of 101 ha yr^{-1} for RCP4.5 and 115 ha yr^{-1} for RCP8.5. Wildfires were assumed to experience variable tree mortality, depending on the forest cover type. Chosen values were 15% of mortality for European larch (Moris et al. 2017), 25% for Norway spruce and 40% for broadleaves (Lilja et al. 2005).

To simulate drought occurrence, we used the SPEI3 of September, representing summer droughts. SPEI remained nearly stable for the RCP 4.5 scenario, while it had a slightly increasing trend in the RCP8.5 scenario. We estimated 10 drought events ($SPEI3 < -1$) under RCP4.5 and 11 for RCP8.5 for the period 2020–2100.

Based on Zhang et al. (2017), we assumed that in the 10% driest years, conifers may experience drought-induced mortality rates of up to 10%, while broadleaves may reach 5%. Following Senf et al. (2020), we further estimated that such 10%-mortality events would affect 30% of the total forest area, and 5%-mortality events would affect 40% of the total forest area. Based on these assumptions, we calculated the annual area affected by drought-related mortality and instructed the model to apply the corresponding mortality rates to the respective forest shares (randomly allocated across management units), distinguishing between conifers and broadleaves.

Management

Management in CBM is implemented with the same logic of disturbances. Different interventions can be planned and assigned to only some eligible stands. Each intervention is associated with different carbon flows, directed to the HWP pool, to the soil pool, to the litter pool and to other deadwood pools.

We simulated four management options in the study area:

i) No management;
ii) Regional Law (business as usual): based on the Regional Forest Law of Region Lombardy (Regione Lombardia 2007), which provides both maximum harvest intensity and minimum rotation length for all forest types. For management units that have a priority role for hydrogeological risk reduction or biodiversity conservation, according to the existing management plan zonation, we reduced allowed harvest intensity by 5%, and by 10% if the slope was steeper than 80% to reflect physical management limitations;
iii) Preventive: we simulated the creation of firebreaks by applying a harvest rate of 95% every 15 years for broadleaved coppices and 40% every 10 years for coniferous high forests, in a buffer of 50 m around all roads. We assumed that preventive management could reduce future burned area by either 30% or 60% across the entire study area each year. This design enabled us to assess the model's sensitivity to different levels of wildfire prevention management effectiveness;
iv) Enhanced Production: we increased by 5% the harvest rates in conifer eligible forests in order to obtain more timber for material substitution purposes.

This design allowed the simulation of each Management Unit under five different interventions.

Each of these management options was applied to 25% of the forest area (randomly allocated to eligible management units), based on information on the extent of management contained in management plans. For example, the Regional Law scenario consisted of 25% of the total area managed following Regional Law prescriptions, while 75% remained unmanaged. The harvesting activities were planned on a decadal basis.

We performed 10 simulations with CBM, corresponding to the combinations between silvicultural options (No Management, Regional Law, Preventive silviculture with 30% wildfires reduction, Preventive silviculture with 60% wildfires reduction, Enhanced Production), and climate scenario (RCP4.5 and RCP8.5).

HWP carbon stock

We extracted yearly harvested volumes from the outputs of each CBM simulation in order to calculate the overall carbon content of HWP. Starting from the harvested volumes, we calculated the net HWP volume by applying an overall residues ratio of 45% (Giordano 1981), thus accounting for residues generated in the forest and in the sawmill. Subsequently, we divided the net HWP volume into different assortments (Table 1) to keep track of their different lifetimes. Half-life values were assigned according to the recommendations of the IPCC (Pingoud et al. 2006).

To calculate the stock in HWP, we applied the method described in the IPCC Guidelines for National Greenhouse Gas Inventories (Chap. 12: Harvested Wood Products) (Pingoud et al. 2006), which assumes exponential decay based on the half-life of each product over time. We assumed that the fraction of domestic production was 100%, meaning that we considered timber from our study area only and not imported timber. We set a carbon fraction of 0.47. Finally, we used Eq. 1 to calculate, on a yearly basis, the carbon storage in HWP, divided by product and species group (conifer or broadleaf).

Equation 1—Carbon stored in harvested wood product in year i

$$C\left(i+1\right)=e^{-k}*\;C\left(i\right)+\left[\frac{\left(1-e^{-k}\right)}{k}\right]*inflow\left(i\right).$$

where i is the year, $C(i)$ is the carbon content at the beginning of the year i, $inflow(i)$ is the inflow of the HWP pool during the year i, k is the decay constant in first-order decay calculated as $ln(2)/HL$, and HL is the half-life.

Table 1 Percentage of different assortments and their half-life

Species group	Assortment	Percentage of net volume (%)	Half-life (years)
Conifer	Sawnwood	65	35
	Pallets	25	5
	Beams	10	35
Broadleaves	Sawnwood	7.5	35
	Panels	7.5	25
	Firewood	85	1

Substitution effects

We assessed the effect of substitution in the material and energy sector using the harvest output from CBM and the assortment table described above.

