TimberTracer: A Comprehensive Framework for the Evaluation of Carbon Sequestration by Forest Management and Substitution of Harvested Wood Products.

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Abstract

Carbon storage in harvested wood products (HWPs) and the associated substitution effects resulting from their utilization over fossil fuels and energy-intensive materials are pivotal strategies in climate change mitigation. Recognition of this nature-based solution as integral to climate change mitigation targets is notably solidified in many Nationally Determined

Contributions (NDCs) submitted by Parties under the Paris agreement. The need to integrate greenhouse gas (GHG) emissions and removals from HWPs in the accounting obligations under the Paris Agreement, along with the necessity to guide decision-making in forest management to optimize the climate change mitigation effect across the entire forest sector, necessitates typical decision-oriented tools known as carbon accounting models. Among these, wood products models (WPMs), that are specifically dedicated to projecting carbon in HWPs and potentially estimating the substitution effect. In this paper, we propose a novel, comprehensive framework called '*TimberTracer'* designed to explicitly simulating carbon stock in HWPs over temporal scales, substitution effects, and carbon emissions from wood decay and bioenergy. Furthermore, this model can be coupled with forest dynamics models to simulate the long-term effects and interaction between forest management and wood-use scenarios. The model, coupled with the 3D-CMCC-FEM growth model, was applied to the Laricio Pine (*Pinus nigra* subsp. *laricio*) situated in the Bonis watershed in southern Italy. The aim was to dynamically assess the impact of three forest management practices (clearcut, selective thinning, and shelterwood) and four wood-use scenarios (business as usual, increased recycling rate, extended average lifespan, and a simultaneous increase in both the recycling rate and the average lifespan), throughout ~140-year planning horizon (1958-2095), on the overall carbon balance. This investigation, covering HWPs stock, C emissions, and the substitution effect, revealed that selective thinning emerged as the optimal forest management scenario. Additionally, the simultaneous increase in both the recycling rate and the half-life time proved to be the optimal wood-use scenario.

1. Introduction

Terrestrial ecosystems play a major role in the global carbon cycle owing to their inherent ability to gain carbon through photosynthesis and release it through respiration. The terrestrial biosphere provided a net sink for ~21% of carbon dioxide emitted by fossil fuel burning during the 1990-2021 period (Gulev et al., 2021), with the major part occurring in forests (Pan et al., 2011). This climate change mitigation role of forests has been widely recognized by the United Nations Framework Convention on Climate Change (UNFCCC) being part of the periodical national GHG inventories and contributions to the Paris Agreement (79% of the submitted Nationally Determined Contributions – NDCs covers the forest sector under mitigation targets, according to Crumpler et al., 2021).

Forests ecosystems, if and when sustainably managed, offer a dual avenue for greenhouse gas (GHG) mitigation through processes that are mutually exclusive, namely sequestration and substitution (Schulze et al., 2022). Reducing harvest yields a positive impact on the forest carbon stock in the short to medium term but would adversely induce a long-term negative impact on the wood-chain value and a counterproductive effect specifically on carbon sequestration as aging trees exhibit decreased growth and carbon use efficiency (Nabuurs et al., 2013; Collalti et al., 2020). Conversely, the promotion of wood use would lead to the substitution of energy-intensive materials (e.g., steel or concrete) or fossil fuels, further compounded with the storage of carbon within harvested wood products (HWPs) (Leskinen et al., 2018). Given the trade-offs among different options (i.e., carbon sequestration, energy substitution, and material substitution), the most effective mitigation strategy would be the one that optimally balances and integrates all the mitigation components (Pingoud et al., 2010; Pilli et al., 2015; Dugan et al., 2018).

The acknowledgment of HWPs as integral to climate change mitigation occurs in many NDCs submitted by Parties under the Paris Agreement (Crumpler et al., 2021; Di Lallo et al., 2023), within which countries voluntarily set binding GHG accounting obligations and targets to reduce GHG emissions and increase carbon removals (Grassi et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) provides several approaches for estimating the GHG emissions and removals associated with HWPs and encourages deviating from the conventional "instantaneous oxidation" approach (i.e., carbon in harvested biomass is considered as released into the atmosphere immediately after the harvesting) towards more accurate methods (Sato & Nojiri, 2019; Kayo et al., 2021). The need to integrate and improve carbon reporting for HWPs into the NDCs commitment, along with scientific and political considerations for defining an optimal forest mitigation strategy, emphasizes the urgent requirement for enhancements and advancements in tools that predict the development of carbon dynamics in HWP – technically known as harvested wood product models (WPMs) which are used to estimate the carbon dynamics of HWPs and assess their effects on the mitigation of climate change (Király et al., 2023).

In spite of their importance WPMs are often neglected and excluded by most of the forest growth models (Vacchiano et al., 2012). The few existing WPMs, depending on the scope and objective of their developments (for a comprehensive review of WPMs, please consult Brunet-Navarro et al., 2016), use different modeling approaches that have been proved to influence the results of carbon accounting in HWPs (Peng et al., 2023). The bookkeeping modeling approach, which relies on the use of default values, has the advantage of being applicable widely due to its simplicity and low data requirements. However, it has a limited ability to accurately represent local contexts. For example, applying the CO2FIX spreadsheet model (Schelhaas et al., 2004) to quantify carbon stocks of primary wood products derived from timber harvested in the Thuringian states forest (central Germany) resulted in a 22% overestimation of products with a short half-life. This, in turn, led to an underestimation of the overall half-life of the entire stock (Profft et al., 2009). On the other hand, modeling approaches such as material flow analysis (MFA) use specific parameters, like allocation and conversion factors and offers the advantage of traceability of the production chain and the production of reliable results (Mantau, 2015). This approach also enables the use of regional-specific data and tracking carbon over time. The temporal component is crucial for various applications, including assessing the impact of the silvicultural itinerary or the planning horizon on the GHG balance of the forest sector and to potentially evaluating the global warming potential of different mitigation projects (Levasseur et al., 2010; Cherubini et al., 2011). Another modeling method employed for carbon estimation in HWPs is the life cycle assessment (LCA). Typically, LCA is applied to particular instances to evaluate carbon flows within a specific product group or functional unit. It is also utilized to estimate secondary effects, such as substitution or the social values associated with carbon storage (Grossi et al., 2023). This method which has the advantage of providing high accuracy and traceability may hardly be applicable to the national level due to its large data requirements.

To accurately project storage and emissions in/from HWPs, models should include components that influence carbon pools and emissions. Among rarely covered aspects by WPMs are recycling, substitution, and bucking allocation (Jasinevičius et al., 2015; Brunet-Navarro et al., 2016). The practice of cascading wood products extends their lifespan, consequently delaying the release of GHG emissions into the atmosphere. Brunet-Navarro et al. (2017) conducted theoretical simulations to assess the impact of elevating recycling rates on carbon storage within wood products in the European (EU-28) wood sector and revealed compelling results. Specifically, an increase in the recycling rate from 10% to 20.9% between 2017 and 2030 was projected to yield a notable emission saving of nearly 5 $MtCO_2$ (Brunet-Navarro et al., 2017). The substitution of materials with high energy requirements for production or the replacement of fossil fuels with less energy-demanding wood can permanently and cumulatively avoid emissions. For instance, in a case study comparing two functionally equivalent buildings – one constructed with a wooden frame and the other with a reinforced concrete frame – the manufacturing process emitted 45% less carbon in the wooden structure while also requiring less energy (Sathre & Gustavsson, 2009), which underscores the importance of considering the substitution effect in the WPMs design. The bucking allocation involves the disaggregation of logs into different HWPs based on quality and dimensional criteria. It is crucial to consider this process when assessing the effects of management (e.g., rotation, thinning intensity or interval). For instance, studies that include the bucking allocation process suggest considering longer rotations for optimizing carbon stock in the forest sector (e.g., see Pingoud et al., 2010), while those excluding it recommend shorter rotations (e.g., see Kaipainen et al., 2004). This is because models not incorporating the bucking allocation module use predefined default values to allocate harvested volume to HWPs. The higher the productivity, the greater the quantity of products produced – a scenario typically observed in shorter forest rotations. In contrast, when the bucking allocation is accounted for, the optimization of carbon stock would favor the production of HWPs with a longer lifespan, generally derived from larger stems – a scenario typically observed in longer rotations modeling analyses (Dalmonech et al., 2022).

In this paper, we have pioneered the development of an open-source Python-based model to comprehensively account for the various components that directly or indirectly influence carbon pools and emissions – some of which are typically overlooked by existing forest/vegetation models – and to provide insights into the temporal dynamics of both carbon sequestration and emissions associated with HWPs. Named *TimberTracer*, our model is specifically tailored for a comprehensive analysis of wood products, and it encapsulates a robust framework for carbon sequestration analysis, enabling users to meticulously evaluate the quantity of carbon sequestered within diverse wood products. Furthermore, *TimberTracer* incorporates temporal insights, enabling stakeholders to scrutinize the evolving patterns of carbon sequestration and emissions over time. Remarkably, to assess the climate change mitigation potential for the entire forest sector, *TimberTracer* can be seamlessly coupled with any forest growth model, whether individual-tree or stand-based level, such, as GO+ (Moreaux et al., 2020) or 3D-CMCC-FEM (Collalti et al., 2014).

The main objective of this study is to examine the impact of forest management and wood utilization on the mitigation potential of HWPs. Focusing on the *Pinus nigra* subsp. laricio (Poiret) forest located in the experimental Bonis watershed in southern Italy (Collalti et al., 2017), we employ a carbon modeling framework by combining the 3D-CMCC-FEM model with *TimberTracer*. This integrated framework is used to simulate the evolution ~140-years (1958-2095), the HWP stock, carbon emissions, and the substitution effect under three management and four wood-use scenarios, as elaborated in subsequent sections.

