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Climate-change mitigation strategies at the level of a forestry company in the light of age-class legacy effects

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Abstract

Key message We analyzed the future carbon balance of 47,000 ha of forests dominated primarily by Scots pine (*Pinus sylvestris* L.) and managed by the Szombathely Forestry Company in Hungary. Biomass, harvested wood products, and substitution effects were considered. Strong age-class legacy effects predetermine the biomass pool to turn into a carbon source with increased harvest. The highest harvesting intensity scenario proved most favorable for the overall carbon balance up to 2055.

Context Forests and wood utilization play a key role in climate change mitigation by enhancing carbon sinks, increasing offsite carbon stocks, and promoting resource efficiency through material and energy substitution.

Aims This case study examines the 47,000 ha forest managed by the Szombathely Forestry Company in western Hungary, dominated by climate-vulnerable coniferous species. Climate projections for the region indicate an inevitable shift to climate-resilient broadleaved species, requiring increased harvesting and regeneration. The study analyzed age-class structure, wood mobilization potential, and future carbon balances to assess the climate change mitigation impacts of intensified harvesting.

Methods We used the Forest Industry Carbon Model, a yield table-based tool specifically designed to integrate data from the Hungarian Forest Authority's database and to simulate forest stand-based carbon stock changes, wood product carbon balances, and substitution effects. We examined the future carbon balance under a business-as-usual scenario and scenarios with final harvest areas expanded by 10%, 20%, 30%, and 40%.

Results Our analysis revealed strong age-class legacy effects, with a large area approaching harvesting age, signaling a key management decision. Our simulations indicated that biomass would become a carbon source if harvesting intensity increased by more than 10%, while a 40% increase was the most favorable scenario for the overall forest industry carbon balance.

Conclusions We conclude that the company should base its management decisions on the broader carbon balance of the forest-based sector, while adhering to the Forest Authority's harvesting age prescriptions to ensure long-term sustainability.

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Keywords Carbon storage, CO_2, Forest industry, Harvested wood products, Product and energy substitution, Forest management

1 Introduction

Forests and wood use can contribute to climate change mitigation by enhancing carbon sinks through improved forest management, maintaining carbon stocks by preventing disturbances, increasing offsite carbon stocks, and promoting material and energy substitution through changes in industry production structures and enhanced resource efficiency (Verkerk et al. 2014, Hurmekoski et al. 2022, Verkerk et al. 2022). The effectiveness of climate change mitigation strategies in the forest-based sector should be evaluated across various contexts and timeframes, considering the combined climate change mitigation impacts of forests and wood utilization in the technosphere (Hurmekoski et al. 2022). Replacing more energy-intensive products, such as fossil fuels or energy-intensive materials, with forest biomass significantly contributes to emission reduction (IPCC 2022, Hall et al. 1994, Nabuurs et al. 2002).

At the European level, the forest carbon sink amounts to − 373.5 $MtCO_2eq$/year, with harvested wood products contributing an additional − 40.6 $MtCO_2eq$/year (EEA 2019). Holmgren (2020) reports that in 2018, the material and energy substitution impact of wood use in Europe was − 410 $MtCO_2eq$/year. Since forests in Europe grow relatively slowly, increasing wood harvesting intensity reduces the carbon stocks in forest biomass in the short to medium term compared to a baseline harvest regime (Hurmekoski et al. 2022).

A study on boreal and temperate forests (Luyssaert et al. 2008) demonstrated that forests aged 15 to 800 years can accumulate carbon. Nevertheless, forest carbon accumulation declines with increasing stand age and eventually stabilizes at an equilibrium level (Odum 1969; Luyssaert et al. 2008, Fiorese and Guarsio 2013). This means that young, growing forests act as carbon sinks by converting carbon into living biomass, while old-growth forests, even when undisturbed, mainly serve as carbon stocks since their biomass has reached its storage limit, and only a very slow accumulation continues in the soil (Fiorese and Guarsio 2013). However, under increased climate forcing, severe natural disturbances and carbon emissions are anticipated (Verkerk et al. 2022, Kurz et al. 2008). Recent studies have observed rising disturbance frequencies (Senf and Seidl 2021), a doubling of canopy mortality (Senf et al. 2018), and heightened vulnerability of Europe's forests to climate-driven disturbances, such as storms, fires, and insect outbreaks (Forzieri et al. 2021). In this context, extracting biomass and converting it into harvested wood products can establish a long-term carbon reservoir, promote the regeneration of overmature forests, and support climate adaptation and improved forest management (Borovics et al. 2023). When evaluating the climate change mitigation pathways of the forest industry, the critical issue is the time frame in which the reduced carbon stock in forests can be compensated for by enhanced forest growth resulting from improved management practices and by the benefits of wood utilization (Hurmekoski et al. 2022).