Material substitution was evaluated by assuming that the sawnwood obtained could be used for the construction of timber-framed houses. The Displacement Factor (DF), as defined by Sathre and O'Connor (2010), represents the GHG emissions avoided by substituting a mineral or fossil-based product with a functionally equivalent wood-based product. We used the house model considered for our study area in a previous study (Brocco et al., 2025) with a DF value of 0.64. To investigate the impact of DF variation on the overall results, we applied a sensitivity analysis varying the DF value from 0.64 to 6, and compared the outcome with the overall balance of the No Management scenario.

Regarding energy substitution, we assumed that all residues and firewood could replace energy derived from burning methane. We calculated the amount of energy obtainable from burning wood, considering an energy content of 4046 kcal kg^{-1}. Then, we used the IPCC emission factors for wood (112 000 $kgCO_2\ TJ^{-1}$) and methane (56 100 $kgCO_2\ TJ^{-1}$) to calculate the emissions corresponding to the calculated energy, and, subtracting them, we obtained the avoided emissions. For wood-related emissions, we also applied the global warming potential of biogenic CO_2 (GWP_bCO_2) as proposed by Adetona et al. (2023). This approach accounts for biomass combustion not as climate neutral, but with an impact due to time lags between instantaneous emissions and delayed carbon resorption by the forest, depending on the type of biomass, forest management system, and forest growth rate (Cherubini et al. 2011). In our case, we used the average value of 0.4 tCO_{2b}/tCO_2 in 100 years, as indicated by Adetona (2023) for forest residues.

Optimization

We obtained the total carbon storage in 2100 under different climate, management and disturbance scenarios, summing biomass pools in year 2100, the HWP carbon pool remaining in year 2100, the cumulative disturbance emissions 2020–2100, and the cumulative emissions avoided through material and energy substitution in the period 2020–2100.

These values have been extracted for each combination of descriptors such as forest cover type, age structure (even- or uneven-aged), management system (coppice vs. high forest), main function (production, protection, tourism and naturalistic), hydrogeologic protection level (based on slope and zones defined by Region Lombardy) and model run.

Then, we set up a linear optimization algorithm aimed at maximizing the climate mitigation effect by 2100 (Eq. 2), using the R package LpSolve (Berkelaar 2003). The area occupied by each unique combination of forest descriptors was considered as a continuous variable in the optimization problem, while the proportion of area assigned to different management options for each combination of descriptors represented the decision variable. We set constraints ensuring that areas allocated to each management option did not exceed the total available area for each combination, and restricted the No Management option with a maximum of 75% of the total forest area, to prevent outcomes associated to a complete abandonment of forest management, which would have undesirable socio-economic consequences.

Equation 2—Linear Programming problem.

$$max \sum i,m \begin{pmatrix} C_{stockForest,i,m} + C_{stockHWP,i,m} \\ +AE_{material,i,m} + AE_{energy,i,m} \end{pmatrix} \cdot A_{i,m}$$

$$\sum {}_m A_{i,m} \leq \; A_i^{tot} \, \forall \, i$$

$$\sum {}_i A_{i,NoManagement} \leq 0.75 \cdot A^{tot}$$

$$A_{i,m} \geq \; 0 \, \forall \, i, m$$

where $A_{I,\ m}$ is the area of forest type i assigned to management option m; A_i^{tot} is the total available area of forest type i; A^{tot} is the total forest area; $C_{stockForest,\ i,m}$ is the carbon stock in above- and belowground biomass; $C_{stockHWP,\ i,m}$ is the carbon stored in harvested wood products; $AE_{material,\ i,m}$ is the avoided emission from material substitution; and $AE_{energy,\ i,m}$ is the avoided emission from energy substitution.

We solved the problem once for each fire prevention level (30% and 60% burned area reduction level) and for each climate scenario, resulting in a total of 4 different solutions. We then compared these solutions to a Business as usual scenario, i.e., 25% of the forest managed with Regional Law and 75% unmanaged.

Results

CBM simulations show a carbon stock per hectare in year 2100 that has higher values for a No Management scenario, with the sole exception of high fertility (HF) Norway spruce (Fig. 3). Both Sweet chestnut and Norway spruce exhibited an increase in carbon stocks across all management scenarios, while European larch and other broadleaves accumulated more carbon only in the absence of management. Carbon stocks for 2100 are very similar between the two climate scenarios. However, Sweet chestnut shows higher carbon storage in RCP4.5, while Norway spruce (low and medium fertility) stores slightly more carbon under RCP8.5.

After aggregating biomass and HWP carbon stocks and avoided emissions under substitution effects, No Management emerged as the most common optimal silvicultural strategy in terms of area (Fig. 4), with assigned areas ranging from 64.5 to 66.7% (for RCP4.5 with 60%, and RCP8.5 with 30% of burned area reduction effectiveness, respectively). Business as usual ("Regional law") was selected as the optimal management over a similar share of total forest area across both levels of burned area reduction (17.0 to 18.1%), while more pronounced differences emerged for Preventive Silviculture (from 10.2 to 10.6% under RCP4.5 and from 15.4 to 15.7% under RCP8.5). The share of area