2. Methods

2.1. Wood products modeling

WPMs are implemented diversly based on their scopes and objectives. An integral model should include the following components: (i) *bucking allocation* involves the disaggregation of stems into different logs destinated to the production of differentiated products according to a set of dimensional and quality criteria typically established by wood industry professionals. Considering this component as an integral part of the TT model, rather than relying on a priori allocation factors, is crucial for minimizing errors resulting from simplification; (ii) *industrial processes* involve the transformation of raw wood into finished or semi-finished products, as well as the recycling or disposal of products when reaching the end of their use. Those processes are characterized by a set of allocation parameters either derived from expert knowledge, local surveys, or previous studies; (iii) *carbon pools* refer to the reservoirs of carbon stored in the diverse wood products currently in use or at disposal sites. HWPs are characterized by an average time in use, primarily linked to their intended purpose. For instance, construction wood is typically long-lived compared to pulpwood, given its use in applications that demand high durability and longevity. In contrast, pulpwood is primarily utilized for paper and pulp production, and its intended use does not require the same level of longevity; (iv) *product removal* refers to the point in time when products are retired from use. To estimate the product removal rate (also known as decay rate), carbon retention curves are used. They are based on the cumulative function of a chosen statistical distribution (e.g., Weibull, uniform, linear, and normal distributions; Brunet-Navarro et al., 2016; Matsumoto et al., 2022) defined by one or more of the following parameters (not an exhaustive list): the time when 50% of the initial carbon stock is left (also known as half-life time), the time when 5% of the initial carbon stock is left, the average life, and the maximum decay rate; (v) *recycling* involves the transformation of HWPs after reaching the end of their use into new products. This theoretically induces a reduction in the decay rate, as an additional amount of products is reinjected after each projection compared to the scenario when recycling is not considered; and (vi) *substitution* refers to the displacement effect resulting from the use of wood to substitute functionally equivalent energy-intensive materials or fossil fuels. The major components and processes described above are graphically illustrated below (Figure 1).

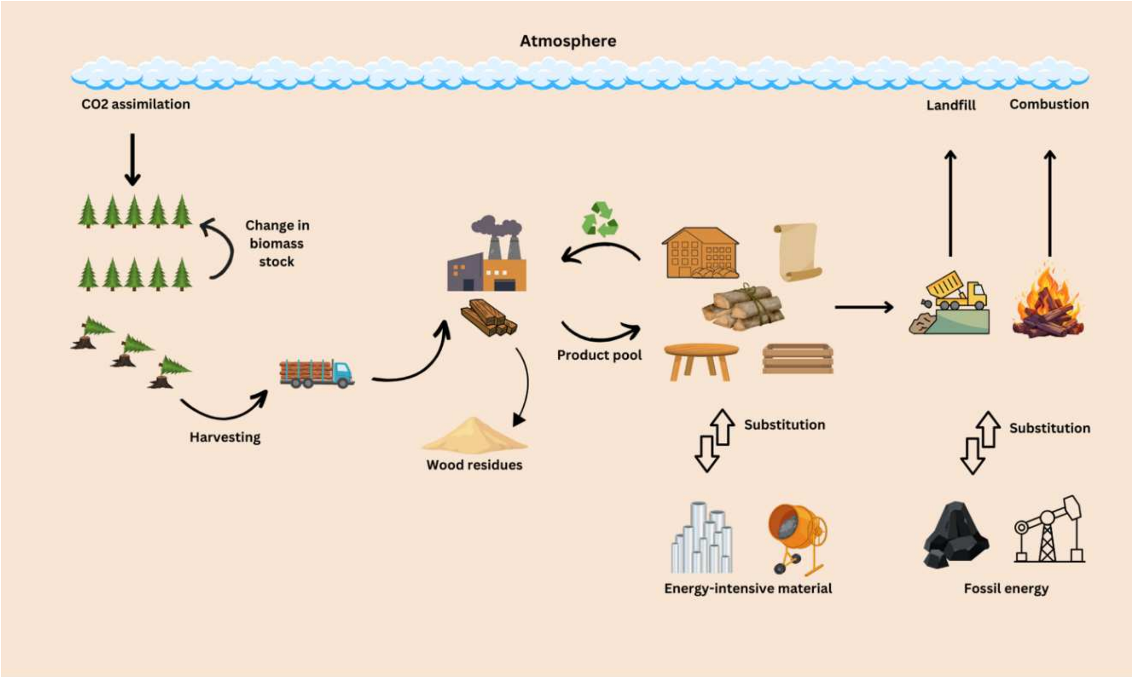

Figure 1: Lifecycle of HWPs - Illustration depicting key stages from production through utilization to end-of-life and natural decay.

2.2. Model description

TimberTracer (TT), a WPM based on the material flow method, was implemented using Python as its programming language. The model simulates overtime the carbon stock in HWPs, carbon emissions from HWP decay, bioenergy, and the substitution effect arising from the use of wood instead of energy-intensive materials or fossil fuel energy. *TimberTracer* could be coupled with forest growth models of different spatial resolution. This versality in the scale level is a result of its design which incorporates stand structure through appropriate statistical distributions.

By incorporating all the previously described components (see previous section 2.1), *TimberTracer* comprehensively accounts for and simulates the temporal dynamics of GHG emissions and removal across all carbon pools outside the forest, including changes in HWPs and disposal sites. Furthermore, the model considers the substitution effect and captures the temporal dynamics of material and energy substitutions. Additionally, *TimberTracer* offers the flexibility of utilizing both tree- and stand-level inputs, facilitated by its integration of a stand structure generator, enabling the transition from stand state descriptors to tree state descriptors. The TT model offers the ability to simulate the entire carbon accounting process using the function `run_model()`. Additionally, it is designed to be modular, allowing running various simulations independently, at specific stages of the carbon accounting process, as described below (Figure 2). Hereafter, we explicitly introduce each module, outlining its role and the functions it encompasses.

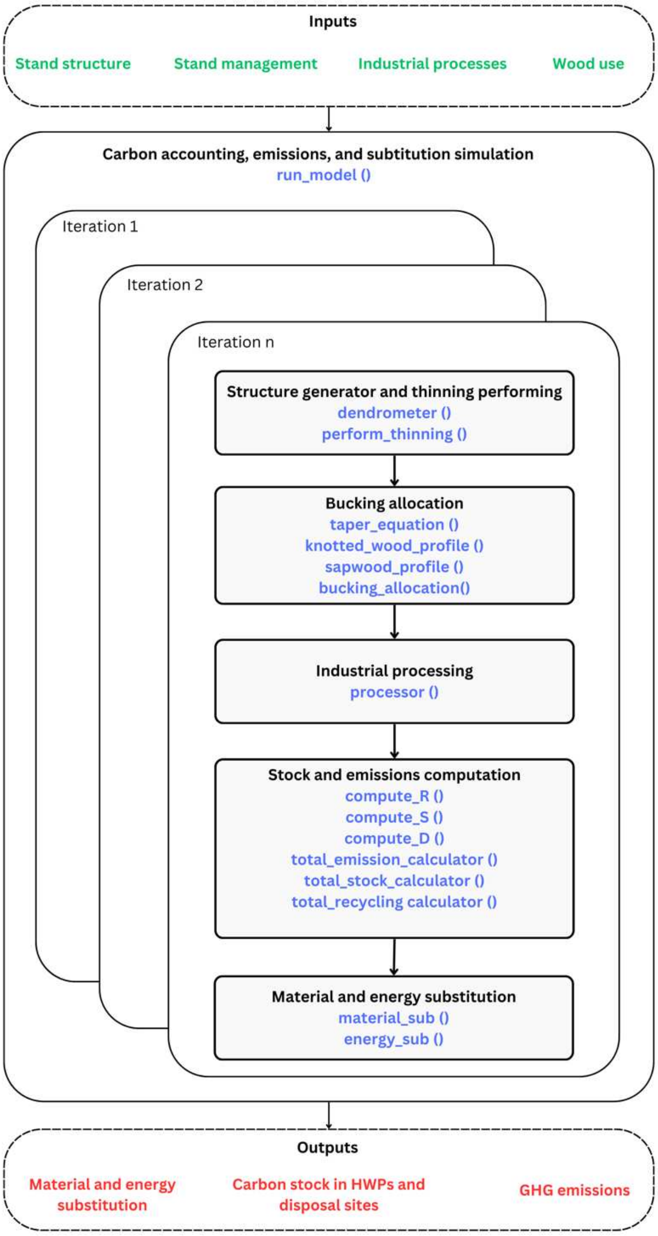

Figure 2: Flowchart of the *TimberTracer* model. In green the inputs, in red the outputs, in black the modules, and in blue the functions within the modules. The number of iterations is equal to the number of management interventions.

2.3. Model inputs and requirements

The *TT* model requires a set of input data for its initialization, including: i- stand structural data (DBH, height, stand density, basal area, bark thickness, sapwood, and heartwood areas); ii- forest management data (planning horizon, rotation period, rotation number, thinning age, thinning intensity, thinning nature); iii- industrial process data (product, priority, number, log length, log diameter, quality criteria, process efficiency); iv- wood use data (lifespan, recycling rate, reallocation scheme, displacement factors). Furthermore, *TimberTracer* necessitates the specification of a well-defined set of parameters mainly required by the dendrometer and the bucking allocation module (for further information on the model parameters and data inputs, please refer to the table in Supplementary 3).

2.4. Model outputs

The `run_model()` function serves as an integrated coordinator, orchestrating the seamless execution of independently developed modules introduced earlier to generate a comprehensive output. The model can be run for a planning horizon (PH)(i.e. the duration of the climate mitigation project implementation) that may encompass multiple rotations (R). The function `run_model()` renders a table of seven columns, presenting simulations of carbon stock in HWPs, annual and cumulative emissions, annual and cumulative material and energy substitution, and yearly recycling (all expressed in tC ha^{-1}).