Korosuo et al. (2023) highlight that the EU forest sink is declining and increasingly diverging from the EU climate targets. About a decade ago, the forest sink began to stabilize as net annual increment and harvest levels reached equilibrium (Korosuo et al. 2023). More recently, a decline in the forest sink has been observed, driven by reduced afforestation, slower growth rates, increased natural mortality, and higher harvest levels (Korosuo et al. 2023). Finland and Sweden, which had shown a steady increase in net increment over decades, are now reporting declines in net increment rates, meanwhile, several Eastern European countries (e.g., Bulgaria, Estonia, Latvia, and Croatia) are promoting increased harvesting to address the skewed age-class structure of older forests that developed due to years of limited management (Korosuo et al. 2023). The current age-class structure of European forests is shaped by a variety of factors, in countries like Italy and Poland, a left-shifted age structure reflects forests still regenerating from past intensive exploitation (Böttcher et al. 2008). While in boreal regions, forests tend to be relatively old due to fire suppression (Axelsson et al. 2002). Slovenia, on the other hand, has the most right-shifted age-class structure (Böttcher et al. 2008). The forest age-class structure of a country or region strongly influences current carbon stocks and projected future carbon stock changes (Böttcher et al. 2008). According to Böttcher et al. (2008), under the same management regime, a region with a left-shifted age-class structure (predominantly young forests) will experience increasing forest carbon stocks, while a region with a right-shifted age-class structure (predominantly older forests) is likely to see decreasing carbon stocks. This age-class legacy effect can even overwhelm effects of post-1990 management (Canadell et al. 2007; Böttcher et al. 2008). It is therefore crucial to adopt a holistic perspective on the forest industry, encompassing on-site carbon storage, carbon storage in forest products, and substitution effects, to evaluate the sector's overall carbon balance. This approach allows for no-regret forest management decisions even in the face of decreasing carbon sinks or increasing emissions from the forest biomass pool predetermined by a right-shifted age-class structure.

Borovics et al. (2024) evaluate the national carbon balance of Hungarian forests under three representative silvicultural strategies: business-as-usual, reduced harvest with increased conservation, and increased harvest with regeneration. Their findings show that, at the national level, the increased harvest and regeneration strategy is the most favorable. It maintains forest biomass pools as a carbon sink while achieving Hungary's Land Use, Land-Use Change, and Forestry (LULUCF) targets under EU legislation. However, this raises the question of whether the same strategy is effective in regions where forest age-class structures are more skewed than at the national level. In such cases, even a slight increase in harvesting intensity could cause forest biomass pools to become a carbon source. To address this, we conduct a case study to downscale the modeling framework used by Borovics et al. (2024) to the level of a forestry company.

Hungary, despite its relatively small land area (9,302,260 ha), exhibits notable diversity in site conditions, forest compositions, and management practices. Within this context, the Szombathely Forestry Company is distinguished on the national level by its exceptionally high proportion of coniferous stands. These stands were predominantly established through artificial afforestation during the last century, influenced by forestry policy trends and the need to meet increasing industrial timber demand. Coniferous species in Hungary are particularly susceptible to the adverse impacts of climate change, as they are situated near their xeric tolerance limits. Despite this, within the 47,000 hectare area managed by the Szombathely Forestry Company, coniferous forests are characterized by continuously increasing rotation ages. Furthermore, the age-class distribution of these stands is heavily skewed toward older age-classes. Current climate projections suggest that transitioning from coniferous to climate-resilient broadleaved species will become necessary in the medium term in the area (Illés and Móricz 2022). The potential collapse of these aging coniferous stands represents a critical risk factor, necessitating a re-evaluation of current silvicultural strategies. Implementing strategies to increase harvest rates and gradually replacing the existing stands with more climate-resilient tree species may offer a viable pathway forward. A detailed assessment of the carbon balance implications of these harvesting strategies could provide essential insights into addressing this issue while enhancing understanding of their potential contributions to climate change mitigation.