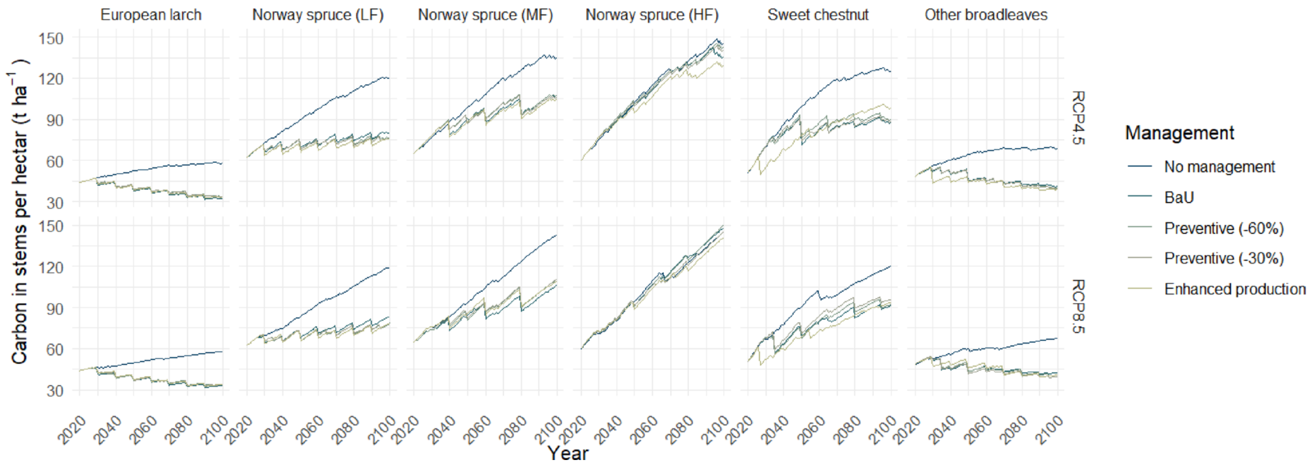


Fig. 3 Carbon storage in stems per forest type and management

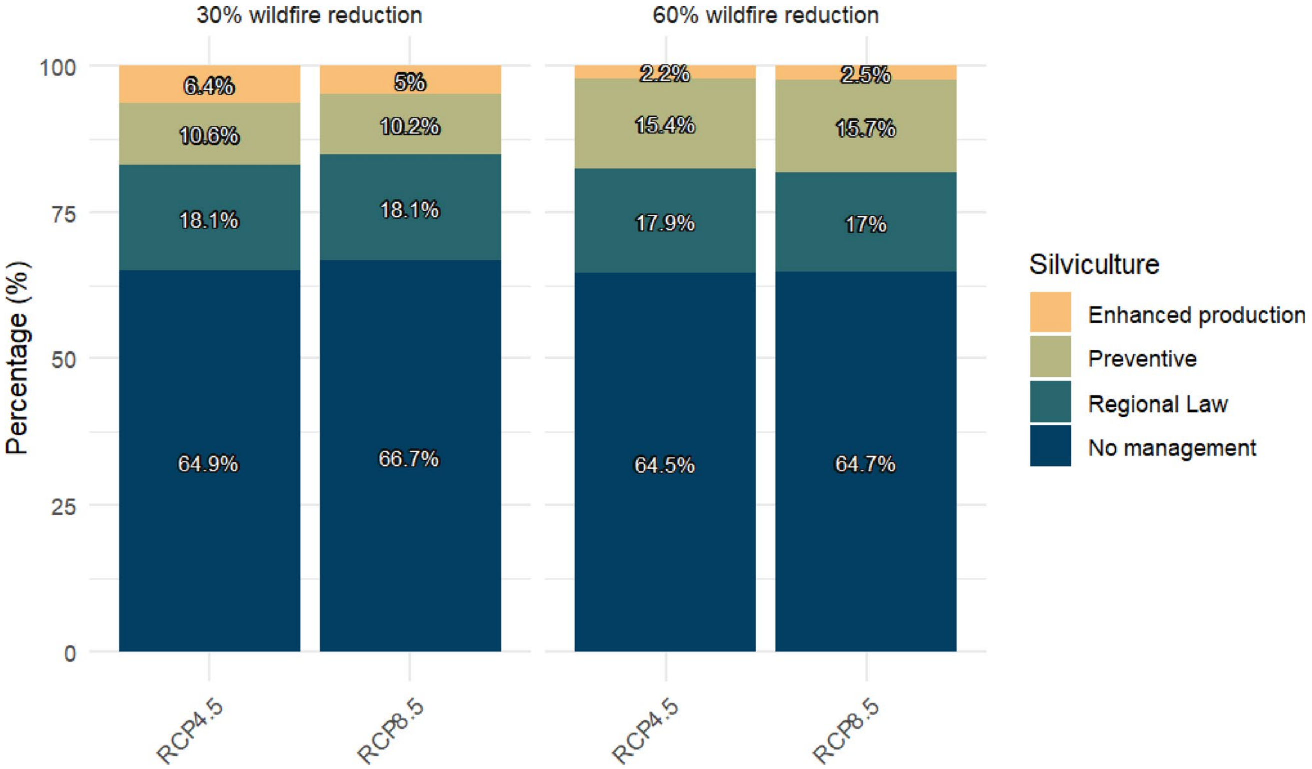


Fig. 4 Composition of optimized managements in terms of assigned area

allocated to Preventive silviculture increased with the effectiveness of fire prevention measures and, for greater burned area reduction, with the severity of climate change, while the opposite trend was observed for Enhanced Production.