2.5. The model structure

2.5.1. The structure generator and thinning performing module

TimberTracer is designed for compatibility with both tree- and stand-level data, providing flexibility in data input. This capability is realized through the incorporation of a structure generator module that implements the statistical distribution (e.g., Weibull distribution) of the diameter at breast height (DBH) within the stand level. It also assigns trees to different bio-sociological classes of status (i.e., dominant, co-dominant, intermediate, and overshadow trees) based on their total height, as implemented in the `dendrometer()` function. *TimberTracer* further considers thinning operations, characterized in the model by three descriptors: type, intensity, and timing, implemented in the `perform_thinning()` function, which renders dendrometry information about each individual thinned tree.

2.5.1.1. The structure generator

The transition from stand state descriptors to tree state descriptors would be feasible if the stand structure is well understood. The latter is typically likened to a statistical distribution. There are numerous mathematical formulations for statistical distributions in forestry, with one of the most employed being the Weibull distribution (Q. V. Cao, 2004). The probability density function of a Weibull random variable denoted as $X \sim Weibull(sh, sc, loc)$ is:

$$f(x, sh, sc, loc) = \frac{sh}{sc} \times \left(\frac{x-loc}{sc}\right)^{sh-1} \times e^{-\left(\frac{x-loc}{sc}\right)^{sh}} \quad \text{(Equation1)}$$

Where *f* is the probability density function, *x* is the random variable, *sh* represents the shape, *sc* denotes the scale, and *loc* indicates the location.

If the location is not provided, but the shape and scale are (2-parameter Weibull distribution), then the location will be predicted using the following equation:

$$E(x) = loc + sc \times \Gamma(1 + \frac{1}{sh}) \quad \text{(Equation2)}$$

$$loc = E(x) - sc \times \Gamma(1 + \frac{1}{sh}) \quad \text{(Equation3)}$$

Where *E(x)* is the mathematical expectancy of *x* and *Γ* is the gamma function.

After fitting the parameters of the Weibull distribution supposed to represent the structure of the forest stand at different stages of development, the next step is to compute the number of trees by each diameter class. For this specific purpose, the cumulative distribution function of the Weibull function is applied to the concerned diameter class following the equation:

$$N(class) = \left[e^{-\left(\frac{lower\ bound-loc}{sc}\right)^{sh}} - e^{-\left(\frac{upper\ bound-loc}{sc}\right)^{sh}}\right] \times N \quad \text{(Equation4)}$$

Where *N* represents stand density, and the lower bound and upper bound define the DBH class interval.

2.5.1.2. The thinning process

A thinning operation involves removing stems to benefit a tree or a group of trees deemed essential to ensure optimal growth conditions (Sohn et al., 2016). It focuses on enhancing wood quality and stand stability. The thinning intervention can be characterized by three elements: i- the type of cut (from the above, from the bottom, or neutral), which denotes the distribution of removed stems among various diameter categories of standing trees within the stand; ii- the thinning intensity which expresses the magnitude of the extraction conducted within the stand. It can be quantified by both the number of stems harvested and the implementation rate relative to the before-thinning stand population; iii- the period, commonly referred to as rotation, is the time interval between two successive thinning cuts within the stand. It varies depending on the tree species, age, and site conditions (T. Cao et al., 2006).

Bio-sociological tree status plays an important role in some thinning concepts, for example, for the selection of thinning trees in thinning from above and below (Fabrika & Vaculčiak, 2009). A simplified classification groups trees into four categories: **1-** dominant trees; **2-** co-dominant trees; **3-** intermediate trees; and **4-** overshadow trees. This classification consists of the definition of the position of each tree in terms of its height by reference to the other trees of the stand. As part of the process, the dominant height of the plot (**$h_{95\%}$**) as well as the height to the base of the crown (**hc**) are calculated. The classification of the trees into a scale is performed following the rules presented in the Table 1.

Table 1: Bio-sociological status criteria based on the tree height.

Criteria	**Bio-sociological status**
$hi \geq h_{95\%}$	Dominant tree (1)
$\frac{h_{95\%} + hc}{2} \leq hi < h_{95\%}$	Co-dominant tree (2)
$hc \leq hi < \frac{h_{95\%} + hc}{2}$	Intermediate tree (3)
$hi < hc$	Overshadow tree (4)

The thinning operation follows the approach implemented by (Fabrika & Ďurský, 2005). For thinning from below and thinning from above, trees belonging to a specific bio-sociological class are prioritized for each thinning type. In the case of neutral thinning, trees are harvested without consideration for their bio-sociological status. Further details are provided in the following.

Thinning from below (4+3) => 2

The process consists of removing trees belonging to the dominated bio-sociological sub-groups. The process of removing is parallel in 4+3 (Overshadow and Intermediate). If the removal amount is not reached by 4+3, the process continues sequentially in sub-group 2 until reaching the required number of trees satisfying the initial condition.

Thinning from above (1+2) => 3

The process consists of removing trees belonging to the dominating bio-sociological sub-groups. The process of removing is parallel in 1+2 (Dominant and Co-dominant). If the removal amount is not reached by 1+2, the process continues sequentially in sub-group 3 until reaching the required number of trees satisfying the initial condition.

Neutral thinning (1+2+3+4)

The process consists of removing trees regardless of the bio-sociological sub-group to which they belong. The process is parallel in 1+2+3+4 and continues until satisfying the required removal amount.

2.5.2. *The bucking allocation module*

TimberTracer allocates logs from thinned trees to HWPs, considering determinant factors such as stem log diameter and quality. The qualitative grading of logs involves several criteria, with the proportion of knotted wood and sapwood-to-heartwood ratio being among the most commonly used in the literature (Bucket et al., 2005; Longuetaud et al., 2012; Thurner et al., 2019). The bucking allocation is practically implemented within the model through two sequential steps. The first step involves dressing the stem profile of each individual tree using the `taper_equation()` function which renders the diameter over bark (dob) at any point along the stem. Simultaneously, the knotted wood profile is dressed using the `knotted_wood_profile()` function while the sapwood and heartwood profiles are established with the `sapwood_profile()` function. The second step consists of combining the tree stem profile (including taper, knotted wood, sapwood, and heartwood) with the bucking allocation criteria defined by wood industry professionals to disaggregate trees into different logs. This entire process is implemented in the `bucking_allocation()` function (please refer to Supplementary 2 for more information on the bucking allocation criteria).

2.5.2.1. *Stem profile generator*

To achieve a precise stem profile dressing, the *TimberTracer* uses a comprehensive set of equations, which will be thoroughly described in this section (see Figure 3 for a graphical representation of the stem profile).

The taper profile refers to the degree to which a tree's stem diameter decreases as a function of height above ground. Taper is often represented by mathematical functions fitted to empirical data, called taper equations. One such function, attributed to (Max & Burkhart, 1976) and used by default in the model is:

$$y(z) = b_1 z + b_2 z + b_3(z - a_1)^2 I_1 + b_4(z - a_2)^2 I_2 \qquad \text{(Equation 5)}$$

where $y = (\frac{dx}{dbh})^2$; dx = is the upper stem diameter over bark (dob) at a given height h of the tree, $z = 1 - \frac{h}{ht}$ = the complement of the relative height with ht being the tree total height; a_1 and a_2 = join points to be estimated from the data, $I_k = 1$ if $z > a_i$ and 0 otherwise, $k = 1,2$, b_p's = regression coefficients with, $p = 1, 2, 3, 4$.

The crown base height (h_c) refers to the level of insertion of the last branch of the crown within the stem, it is generally predicted from the total height using an allometric equation. One such equation is the power function expressed as follows:

$$h_c = a {h_t}^c \qquad \text{(Equation 6)}$$

where *a* and *b* correspond respectively to the amplitude and the exponent of the relation.

The DBH of a tree could be also predicted from its total height. One such function is the power function expressed as follows:

$$dbh = alpha \times {h_t}^{beta} \qquad \text{(Equation 7)}$$

where *alpha* and *beta* correspond respectively to the amplitude and the exponent of the relation. In tree analysis, a crucial step involves shaping the crown base profile to differentiate knotted from intact wood. To establish this profile, a combination of the three equations (5-7) is utilized. In practice, the approach entails reconstructing the historical crown base height limits and considering that the area from the curve towards the bark represents the knotted wood, while the area from the curve towards the pith represents the intact wood.

$$z_c = 1 - a({h_c}^{c-1}) \qquad \text{(Equation 8)}$$

$$d_c = \sqrt{y(z_c)} \times alpha \times [(\frac{h_c}{a})^{\frac{1}{c}}]^{beta} \qquad \text{(Equation 9)}$$

where z_c represents the complement to the relative height at the level of the crown base and d_c refers the diameter of the intact wood.

The sapwood profile is determined based on the simplified assumption that the sapwood width and bark thickness remain constant within the tree level (Longuetaud et al., 2006). The width of knotted wood, which naturally varies within the tree level, is calculated as the difference between the diameter at a specific height obtained from the taper profile and the sum of the sapwood width and bark thickness.