The aim of this study was to assess the current and future carbon balance of forests managed by the Szombathely Forestry Company and to evaluate the climate change mitigation impacts of intensified harvesting, considering the carbon balance of living biomass, harvested wood products, and the effects of product and energy substitution. We also aimed to examine the current and projected age-class structure under different harvesting scenarios to identify age-class legacy effects and their management implications. For modeling, we used the Forest Industry Carbon Model (Borovics et al. 2024; Kottek et al. 2023; Kottek 2023; Király et al. 2023a,b) and data from the National Forestry Database.

2 Materials and methods

2.1 The characteristics of forests managed by the Szombathely Forestry Company

In Hungary, the forest area covers 2 million hectares, with 55% of these forests being state-owned and managed by 21 state forestry companies. The Szombathely Forestry Company manages 47,000 ha forest area in the western part of the country (Fig. 1). The company manages forest lands under diverse site conditions, from subalpine pine forests in the Őrség area to dry Turkey oak (*Quercus cerris* L.) forests in the Kemenesalja region and forests growing on the floodplain of the Dráva River.

In 2020, 12% of the company's forest area was managed using non-clearcutting silvicultural systems. This included 750 hectares of continuous cover forests, 850 hectares under non-production forest management, and 3700 hectares under transitional forest management. Coniferous species constitute 44% of the standing volume of the forestry company (Fig. 2), with nearly one-third of its forest area being pine forests. Two-thirds of the annual harvested timber volume also comprises coniferous species, primarily Scots pine (*Pinus sylvestris* L.). Considering the susceptibility of coniferous species, particularly Norway spruce (*Picea abies* L. H. Karst.) and Scots pine, to the adverse effects of climate change in Hungary (Mátyás et al. 2018; Ujvári-Jármay et al. 2016, Lakatos et al. 1999), it is increasingly important to develop adaptation strategies and implement tree species replacements in affected areas. However, these strategies would require increasing harvest levels.

2.2 Input data source: National Forestry Database

In this study, the National Forestry Database served as our primary data source. The National Forestry Database is the official database of the Forest Authority in Hungary, housing detailed information at the forest stand level, also referred to as forest sub-compartments. Each forest