No Management was selected as the optimal strategy across the largest share of forest area for each forest cover type, under all combinations of climate and fire prevention scenarios (Fig. 5). Differences emerged when other optimal management strategies were selected: for low-fertility (LF) Norway spruce, Enhanced Production was assigned to 15% of total forest area under RCP4.5 and 30% burned area reduction, compared to lower percentages under other scenarios (1–2%). For other broadleaves, the share of Enhanced Production decreased with fire prevention effectiveness and climate change severity. Similarly, the area assigned to No Management decreased and the area assigned to Preventive silviculture increased under high fire prevention effectiveness. Finally, Sweet chestnut showed a pattern similar to low-fertility Norway Spruce, with higher percentages of Enhanced production and 30% burned area reduction (13%), replaced by Preventive silviculture in the other cases.

Considering the average climate mitigation potential across the part of the forest area subject to management alternatives (i.e., 25% of the total), the No Management option emerged as the most effective, with forest carbon stocks ranging from 54.82 to 54.84 $MtCO_2$ (corresponding to 984.2 and 984.6 tCO2 ha^{-1}) in year 2100 (Fig. 6). In all other management scenarios, the HWP pools were higher, yet the total climate mitigation potential was lower, with the optimized management with 60% burned area reduction representing the second-best option under both climate scenarios (54.22 and 54.26 $MtCO_2$ for RCP4.5 and RCP8.5, respectively, corresponding to 973.6 and 974.2 tCO_2 ha^{-1}). Even in managed scenarios, the contribution of HWPs remained marginal compared to forest carbon stocks, contributing approximately 1% of the total mitigation potential in the best case (under the Enhanced Production scenario across both climate pathways).

When comparing the results of each management scenario and optimized scenarios with Business as Usual (BaU), the No Management scenario again represented the most effective option, despite producing a significant reduction in the mitigation potential from harvested wood products under both climate scenarios (Fig. 7). All other management options resulted in a lower mitigation potential compared to BaU. Also, BaU produced the highest mitigation potential among all “standard” management scenarios, except for Enhanced Production under RCP8. Conversely, the optimized scenarios consistently improve the overall mitigation potential over BaU in all cases: under the RCP4.5 climate scenario, the improvement varied from 9.2 to 9.6 tCO_2 ha^{-1} depending on the effectiveness of burned area prevention (30% and 60% reduction, respectively), and from 9.6 to 10.3 tCO_2 ha^{-1} under RCP8.5.