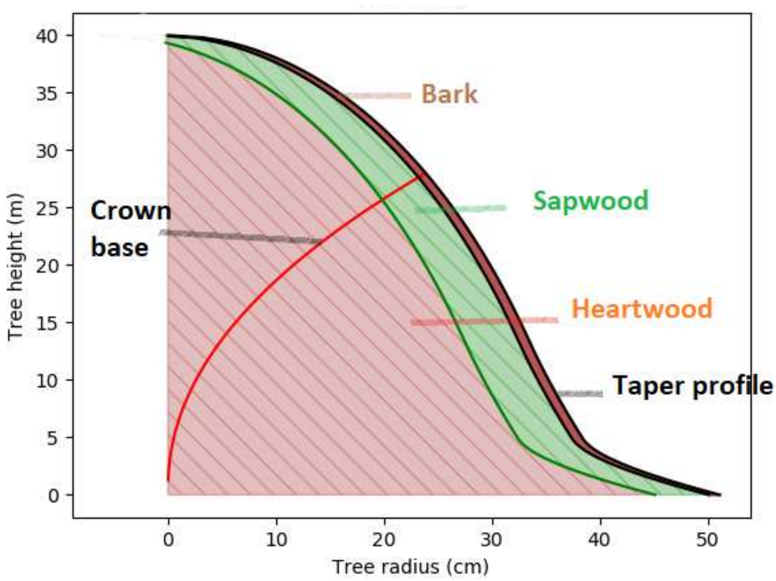

Figure 3: Graphical representation of stem longitudinal profile

2.5.2.2. Stem disaggregation

Stems are disaggregated into different logs based on specific criteria, typically established by wood industry professionals. These criteria, tailored to each species, include both dimensions and quality considerations, and they are organized hierarchically. To elaborate, the model initially checks if the stem aligns with the criteria for producing a designated log intended for a specific product. If this is not the case or if the maximum desired number of this specific log has been reached, the model then advances to the next HWP based on a hierarchy defined by the user. In *TimberTracer*, log dimensions are characterized by the length and small end diameter of the log, while log quality is assessed through ratios of knotted wood ($Ø_{KW}$) to heartwood ($Ø_{HW}$) and knotted wood to small end diameter ($Ø_{SE}$). The model checks these criteria (e.g., $Ø_{SE} \geq 25$ cm, $(Ø_{KW} / Ø_{HW})^2 \leq 13\%$, and $Ø_{KW}/ Ø_{SE} \leq 30\%$) by implementing a bisection algorithm that automatically performs the search for the corresponding height validating the given criteria.

2.5.3. The processor module

Logs are processed to match their intended products, employing the standard industry method for each type of product. The efficiency rate of this industrial transformation, a theoretical measure, depends on how the processing is done, and this varies based on the targeted product. In *TimberTracer*, the production of HWPs is calculated using the efficiency rate which is product-specific. Subsequently, any process losses (i.e., 1 – efficiency) are redistributed among other products according to a scheme defined by the user. This process is implemented in the `processor()` function.

2.5.4. The stock and flow module

TimberTracer simulates the evolution of carbon in HWPs and disposal sites including both mill and landfill sites throughout the planning horizon (PH) using the `total_stock_calculator()` function. After each annual projection, a portion of the carbon in HWPs undergoes decay based on product-specific decay function (refer to `compute_D()` in the model). Subsequently, a fraction of the decay is recycled and reinjected into the HWPs carbon pool (refer to `compute_R()` in the model), another portion is directed to firewood, while the remaining part is sent to landfills. Furthermore, *TimberTracer* simulates the evolution of the total emissions resulting from the firewood combustion and the decay of carbon pool in disposal sites, accounted for as an instantaneous oxidation, using the `total_emission_calculator()` function.

In *TimberTracer*, the product removal rate (i.e., decay rate) is determined using the cumulative distribution function (CDF) of a normal distribution, which is defined by its mean and standard deviation. The mean represents the average lifespan of a product, while the standard deviation reflects the change in the dynamic decay, typically expressed as a fraction of the average lifespan (e.g., a fraction of 1/3 as used in Brunet-Navarro et al., 2017). In the following, the CDF formulation is presented.

$$CDF(x;\ lifespan, lifespan \times \text{fraction}) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x - lifespan}{lifespan \times fraction \times \sqrt{2}}\right)\right] \quad \text{(Equation 10)}$$

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad \text{(Equation 11)}$$

where CDF is the cumulative distribution function and erf is the error function.

2.5.5. The substitution module

TimberTracer simulates the climate change mitigation effect in terms of avoided emissions resulting from the substitution of fossil fuels by bioenergy and energy-intensive materials by wood products. The carbon mitigation potential is closely linked to the specific solution being substituted and is calculated using the displacement factor (DF in tCO_2-eq m^{-3}), a measure of the amount of GHG emissions avoided when wood is used instead of the current solution (Sathre & O'Connor, 2010). The computation of the substitution is perfomed separately for material and energy substituiton using the `material_sub()` and `energy_sub()` functions, respectively. The substitution is estimated using the following equation:

$$substitution = wood\ volume \times DF \times k \qquad \text{(Equation 12)}$$

where $k = \frac{12}{44}$ is the constant used to convert tCO_2 to tC

3. Use case

3.1. Study area

The Bonis experimental watershed located in the mountain area of Sila Greca (39°28′49″ N, 16°32′07″ E; from 975 to 1330 m a.s.l.) in the Calabria region, southern Italy was chosen as the study area in this work (Collalti et al., 2017; Testolin et al., 2023). Almost 93% of its total area is covered by forests, dominated by ~60 years old artificial Laricio pine stands. The stands were planted in 1958 with an average density of 2425 sapling ha^{-1} (Nicolaci et al., 2015) and underwent a thinning treatment in 1993 with basal area (BA) removal of 25 % (Callegari et al., 2003). The forest was equipped with 14 circular survey plots, each with a radius of 12 meters, for monitoring since 1993, and they were surveyed until late 2016.

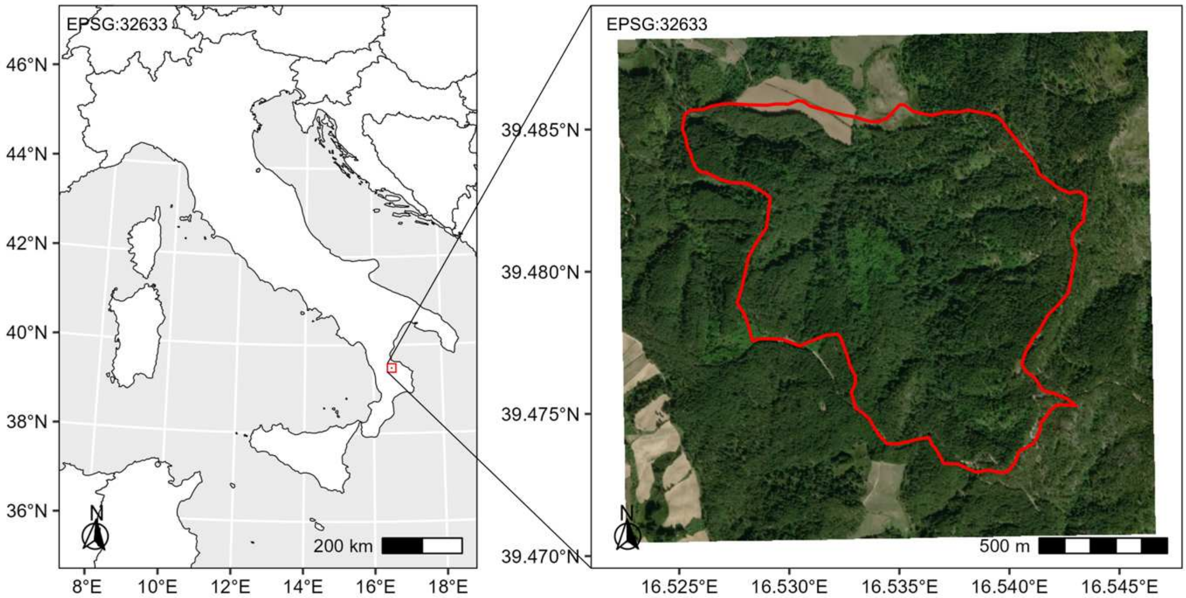

Figure 4: Map of the geographical situation of the Bonis watershed (right sub-figure) inside the Italian territory (left sub-figure).

3.2. Scenarios building

For the management scenarios, we tested three options reflecting different goals. All the options were simulated to take place after 2016, which is the last year of plot surveying. The first option simulates light thinning intensity, corresponding to a 28% reduction of Basal Area (BA) at an interval of 15 years, aiming to reproduce silvicultural interventions favoring natural forest dynamics. An additional production-oriented option, known as clearcut, simulates a complete harvest followed by replanting 80 years after the establishment of the plantation. A third option, representing a more sustainable alternative to clearcutting, simulates a shelterwood. This involves two light thinnings (20% reduction of BA) with a 10-year interval, followed by seed-favoring cut after 80 years from the original planting (80% reduction in BA) and removal cut 10 years later.

For the wood-use scenarios, four different options were developed. The ‘Baseline scenario’ (‘Business as Usual’, BAU) kept the recycling rate and products lifespan values constant. In the ‘Longevity scenario’, the lifetime of products was increased by 10 %. In the ‘Reuse scenario’, the recycling rate of products was increased by 10%. In the ‘Sustainability scenario’, both the lifetime of products and the recycling rate were increased by 10% (See Supplementary 4 for further details).

Table 2: Forest management and wood use scenarios

Group	Name	Features
Forest management	Selective thinning	28% reduction of BA at an interval of 15 years
	Clearcut	Complete harvest followed by replanting at 80 years.
	Shelterwood	Two light thinning (20% reduction of BA) with 10-year interval, followed by seed-favoring after 80 years (80% of BA) and removal cut 10 years later
Wood use	BAU	Constant recycling rate and product lifespan
	Longevity	10% increase in product lifespan
	Reuse	10% increase in recycling rate
	Sustainability	10% increase in both product lifespan and recycling rate

3.3. Modeling framework and the required data

The *TimberTracer*, a WPM that tracks carbon in HWPs which was extensively introduced in this paper, was coupled with 3D-CMCC-FEM (‘*Three Dimensional – Coupled Model Carbon Cycle – Forest Ecosystem Module’* v.5.6 BGC; Mahnken et al., 2022), a stand-level process-based model that annually provides data on the forest state (e.g., density, DBH, BA, and total height). The integration of the two models was considered as the modeling framework for achieving the objectives of this study.