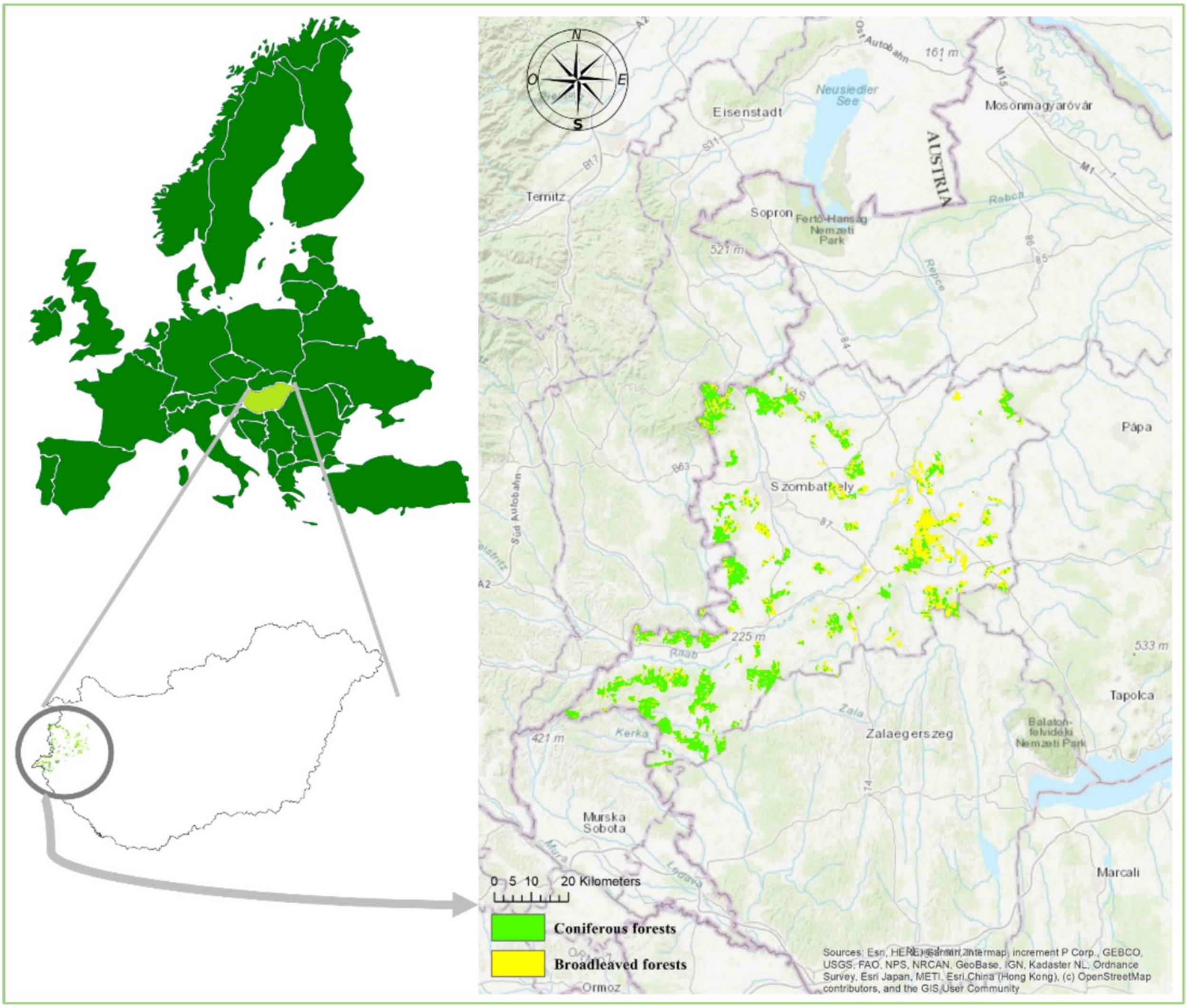

Fig. 1 Forests managed by the Szombathely Forestry Company, Hungary

sub-compartment is thoroughly documented with over 300 numerical attributes and digital maps (Tobisch and Kottek 2013). These attributes include ownership status, forest manager details, area size, protection status, site characteristics, soil sampling specifics, dendrometrical measurements, tree species composition, historical harvest and regeneration data, planned harvests, and prescriptions for regeneration and afforestation (Kottek et al. 2023). Dendrometrical parameters are measured every 10 years during forest management planning. Forest Management Plans are developed by the Forest Authority, specifying tasks and their recommended timelines for the subsequent decade (Kottek et al. 2023). Harvesting age prescriptions for each tree species row (subunit of the forest sub-compartment) are also defined in Forest Management Plans, tailored to the species and local environmental conditions, ensuring sustainable forest management (Borovics et al. 2023). In this study, we used the data of all forest sub-compartments managed by the Szombathely Forestry Company as inputs for modeling the future state of forests using the Forest Industry Carbon Model. Additionally, harvesting age prescriptions stored in the database were used to evaluate the maximum sustainable wood mobilization potential over the next 30 years.

2.3 Used methods, models, and the parameterization of the scenarios

For the modeling, we used the Forest Industry Carbon Model (Borovics et al. 2024) which is a substantially newly developed version of the Distributions Applied on Stands (DAS) forest model (Kottek et al. 2023; Kottek 2023) supplemented with harvested wood product and product and energy substitution submodules (Király