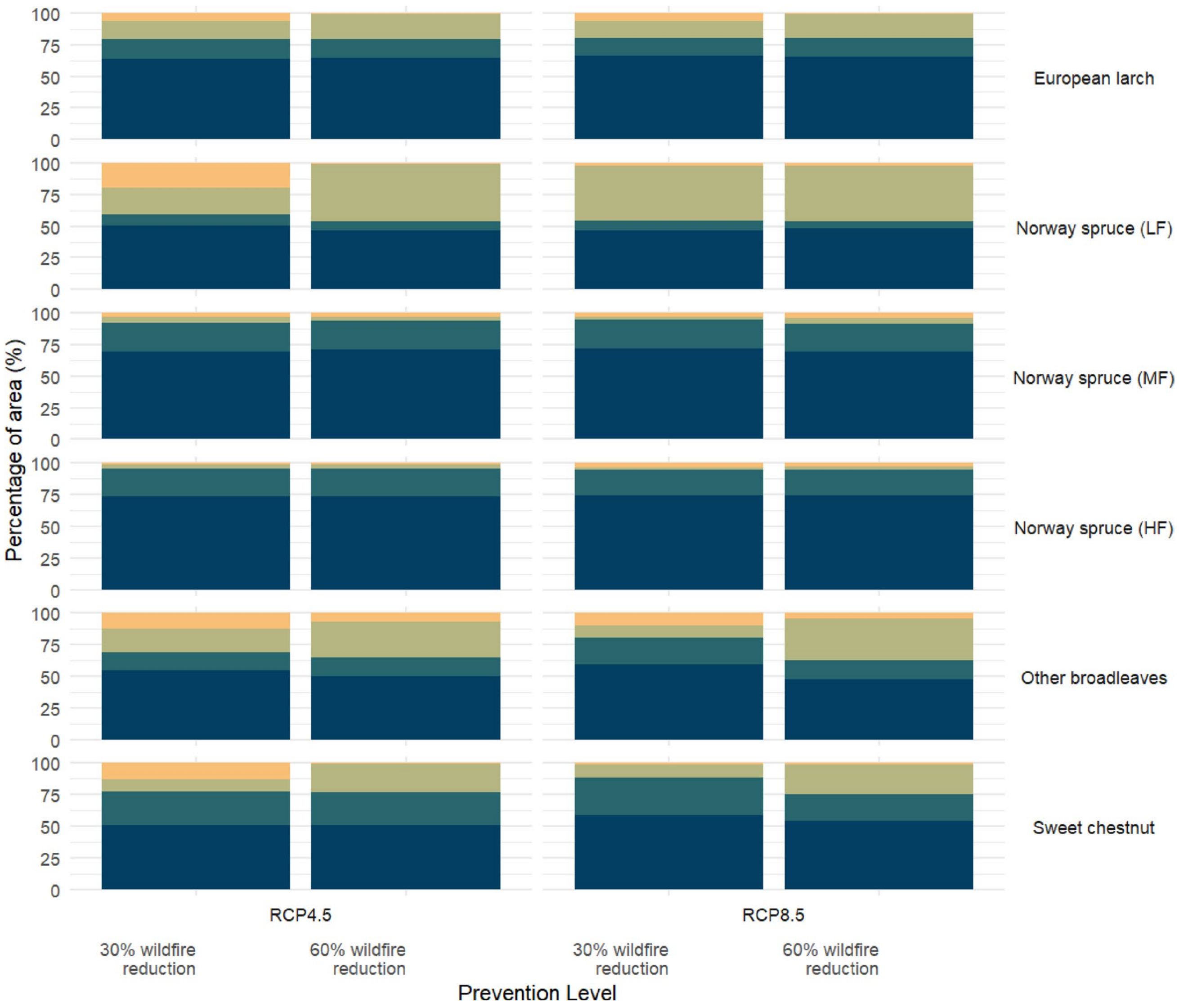


Fig. 5 Optimized scenarios detailed per species

Finally, the sensitivity analysis of displacement factors from material substitution showed of that DF = 5 would be the minimum value of substitution effects to fully compensate for losses in forest biomass carbon (i.e., total carbon balance higher than under no management) in forest under all management and climate scenarios (Fig. 8).

Discussion

We developed an integrated modelling framework combining empirical, process-based, and statistical approaches to assess the climate change mitigation potential of Alpine forests. The framework allowed us to quantify carbon dynamics, substitution effects, and optimize management strategies through linear programming. Our results highlight the value of integrating multiple methodologies to account for all drivers of future forest carbon balance, and to inform forest management strategies at a landscape level while still preserving detail on the local level.

Chestnut is disadvantaged under severe climate change scenarios (RCP8.5), while Norway spruce benefits from these conditions. European larch exhibits a slow growth rate, making high harvest rates less sustainable, particularly when compared to Norway spruce. Bugmann et al. (2015) highlight that temperature-limited alpine forests could benefit from climate change in terms of productivity, whereas low-elevation forests may experience negative impacts. Similarly, Lévesque et al. (2013) report that conifer alpine could suffer negative effects under increased drought conditions. However, in our projections, SPEI does not indicate a substantial increase in drought frequency and severity,