The 3D-CMCC-FEM model requires a set of input data for its initialization which includes: (1) model species parameters set which was derived from a recent work that validated the model for Laricio pine stand in the Bonis watershed (Testolin et al., 2023); (2) daily time series of meteorological fields (e.g. incoming shortwave radiation, maximum and minimum temperature, relative humidity or vapor pressure deficit, precipitation). For the period from 1958 until 1976 climate data was derived using the mountain microclimate simulation model MT-CLIM (Thornton & Running, 1999) forced by temperature and precipitation series measured by the nearby Cecita meteorological station (39°23′51″ N, 16°33′24″ E; 1180 m a.s.l.), while for the period from 1976 to 2005, gridded climate time series were used. The latter derived from bias-corrected outputs of the regional climate model COSMO-CLM (Rockel et al., 2008) at around ~8 km horizontal resolution (Bucchignani et al., 2016; Zollo et al., 2016), and driven by the general circulation model (GCM) CMCC-CM (Scoccimarro et al., 2011) under historical GHG forcing (see Testolin et al., 2023 for details). Additionally, measured values of global annual atmospheric CO_2 concentration were derived from Meinshausen et al. (2011) and used for the period from 1958 to 2005. A random sampling of both climate and CO_2 data within the period between 1990 and 2005 was performed as representative of an additional synthetic period of 90 years assuming unchanging climate and atmospheric CO_2 conditions, to simulate in total 138 years; (3) stand initialization data for the year 1958 which included stand density: 2425 saplings ha^1, DBH: 1 cm, height: 1.3 m, age: 4 years, elevation: 1131 m a.s.l., soil texture (clay: 20 %; silt: 26 %, sand: 54 %) and depth: 100 cm (Buttafuoco et al., 2005; Nicolaci et al., 2015; Moresi et al., 2020). Testolin et al. (2023) provides an extensive description of model validation (before and after thinning) at the Bonis site for both carbon fluxes and stocks such as DBH, stand density and gross primary productivity (GPP).

In addition, *TimberTracer* also requires a set of inputs and parameters necessary for its initialization: (1) he bucking allocation criteria, developed to segregate solid-wood products based on quality requirements for specific end uses across various wood products, are standardized and can be applied irrespective of log source and sawmill producer (Jozsa & Middleton, 1994). Potential wood products from Laricio pine stems were inventoried by consulting five sawmill industry experts, and the amalgamation of all possible products was retained for this study. Furthermore, the bucking criteria used in this study are those commonly found in the literature (CTBA, 2001); (2) the transformation efficiency of each log category, a geometric yield as well as the loss reallocation were defined with the assistance of sawmill industry professionals; (3) for the recycling rate, we suggest that the recycling rate of waste wood products was constant at 10% during the planning horizon while lifespan of each product was reviewed from published studies (Burschel, Kürsten, et al., 1993, 1993; Karjalainen et al., 1994; Nabuurs, 1996; E. Skog & A. Nicholson, 1998; Eggers, 2002; Masera et al., 2003; Pingoud et al., 2003); (4) displacement factors for the substitution were derived from the literature (Sathre & O'Connor, 2010; Suter et al., 2017); (5) model dendrometry parameters, including stand structure, taper model, crown base height equation, and diameter-to-height parameters, were fitted to the forest data collected from the experimental plots of the Bonis watershed forest, while the species density was derived from the literature (Dias et al., 2018).

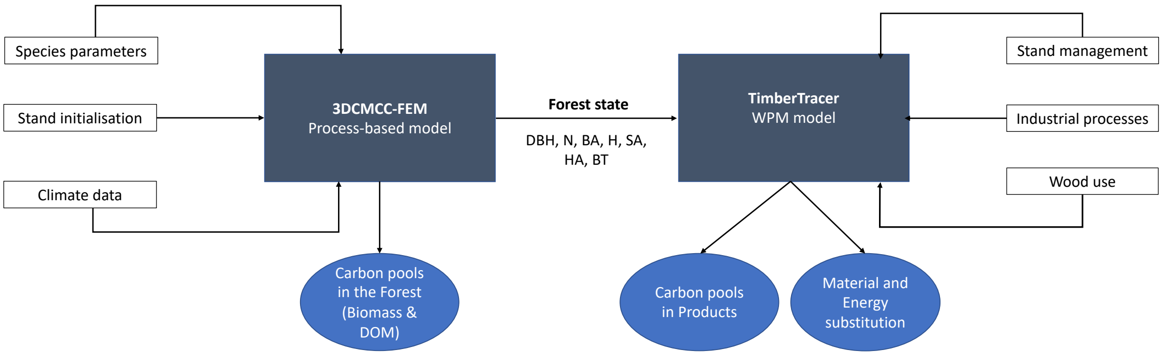

Figure 5: carbon modeling framework coupling a forest process-based model (3DCMCC-FEM) and *TimberTracer* a harvested-wood product model. DBH is the stand mean diameter at breast height, N is the stand density, BA is the stand basal area, H is the stand mean tree height, SA is the sapwood area of the mean tree, HA is the heartwood area of the mean tree, and BT is the bark thickness of the mean tree.

3.5. Results

3.5.1. Introduction

In this simulation, the net carbon balance, calculated as the difference between carbon stored in HWPs, the avoided emissions as effect of the substitution of material and fossil fuel, and carbon emissions from HWPs end-life, was estimated for three different forest management schemes and four wood use scenarios providing insights into the overall carbon balance at each point in time throughout the projection period. These estimations were derived from the modeling exercise, relying on both silvicultural itinerary and product utilization over the use and end-use periods. To analyze the effects of various wood use scenarios on the overall carbon balance over time, we compared each scenario with the business-as-usual (BAU scenario. Furthermore, to assess the impact of different forest management scenarios on the overall carbon balance over time, we conducted individual comparisons while maintaining the same wooduse scenario each time. In this work we use positive values to represent carbon removals while negative ones are C emissions.

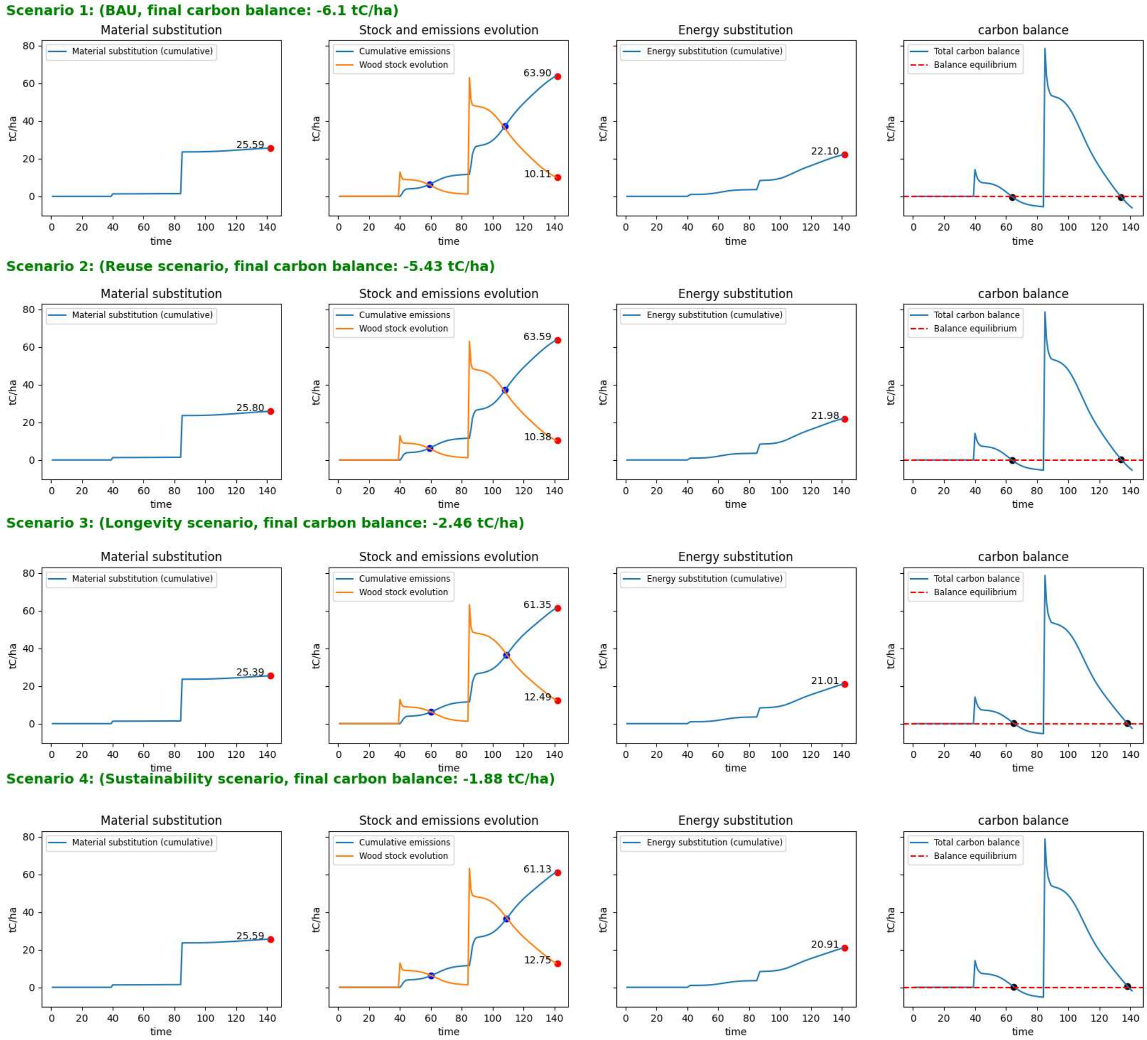

Figure 6: Clearcut management among different wood-use scenarios is demonstrated to showcase variations in Harvested Wood Products (HWPs) carbon stock, material and energy substitutions, carbon emissions, and the overall carbon balance (tC ha^{-1}). Blue points represent the equalization between HWPs and emissions, while black points indicate neutrality of the overall carbon balance. The red dashed line corresponds to the overall carbon balance neutrality. Negative values of the overall balance indicate positive emissions, while positive values indicate positive sequestration.