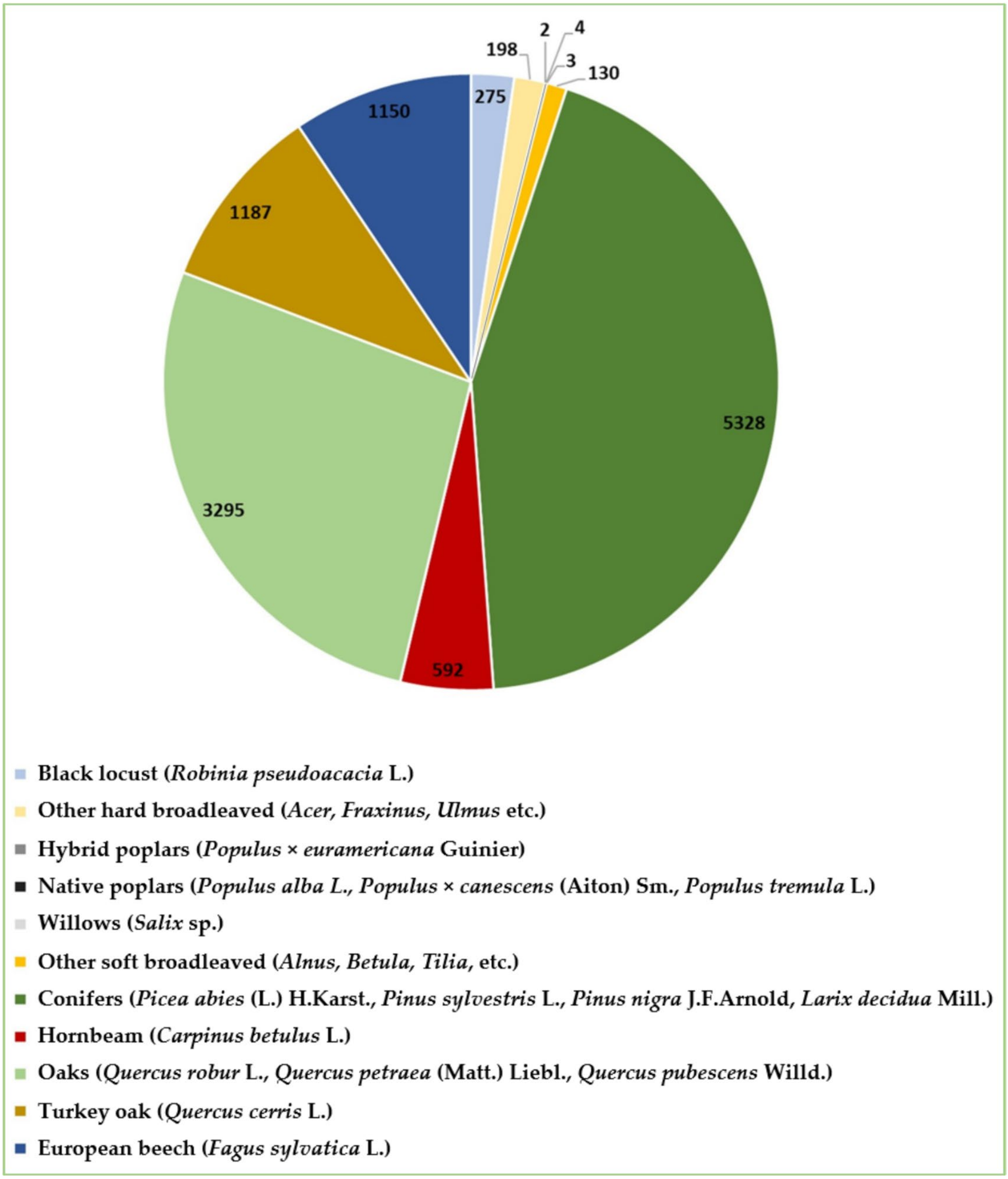

Fig. 2 Distribution of the standing volume among tree species in forests managed by the Szombathely Forestry Company in 2021. Data labels are given in 1000 m^3 units

et al. 2023a,b). Our modeling approach did not take into account the potential future impacts of climate change that could lead to increased forest damage.

The Forest Industry Carbon Model was developed as part of the ForestLab project (Borovics 2022). It is an empirical model, and it is specifically designed to align with the data structure of the National Forestry Database. This compatibility allows the model to be initialized by importing tree species row level dendrometrical data from the database. The Forest Industry Carbon Model employs 20 species-specific yield tables, identical to those used in the National Forestry Database. The model has been validated against historical data from 2006 to 2015, demonstrating a deviation of only 1.1% from the recorded national volume stock data.

The model regulates final harvests using harvesting age distributions, which assign a probability of final harvest to each age-class. These age-dependent harvesting probability ratios are derived from historical data from the National Forestry Database specific to the Szombathely Forestry Company. Consequently, the model does not predetermine the final harvest time for a forest stand. Instead, sub-compartments are randomly selected for harvest according to their age, area, and the age-dependent harvesting probability ratios, in alignment with the total area designated for final harvest as specified in the parameter sheet. Sub-compartments with special nature conservation requirements and continuous cover forests are excluded from final harvest. Thinning operations in the model are also based on historical data. Regenerations after final harvest are modeled using forest regeneration transition matrices, derived from National Forestry Database data from 2006 to 2020 and specific to the Szombathely Forestry Company.