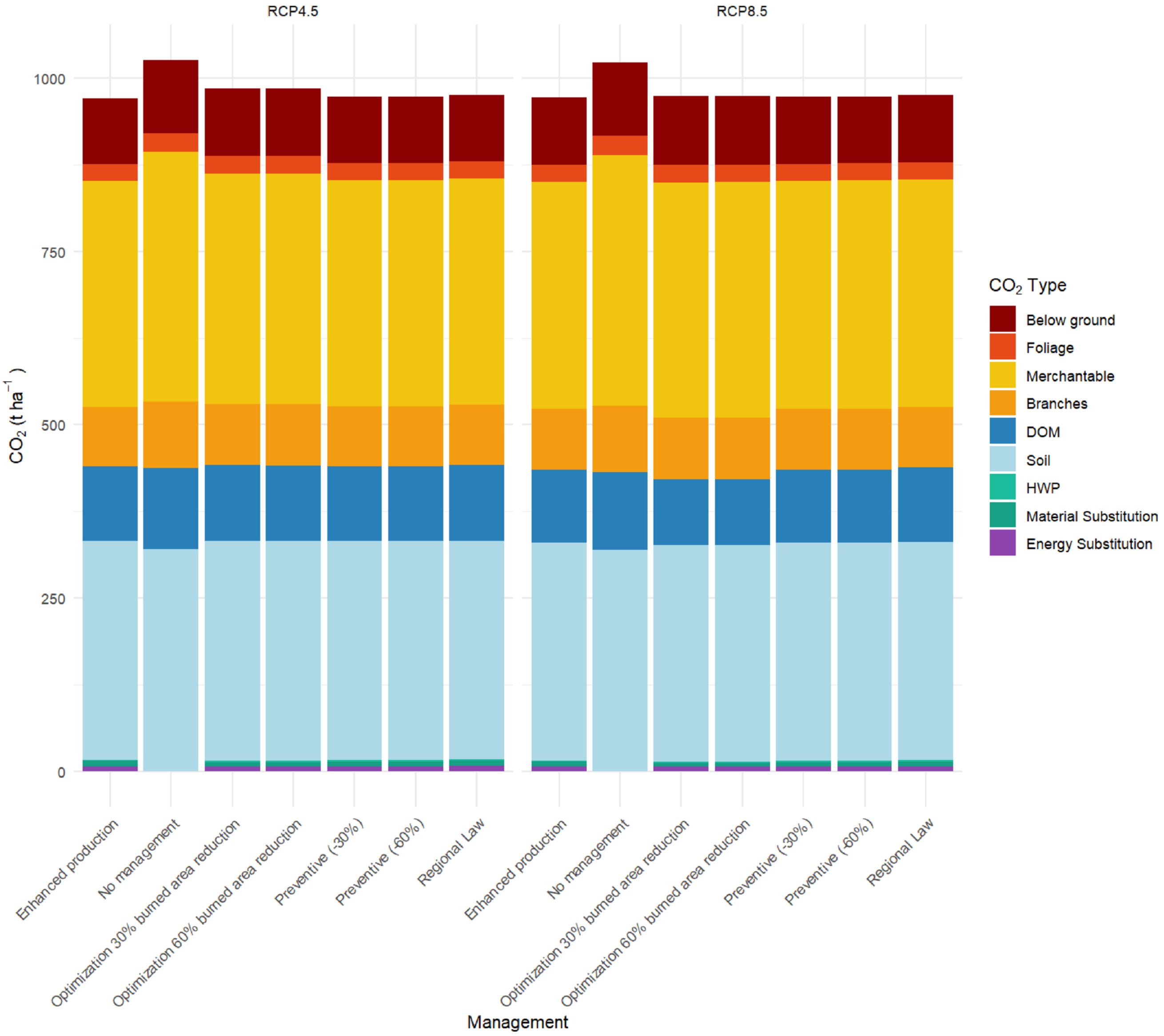
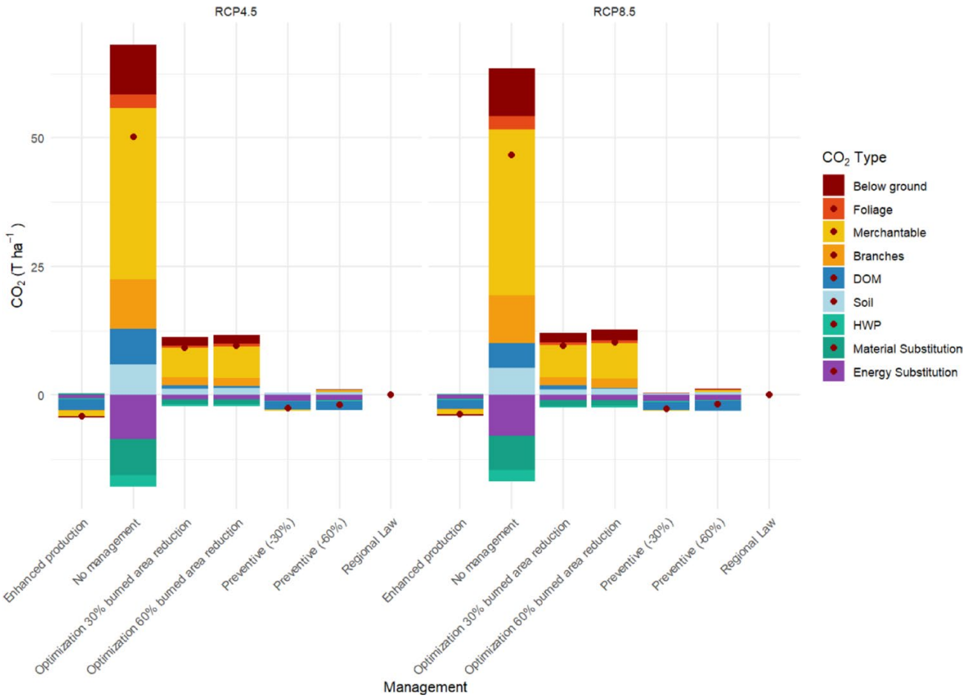


Fig. 6 Total climate mitigation potential of different managements

hence this effect is not visible on the growth of the forest in our study area.

Our simulations show that the No Management scenario achieves the highest carbon stock in forest biomass, which cannot be compensated by substitution effects of HWP, at least for displacement factors lower than 5. This confirms that storing carbon in forest biomass remains one of the most effective strategies (Ameray et al. 2021; Psistaki et al. 2024). This could seem in contrast to several studies that underline the high potential mitigation for material substitution (e.g., Petersen and Solberg 2005), but that fail in considering the full spectrum of forest growth dynamics and impacts of harvest, such as age-class modification, altered forest dynamics or delayed carbon sink post-harvest. Leskinen et al. (2018) highlighted the importance of considering also forest carbon stock variations and forest dynamics when estimating substitution effects. Based on our analysis, this result is largely due to an increase in forest carbon stock (highest in the No Management scenario), suggesting that intensifying harvesting to enhance HWP carbon pools and substitution effects may not consistently improve the overall climate mitigation. This aligns with Niemi et al. (2025), who found lower carbon benefits provided by HWP than the carbon debt generated by increased harvest. Also, Braun et al. (2016) found a higher forest carbon storage under low harvest intensities in Austrian forests: even though higher harvest scenarios offer greater mitigation potential for HWP, these effects were not enough to justify the decrease of forest carbon stock caused by harvest. Similar findings by Soimakallio (2021) indicate that in temperate forests the

Fig. 7 Differences of climate mitigation potential between management scenarios and BaU