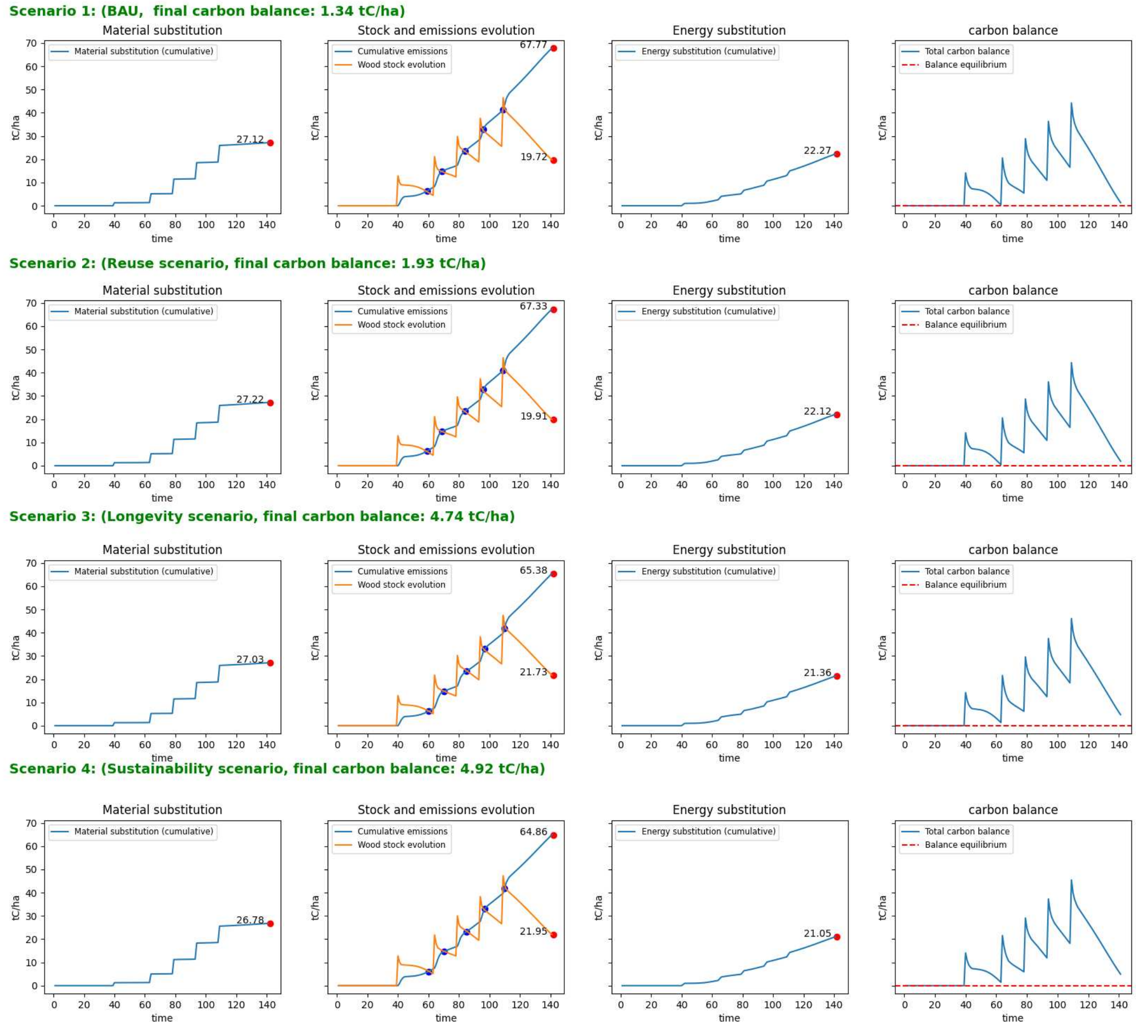

Figure 7: Selective thinning management among different wood-use scenarios is demonstrated to showcase variations in Harvested Wood Products (HWPs) carbon stock, material and energy substitutions, carbon emissions, and the overall carbon balance (tC ha^{-1}). Blue points represent the equalization between HWPs and emissions, while black points indicate the neutrality of the overall carbon balance. The red dashed line corresponds to overall carbon balance neutrality. Negative values of the overall balance indicate positive emissions, while positive values indicate positive sequestration.

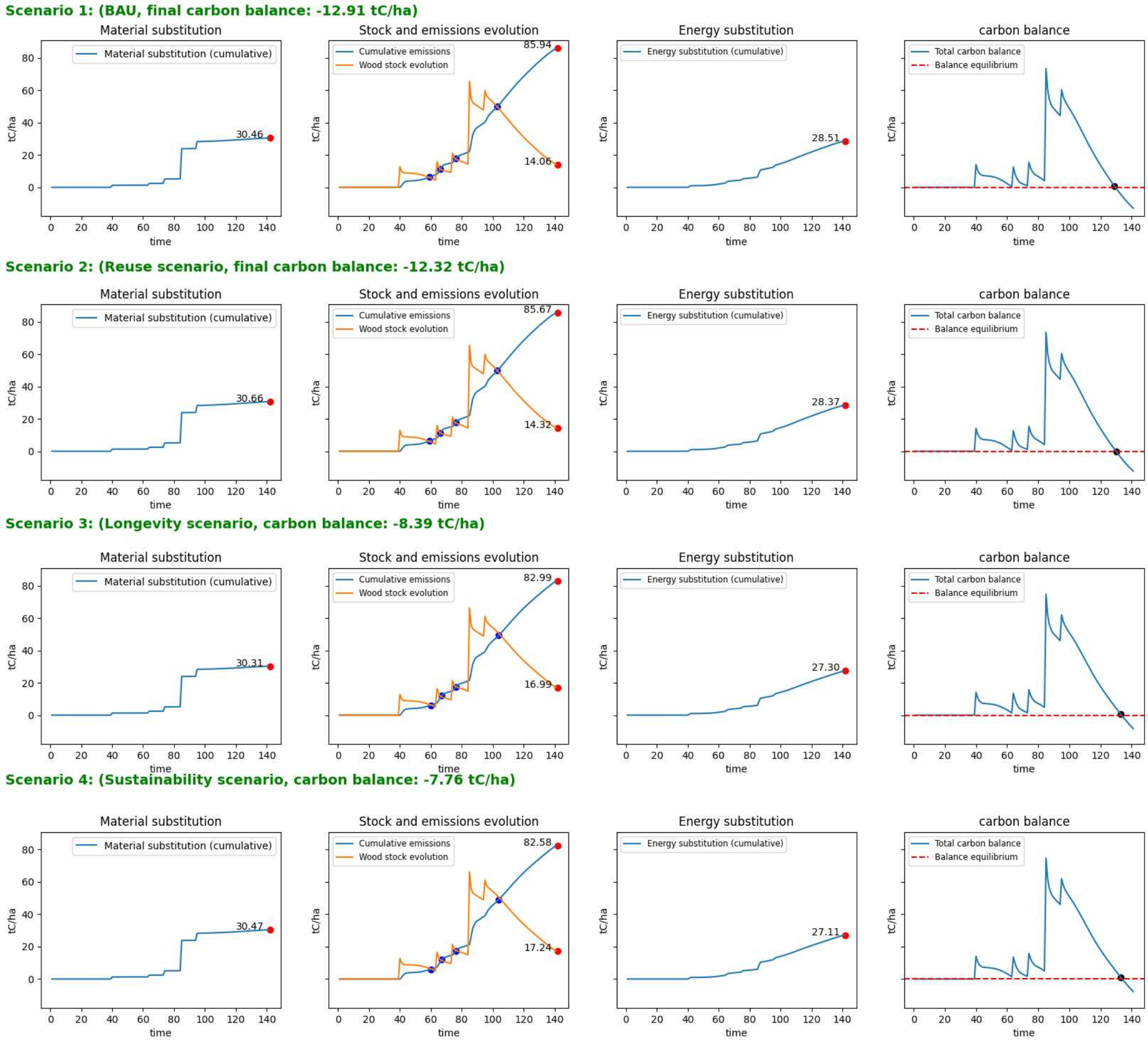

Figure 8: Shelterwood management among different wood-use scenarios is demonstrated to showcase variations in Harvested Wood Products (HWPs) carbon stock, material and energy substitutions, carbon emissions, and the overall carbon balance (tC ha^{-1}). Blue points represent the equalization between HWPs and emissions, while black points indicate the neutrality of the overall carbon balance. The red dashed line corresponds to the overall carbon balance neutrality. Negative values of the overall balance indicate positive emissions, while positive values indicate positive sequestration.