The model's harvested wood product submodule is based on IPCC methodology, with carbon stock and product decay modeled using first-order decay equations as outlined in IPCC (2006, 2019) guidelines for greenhouse gas inventory preparation. The harvested wood product submodule has been validated using data from the Hungarian Greenhouse Gas Inventory for the period 1965–2020, under the assumption of instantaneous oxidation. In this scenario, the reported and modeled datasets exhibit 90% consistency. Product substitution effects are modeled following the methodology outlined in the European Forest Institute report (Leskinen et al. 2018). As Hungary lacks country-specific substitution factors, the average product substitution factor of 1.2 kg C/kg C from Leskinen et al. (2018) was used. For energy substitution, a factor of 0.67 kg C/kg C was selected, consistent with the values reported by Myllyviita et al. (2021), Knauf et al. (2015, 2016), Härtl et al. (2017), and Schweinle et al. (2018). Detailed descriptions of the harvested wood product submodules are provided by Király et al. (2024). Wood waste management data originates from the National Environmental Information System (2024) and the Hungarian Greenhouse Gas Inventory (NIR 2023). The modeling framework used is shown in Fig. 3.

We used the Forest Industry Carbon Model to forecast future carbon sequestration and emissions of both above- and below-ground forest biomass across five scenarios, encompassing business-as-usual scenario and scenarios with increased harvesting intensities.

To parameterize the business-as-usual scenario, we developed regeneration matrices and explicitly defined final harvesting probabilities for the Szombathely Forestry Company's area. Additionally, we evaluated the age-class distribution of the company's forests by tree species group. This process involved querying the National Forestry Database for the area of each 10-year age-class within each tree species group, which was then utilized to initialize the model.

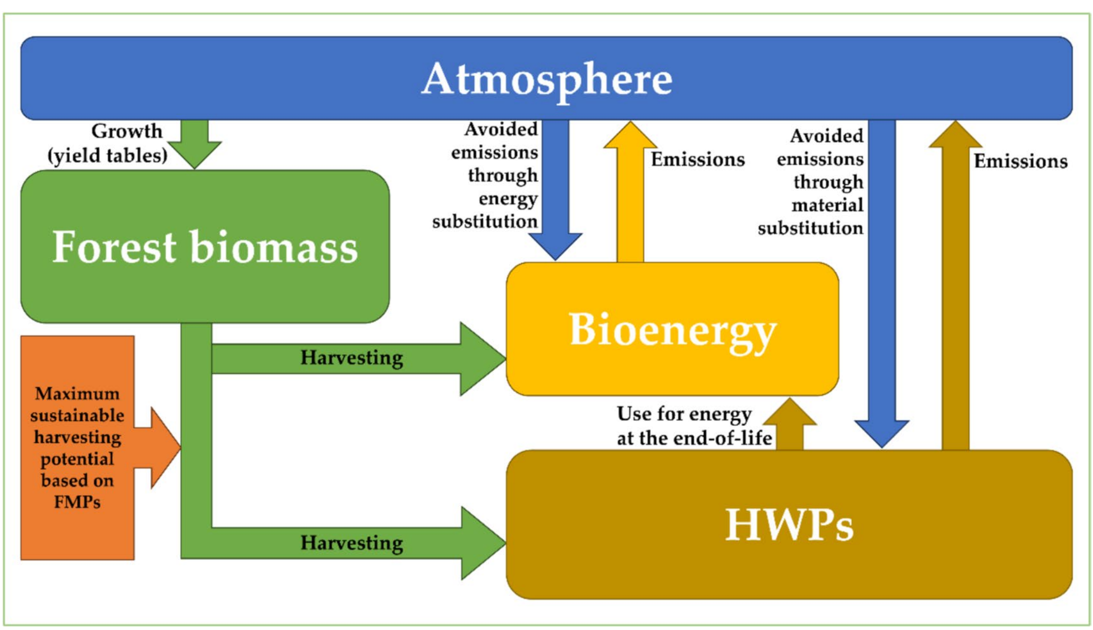

Fig. 3 Flowchart of the modeling framework used in this study, incorporating the forest, harvested wood product, and substitution modules of the Forest Industry Carbon Model