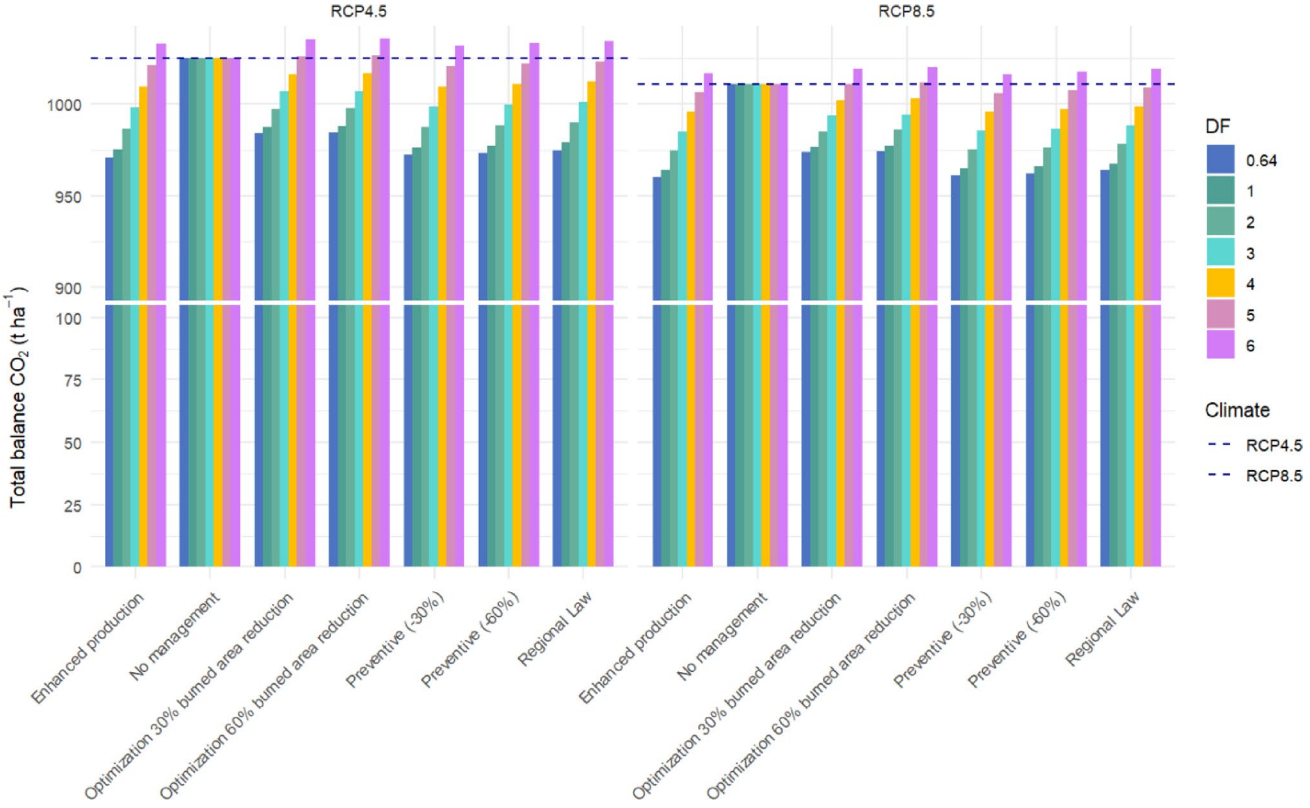


Fig. 8 Total climate mitigation varying with different displacement factors

harvest-related carbon debt would be higher than the benefit associated the harvested wood in the technosphere, in the short-, mid- and long-term.

Nevertheless, it should be noticed that our No Management scenario does not include potential socio-economic benefits related to HWP and maintaining or increasing silvicultural activities in mountain territories, which are unrelated to carbon storage and substitution effects. We tried to partially incorporate such considerations by not allowing No Management to be applied on more than 75% of the existing forest land in our study area. What emerges from the optimized scenarios, however, is that *No Management* is assigned to approximately 64–67% of the forests, meaning that different combinations of the other management scenarios can still provide a higher climate-mitigation effect than the BAU, while allowing an increase in the managed area. This is particularly relevant for forest managers, as it supports the economic sustainability of forest ecosystems while emphasizing the need to strengthen the wood value chain and workforce training for targeted silvicultural operations. Zute et al (2023) present management scenarios similar to ours, but with different outcomes: in this case, the overall carbon storage in forest and HWP is comparable among different scenarios, while the sink is higher in the Intensive Targeted Forestry. Nevertheless, it is worth noticing that this study assumed forest fertilization was carried out (impractical in mountain forests), while it did not consider substitution effects or the impact of disturbances and their mitigation, which played a crucial role in our results. Indeed, linear programming also showed how, assuming a higher effectiveness of wildfire prevention, Preventive silviculture was preferable in both climate scenarios, which highlights the importance of reducing the impact of disturbances for climate mitigation, in line with recent studies (Ascoli et al. 2023; Harris et al. 2019). This effect was stronger under RCP8.5, highlighting that in the case of severe climate change, disturbance prevention will gain importance and will be even more strategic.

Gregor et al. (2022) provided examples of optimization of land-use trajectories, accounting for different land-use changes (such as conversion from conifer to broadleaf forest) and different ecosystem services. Optimal choices varied across Europe, highlighting the necessity to consider spatial variability and ecosystem context when making management choices. In their optimized scenarios, unmanaged forests occupied from 25 to 30% of the area, but these results are hardly comparable to ours since we didn't consider scenarios such as the conversion from coppice to high forest, which may be particularly favorable for climate change mitigation.