3.5.2. Overall carbon balance

The application of wood use scenarios had varied effects across different forest management scenarios, yet recurrent patterns can be identified. Among the various forest management scenarios, the sustainability scenario consistently exhibited the lowest carbon C emissions. To elaborate, over the planning horizon, C emissions decreased by 69%, 267%, and 40%, respectively, for clearcut, selective thinning, and shelterwood managements compared to the BAU scenario (i.e., –6.1, 1.34, –12.91 tC ha^{-1}). Comparable effects were observed with the longevity scenario, resulting in a reduction of C emissions by 60%, 254%, and 35%, respectively, for clearcut, selective thinning, and shelterwood managements compared to BAU. The reuse scenario induced the smallest decrease in C emissions, at 11%, 44%, and 4.6%, respectively, for clearcut, selective thinning, and shelterwood managements compared to BAU (See Tables 3 and 4).

In the context of forest management, selective thinning exhibited pronounced superiority over alternative management approaches in all four wood-use scenarios. Under this management strategy, carbon emissions were intensively reduced compared to the BAU scenario for clearcut and shelterwood management, respectively. Meanwhile, clearcut and shelterwood management demonstrated nearly equivalent effects across the three wood-use scenarios (see Tables 3 and 4).

The overall carbon balance exhibits diverse patterns based on the applied forest management. Specifically, the results consistently demonstrate a positive balance for the selective thinning management approach throughout the entire planning horizon. However, the clearcut management reached equilibrium at either year 64 or 65 under BAU and the reuse scenarios, or under the longevity and sustainability scenarios. The balance remained negative from that point until a significant harvesting event at year 84. Subsequently, a new equilibrium was achieved at either year 134 or 138 under BAU and reuse scenarios, or under longevity and sustainability scenarios. The overall balance remained negative thereafter. In the case of shelterwood management, the balance consistently remained positive until a first equilibrium was reached at either year 129, 130, or 133 under BAU, or under the reuse scenario, or under the longevity and sustainability scenarios. Afterward, the balance remained negative (See Figures 5-7).

Table 3: The overall carbon balance, encompassing removals, emissions, and substitution effects from harvested wood products (HWPs) due to wood use and management scenarios, is expressed in tC ha^{-1}. Negative values indicate net carbon emissions, whereas positive values indicate net carbon removals.

	Wood use scenario			
Management scenario	BAU	Reuse	Longevity	Sustainability
Clearcut	–6.1	–5.43	–2.46	–1.88
Selective thinning	1.34	1.93	4.74	4.92
Shelterwood	–12.91	–12.32	–8.39	–7.76

Table 4: Relative difference in the overall carbon balance (%) between the baseline scenario (BAU) and the alternative wood-use scenarios.

	Wood use scenario		
Management scenario	Reuse	Longevity	Sustainability
Clearcut	11	60	69
Selective thinning	44	254	267
Shelterwood	4.6	35	40

4.5.3. Material and energy substitution

Regarding material substitution, we identified a distinct pattern marked by successive phases of a sharp pulse of increase coinciding with thinning or harvesting operations, followed by a positive pseudo plateau. Among the forest management scenarios, the reuse scenario consistently showed the highest material substitution effect averaging 0.62% more than the BAU scenario (i.e., 25.59, 27.12, and 30.46 tC ha^{-1}; respectively for clearcut, selective thinning and shelterwood). In contrast, the longevity scenario consistently exhibited the lowest potential (averaging 0.53% less than the BAU) while the sustainability scenario demonstrated a comparable effect to the BAU scenario.

For energy substitution, we observed a pattern characterized by successive phases of a moderately intense pulse of increase coinciding with thinning or harvesting operations, followed by a positive slope. Among the management scenarios, the BAU scenario (i.e., 22.10, 22.27, and 28.51 tC ha^{-1}; respectively for clearcut, selective thinning and shelterwood) consistently exhibited the highest energy substitution effect. In contrast, the sustainability consistently showed the lowest energy substitution effect (averaging 5.25% less than BAU), followed by the longevity scenario (averaging 4.41% less than BAU) and finally the reuse scenario (averaging 0.57% less than BAU).

Table 5: Cumulative material and energy substitutions due to the use of particular scenario (in tC ha^{-1}) (Material substitution | Energy substitution).

	Wood use scenario			
Management scenario	BAU	Reuse	Longevity	Sustainability
Clearcut	25.59 | 22.10	25.80 | 21.98	25.39 | 21.01	25.59 | 20.91
Selective thinning	27.12 | 22.27	27.22 | 22.12	27.03 | 21.36	26.78 | 21.05
Shelterwood	30.46 | 28.51	30.66 | 28.37	30.31 | 27.30	30.47 | 27.11

3.5.4. Carbon balance of HWPs

Regarding the carbon emissions from firewood and disposal sites, we observed a pattern characterized by a sustained positive slope interrupted by a sharp pulse of increase coinciding with thinning or harvesting operations. Among the management scenarios, the BAU scenario (i.e., –63.90, –67.77, and –85.94 tC ha^{-1}; respectively for clearcut, selective thinning and shelterwood) consistently exhibited the highest C emissions. In contrast, the sustainability scenario consistently showed the lowest level of emissions (averaging 4.17% less than BAU), followed by the longevity scenario (at 3.64% less than BAU), and finally the reuse scenario (at 0.48% less than BAU).

Regarding the carbon stock of HWPs, it assumes different shapes depending on the type of applied forest management. However, a commonly observed pattern is characterized by a sustained negative slope interrupted by a sharp pulse of increase coinciding with thinning or harvesting operations. Among the management scenarios, the BAU scenario consistently exhibited the lowest HWPs carbon stock (i.e., 10.11, 19.72, and 14.06 tC ha^{-1} for clearcut, selective thinning, and shelterwood, respectively). In contrast, the sustainability consistently showed the highest level of carbon stock in HWPs (averaging 20% more than BAU), followed by the longevity scenario (at 18.2% more than the BAU), and finally, the reuse scenario (at 1.80% more than BAU).

The duration of positive carbon balance differs significantly across various forest management strategies and slightly among different wood-use scenarios (see Table 5). In the case of selective thinning, five positive periods, measured in years, can be observed, with their durations decreasing over time: [20, 6, 6, 3, 1] or [21, 7, 7, 4, 2], respectively, for BAU and the reuse scenarios or the longevity and sustainability scenarios. In the case of clearcut management, two positive periods can be observed with their durations slightly increasing over time: [20, 24] or [21, 25], respectively, for BAU and the reuse scenario or the longevity and sustainability scenarios. Regarding the shelterwood management, four positive periods can be observed with their durations decreasing and then increasing overtime: [20, 3, 3, 19] or [21, 3, 3, 20], respectively, for BAU and the reuse scenario or the longevity and sustainably scenarios.

Table 6: Duration of Positive Balance Between Harvested Wood Products (HWPs) stock and emissions (in years).

	Wood use scenario			
Management scenario	**BAU**	**Reuse**	**Longevity**	**Sustainability**
Clearcut	36	36	41	41
Selective thinning	44	44	46	46
shelterwood	45	45	47	47

4. Discussions

In this study we presented *TimberTracer*, a dynamic model of the carbon balance in HWPs, and coupled it with 3D-CMCC-FEM with the aim to investigate on the effect of different forest management and wood use options on the overall carbon balance of HWPs. Assuming flexibility in both wood utilization and forest management practices, this study case demonstrates that the overall carbon balance can be increased by giving preference to multiple light, non-distant cuttings over a few distant intensive cuttings and promoting wood use for material purposes, including the increase of recycling and products lifetime.

Among various tested wood-use options, the sustainability scenario, representing the synergistic combination of increased recycling rate and extended product lifetime, demonstrated the highest mitigation potential among all wood use options. Increasing the recycling rate involves reinjecting an additional portion into the existing HWPs carbon stock, positively influencing both the level of HWPs stock and the material substitution effect, considering the new products. The increase in the recycling rate results in a reduction in the portion of decay allocated to firewood, crucial for emission reduction due to the balanced relationship between firewood and recycled wood. Furthermore, the extended product lifetime contributes to lowering the decay rate, effectively delaying emissions from HWPs. The last point is strongly supported by the equilibrium analysis of the overall balance, demonstrating that scenarios with a 10% increase in product lifetime typically reach an overall equilibrium well after the other scenarios (see Results).

As far as forest management options are concerned, selective thinning management with regular cutting of approximately the same stand basal area (i.e., ~11 m^2 ha^{-1}) demonstrated the highest mitigation potential among the studied forest management options. It consistently maintained an overall balance above the zero line throughout the 140-year planning horizon. Despite periods where carbon emissions exceeded the HWP carbon stock, compensatory effects of material and energy substitution offset this difference. In contrast, shelterwood management, although prescribing a harvesting of 31.72% basal area higher than selective thinning (i.e., ~57 m^2 ha^{-1}), experienced an overall carbon balance dropping below the zero line around 130 years, a decade before the end of the planning horizon. This could be attributed to the timing of a strong thinning (i.e., 33.44 m^2 ha^{-1}) that occurred earlier at the year 84. The emissions from its decay could not be offset by the last thinning at the year 94 (i.e., 11.51 m^2 ha^{-1}), leading to an overall carbon equilibrium and negative balance thereafter. Despite demonstrating the highest mitigation potential, selective thinning exhibited the shortest period in positive balance among different forest management options (i.e., 38 years compared to 45 and 46 years for clearcut and shelterwood managements, respectively). This suggests that the option characterized by the longest period in positive balance may not necessarily provide the best mitigation potential. Other factors, such as the timing and intensity of harvesting may come into play. In the case of clearcut and shelterwood managements, the last cuttings are early and involve intense interventions, causing the decay of almost the entire stock and justifying the early overall carbon balance equilibrium relatively to the planning horizon.

The outcomes of this study are significantly enhanced by the inclusion of the bucking allocation module in the *TimberTracer* model, which considers the dimensions of logs for the allocation of wood to HWPs. This is crucial because various products have distinct use and post-use properties, leading to diverse time dynamics, and a pre-established allocation may not accurately reflect reality. The role of the bucking allocation was evident across all management options. Each successive intervention, characterized by a higher mean DBH of the harvested stems than the precedent due to the stand's growth dynamic, resulted in the newly HWPs stock exhibiting a slower decay dynamic than the precedent due to the higher portion of long-lived products in the most recent one. For instance, in the case of clearcut management, two interventions were made at the years 39 and 84, yielding decay rates of ~2% per year and 1.5% per year, respectively. The analysis of the bucking allocation in both the initial and subsequent harvests, reveals that, from the first harvest, the production was limited to short- and mediumlived HWPs such as paper and particle, while novel categories of long-lived products were introduced in the second harvest, exemplified by furniture and sawing, which justify the decrease in the decay rate of the HWPs stock (see Appendix A).

These multiple findings align with prior studies in this area. In a theoretical exercise evaluating the mitigation potential of wood product use in the European forest sector, (Brunet-Navarro et al., 2017) demonstrated that increasing each component—whether recycling rate or lifespan—individually by approximately 20% could result in an 8.9% increase in carbon removal by 2030 by reference to the 2017 BAU scenario. Furthermore, the study states that a simultaneous 20% increase in both average product lifespan and recycling rate could yield a 17.3% increase in carbon removal by 2030. Another recent study conducted by Bozzolan et al., 2024) explored the carbon sequestration potential of HWPs in four EU countries, projecting outcomes from 2020 to 2050 across six alternative scenarios. The findings suggest that prioritizing wood use for material purposes, while maintaining a constant harvest, yields the highest mitigation benefits in the short to medium term. Moreover, in a continental study (EU-28) focusing on assessing the consequences of implementing policy choices on GHG emissions and removals, it was revealed that the adoption of the cascading scenario of HWPs led to a slight increase in the net balance between emissions and removals from/by HWPs. The balance was simulated to rise from approximately 34 Mt CO_2-eq in the base period around 2010 to just under 40 Mt CO_2-eq in 2030, as documented by Rüter et al. 2016). In another study aiming to investigate the potential of cascading use of woody biomass in the EU, it was found that GHG emissions could be reduced by 35 MtCO^2-eq year^{-1} as a result of implementing the maximum technical potential to increase recycling of waste wood and paper flows (Bais-Moleman et al., 2018).

From another perspective, the significance of management has been underscored in numerous studies. In Hennigar et al. 2008), the application of five silvicultural itineraries, derived from translating five alternative management objectives for an even-aged forest, resulted in significantly different outcomes regarding the carbon sequestration by HWPs. In another study, (Thornley & Cannell, 2000) concluded that the method of harvesting is crucial showing further that a regular removal of timber from forest in a way that maintains a continuous canopy is likely to give substantially higher sustained yields and amount of carbon storage than periodical clear-felling. The same study suggests that if the objective was to maximize timber volume yield, the optimal management system would be the regular thinning of forest. A physiological explanation of this could be that the continuous canopy cover with a moderately high leaf area index (~ 4 m^2 m^{-2}) provide high light interception and net primary production (Bouriaud et al., under review). Regular thinning ensures that the forest has lower biomass than an undisturbed forest, and it is continuously growing, resulting in lower maintenance respiration (Schulze et al., 2022). In a different context, Bourque et al. (2007) demonstrated that selection harvesting was the preferred method compared to clearcutting when the goal was to maximize total carbon storage in the forest landscape and wood products generated from harvesting over an 80-year planning horizon. This preference was justified by the fact that selection harvesting, in contrast to clearcutting, offers the advantage of maintaining the forest close to its maximum biological productivity. Additionally, it provides a consistent and sustainable yield of desirable wood products at set intervals. In contrast, clearcutting involves harvesting stands when their average DBH reaches 10 cm (merchantable dimension), and their yields exceed 50 m^3 ha^{-1}. This practice is more likely to favor the production of pulpwood due to the smaller size of the harvested trees, which implies a faster decay of the derived products and thus of the HWPs stock.

Limitations and perspectives

When evaluating both the model structure and outcomes derived from the simulation of the use case, it is imperative to considering the ensuing limitations and underlying assumptions. Considering the model's sensitivity to inputs and the dependence of results on the approach used for calculating HWPs stock, emissions, and substitution, it is crucial to account for uncertainties associated with these elements (Cláudia Dias et al., 2009). The *TimberTracer* model tracks wood throughout its entire lifecycle, from harvesting to disposal sites, thereby encompassing major processes in between. This modeling principle is considered advanced due to its capacity to accurately trace carbon over the lifetime of wood products, providing precise results. However, implementing this principle at the national level poses challenges due to the large number and diversity of HWPs, as well as the substantial amount of the required local data (Jasinevičius et al., 2015). As the amount of data increases, the level of compounded uncertainty proportionally rises. A subsequent phase would involve scrutinizing the sensitivity of various model outputs to the input data.

From another perspective, the grading of logs utilizing the bucking allocation module, as exemplified by the implementation in *TimberTracer*, encounters obstacles due to various factors presumed to impact wood quality — such as strength, knottiness, appearance, stiffness, hardness, and durability. It is almost impossible, using exclusively models, to account for all these factors. As an illustration, the implemented module does not account for the presence of residual branches below the crown base and external defects. Furthermore, it is conceivable that variations in knot distribution exist across different management scenarios. Owing to the omission of this parameter in our model, we assert that the disparities in the proportions of HWP classes could be somewhat undervalued. This conjecture remains subject to empirical verification, yet the current capabilities of *TimberTracer* do not permit the necessary resolution for such details. Therefore, future refinements of the model are imperative to enable a more precise evaluation of these nuances.

Given that the maximum climate benefit varies over time for different forest managements (Guest et al., 2013; Röder et al., 2019), we raise questions about the relevance of the fixed planning horizon of 140 years in this study and its capacity to appropriately address the underlying research hypothesis. In this context, we may explore in the future the potential of alternative management strategies, such as clearcut and shelterwood, to be optimal for different planning horizons. Furthermore, we may question the assumption that simulations conducted over multiple rotations can effectively control for instantaneous response.

Moreover, it is crucial to note that carbon neutrality does not necessarily imply climate neutrality. When wood is burned or decays, emissions spend some time in the atmosphere before being sequestered, contributing to climate change in the meantime. In other words, the timing of emissions and sinks has an impact on the overall cumulative climatic impact (Cherubini et al., 2011; Levasseur et al., 2010, 2012). Among the factors affecting this timing are the speed of biomass regrowth (rotation period) and the storage of biomass products (e.g., building, furniture, and paper). Since these factors are closely linked to forest management practices, the assessment of these practices should not only consider the carbon balance but also examine the timing of carbon input and output flows.

Another worth-discussing question concerns the methodological scheme used in this study. Evaluating the potential of various forest management and wood-use options in mitigating climate change necessitates a systemic perspective that considers the diverse pools of the forest sector, including biomass, soil, and products (Grassi et al., 2021; Lemprière et al., 2013). The current study exclusively focuses on the wood products pool, which may not be directly relevant for guiding the decision-making of forest managers. This is particularly important considering that the forest ecosystem constitutes the major contribution of the forest sector in terms of climate change mitigation. To exemplify this recent assertion, Pilli et al. (2015) calculated the emissions and removals linked to HWPs for the historical period (1992-2012) and future scenarios until 2030 in the EU (excluding Malta and Cyprus). They utilized FAOSTAT data on forest product production (see https://www.fao.org/faostat/en/#data/FO). The findings of this research indicate that the average historical sink of HWPs from 2000 to 2012 accounts for 10% of the sink contained in the forest pools. This underscores the importance of including non-HWP carbon pools in decision-making processes as well.

Finally, the results of this use case suggest that shelterwood management is the optimal choice for optimizing the overall carbon balance of HWPs within the defined planning horizon. The rationale behind this preference lies partially in the late thinning operation characteristic of this management scenario, allowing for the carbon stock and substitution to counterbalance total emissions effectively. Notably, this silvicultural practice of partial cutting aligns with natural disturbance–based silviculture, as it mimics natural dynamics by anticipating the imminent mortality of a portion of mature trees (Bose et al., 2014). Moreover, considering the ongoing rapid changes in many ecosystems and their interaction with natural disturbances, which are expected to be significant and less predictable in the future (Seidl et al., 2017), multi-aged forest management systems offer a promising approach to enhance resistance and resilience, which is attributed to the presence of multiple age classes, providing more potential pathways for post-disturbance management and recovery (O'Hara & Ramage, 2013). Within this context, a suggestion arises to guide future studies in accounting for disturbance risks. Neglecting to incorporate such considerations could result in an overestimation of the climate mitigation efficacy associated with various forest management alternatives.

5. Code availability

TimberTracer is a Python based model for all operating systems (Windows, Linux, and Mac OS). It is free and open source (version 1.0.0 with GPL-3 license, requiring Python >= 3x). We openly share our model on GitHub for collaborative research, fostering a community-driven approach to innovation. A tutorial on Google Colab empowers users to harness TimberTracer's capabilities, customize analyses, and integrate it seamlessly into projects. Detailed instructions are available on GitHub, emphasizing TimberTracer's primary objective: providing valuable insights into carbon sequestration, substitution, and emissions progression over time. We encourage users to report any issues and/or desired extensions on our active issues page ().

Later when the GitHub repository will be made public

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Appendix A

Table 7: Clearcut management interventions and the products derived from the thinned wood.

Intervention	**Products**	**Stock (tC)**	**Decay rate (%)**
Thinning	Millsite	1.81	2.02 "(0.26 tC/yr)"
	Paper	2.16	
	Particle	6.88	
	Fire	1,97	
Harvesting	Millsite	5.09	1.47 "(0.93 tC/yr)"
	Paper	5.73	
	Particle	13.83	
	Fire	9.81	
	Furniture	24.89	
	Sawing	2.81	