Indeed, all these results are highly dependent on system boundaries: several studies have focused on HWP carbon stock and on substitution effects without considering the carbon debt originated in forests, the role of disturbances, or without comparing the outcomes against a counterfactual scenario (e.g., Nygaard et al. 2019). Other studies incorporate wider boundaries and processes than the ones in this study, such as timber trade and afforestation, which may offer a more comprehensive evaluation of different management strategies (Forster et al. 2025).

Anyway, our results are based on several assumptions that might vary in different contexts: first of all, material substitution effect—calculated through the displacement factor (0.64 in our case)—is highly variable, depending on the kind of substitution, energy intensity of replaced fossil materials and energies, and the lifetime of wood products (Sathre and O'Connor 2010). Ideally, a combination of different displacement factors would be more accurate, as proposed by Niemi (2025). The sensitivity analysis we performed by varying the factor from 0.64 to 6 showed how the substitution of mineral-framed houses with timber-framed houses would make substantial differences in different scenarios, becoming decisive with DF values close to 5. However, these values can be hardly reached, since commonly DFs have values below 3.8 (Sathre and O'Connor 2010), highlighting the strategic role of preserving forest carbon stocks. In general, different authors indicated that the decarbonization of productive processes will generate a reduction of DFs, and thus of the effectiveness of using wood in the technosphere as a climate mitigation strategy, by mid-century (Hetemäki et al. 2022; Niemi et al. 2025). On the other hand, assumptions behind energy substitution could be considered optimistic, since some parts of the study area are not served by methane distribution (especially more remote localities), and thus heating is carried out by diesel fuel. For this reason, the energy substitution effect might be partially underestimated in this study.

Moreover, management and mitigation scenarios are highly dependent on forest growth and dynamics. A more elaborate approach, utilizing complex landscape-level, process-based (PBM) models such as iLand (Seidl et al. 2012) or Landis (Scheller and Mladenoff 2004) may yield more robust results. This is because process-based models include climate-sensitivity in their very fundamental way of working. In this study, we have simulated disturbances using a statistical approach that is based on past observations, which could produce inaccuracies under uncertain feedbacks and interactions in the climate system (e.g., changing relationships between weather, drought, fire occurrence, and forest mortality). In landscape-level PBMs, relationships between climate and the occurrence of disturbances are more complex, e.g., including the role of vapor pressure deficit, wind direction, and seasonality, which we did not consider in our study. Moreover, a PBM might simulate in a more accurate way the higher probability of disturbances in the absence of management, e.g., due to increased forest density, deadwood biomass, or other forest vulnerability proxies.

On the other hand, integrating all the proposed methods could be challenging when attempting to reproduce the analysis, especially for practitioners. This might be considered a limitation, but there is still some room for simplification. First, initialization data can be retrieved from local management plans when available. Another option is to use one of the several biomass maps developed by different institutions, such as the European Space Agency (ESA, 2022). Similarly, disturbance occurrence could be estimated based on increases in disturbance risk reported in scientific or grey literature.

This study shows that modeling represents a powerful approach, useful to assess the relationship between forests and climate, and that integrating modeling with mathematical optimization can be crucial when it comes to providing practical management guidelines. Such an approach, if properly scaled, can offer practical guidance for policies such as the European Green Deal (European Commission 2019), LULUCF regulations and global mechanisms like REDD+. Also, carbon credit schemes and forest certification systems can benefit from a modeling framework characterized by broad boundaries and optimization. This is particularly true in the case of forest management planning from regional to stand scale, where planners and managers need indications to increase the climatic benefits obtainable by forests and to quantify them for a subsequent valorization from the economic point of view.

Adapting our workflow to different or larger areas could require using less precise input data, for example, related to current management practices or the state of the forest and its growth. In this sense, the method could be applied to data-poor study areas by using remote sensing data to overcome the lack of field data and a simplified parametrization of models. Nevertheless, it could be modified and further developed to include also other processes, such as economic trends (e.g., increase or decrease in traded wood), changes in wood demand, or different kinds of wood substitution. In this sense, fluctuations of timber markets and trends in bioeconomy policies are key factors that should be integrated.

Conclusion

Assessing the climate mitigation potential of forests can be challenging, especially when comparing different management strategies. This is because the boundaries of the analyzed system and the accounting methods largely influence the outcome. In our study, we took into account not only forest dynamics but also the mitigation effects obtainable from harvested wood products. We applied a modeling approach and optimized it with linear programming, generating management scenarios that maximize the climate mitigation effect of forests. Results show how storing carbon in forests remains a prominent strategy to mitigate climate change. This effectiveness is not easily compensated by increasing the HWP pool, unless substituting highly carbon-intensive materials or forms of energy. Nevertheless, HWP can also contribute to the overall climate mitigation effect, especially if obtained through management strategies with the aim of reducing disturbance-related emissions from the forest. Since optimal management differed among local contexts and forest types, avoiding one-size-fits-all solutions and diversifying management strategies across the landscape can always lead to greater climate change mitigation.

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Data availability Data and materials are available upon request to the corresponding author.

Code availability Code and analysis are available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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