For the business-as-usual scenario, we projected the total area designated for final harvest using the historical average final harvest area from 2006 to 2021. We assumed a consistent 1% increase every 5 years in the area under final harvest, in line with the trend observed in the historical data. Additionally, we developed four scenarios with increased harvesting intensity, where we expanded the final harvest area by 10%, 20%, 30%, and 40%, respectively. These scenarios were labeled as the "+10% harvest," "+20% harvest," "+30% harvest," and "+40% harvest" scenarios. The projection spanned from 2024 to 2055.

We also conducted projections for the carbon balance of harvested wood products and assessed the impacts of material and energy substitution using the Forest Industry Carbon Model harvested wood product and substitution modules (Király et al. 2023a,b). For each harvesting scenario, we conducted two harvested wood product projections: one under business-as-usual wood industry conditions (OSAP 2023) and another under intensified wood industry conditions. In this context, intensification refers to increased industrial wood assortments, extended product lifetimes, and enhanced recycling practices (Tables 1 and 2). In this study, we assumed instantaneous oxidation of harvested wood products at the end-of-life stage, as data on landfilled harvested wood products originating from the area of the Szombathely Forestry Company were insufficient for modeling purposes.

Since the product and energy substitution factors used in the modeling are not country-specific, the associated uncertainty in the modeled substitution effects may be higher than that for biomass and harvested wood product carbon sequestration. To address this, we conducted a sensitivity analysis by varying the substitution factors from 20 to 200% and evaluating the relative climate change mitigation performance of the five scenarios.

To define the maximum wood mobilization potential, we used the approach described by Borovics et al. (2023). Initially, we identified and separated stands that were already considered overmature at the start of our modeling period (i.e., 2021). Stands were classified as overmature if their actual age exceeded the harvesting age specified in the Forest Management Plan. After the exclusion of overmature stands, we carried out a simple yield projection modeling for all the remaining forest area based on harvesting age prescriptions. We assumed that each stand is harvested in the same year when reaching its harvesting age, and that it is regenerated with the same species while preserving the original yield class. For detailed descriptions, see Borovics et al. (2023), who carried out the same modeling for the entire area of Hungary. Subsequently, we compared the maximum wood mobilization potential derived from this method with the harvest levels projected by the Forest Industry Carbon Model.

Table 1 Wood industry-related scenario parameterization. The half-lives of product types are expressed in years, while recycling rates are presented as a percentage of total waste generation within specific wood waste categories. Business-as-usual parameters are sourced from the IPCC (2006 , 2019) guidelines and the National Environmental Information System (2024). Parameters for wood industry intensification are determined through expert judgment. Substitution factors are derived from studies by Leskinen et al. (2018), Myllyviita et al. (2021), Knauf et al. (2015 , 2016), Härtl et al. (2017), and Schweinle et al. (2018). For the year 2024, business-as-usual parameters were used in both scenarios. In the intensification scenario, the parameters gradually changed between 2024 and 2050

	2024	2050
Business-as-usual		
Half-life sawnwood (years)	35	35
Half-life wood panels (years)	25	25
Half-life paper and paperboard (years)	2	2
Recycled sawnwood %	25	25
Recycled wood panel %	25	25
Recycled paper and paperboard %	70	70
Substitution factor for wood products (unitless ratio)	1.2	1.2
Substitution factor for bioenergy (unitless ratio)	0.67	0.67
Intensifiedwood industry		
Half-life sawnwood (years)	35	50
Half-life wood panels (years)	25	35
Half-life paper and paperboard (years)	2	2
Recycled sawnwood %	25	60
Recycled wood panel %	25	60
Recycled paper and paperboard %	70	85
Substitution factor for wood products (unitless ratio)	1.2	1.2
Substitution factor for bioenergy (unitless ratio)	0.67	0.67

3 Results

Our investigations revealed that forests of the Szombathely Forestry Company display a right shifted age-class structure (Fig. 4). This pattern is notably pronounced in coniferous species where the age-class of 61–70 years accounts for the largest area, exceeding 3500 hectares. The actual harvest age of coniferous species ranges from 70 to 110 years, depending on yield class. This indicates that the overrepresented age-class approaches its harvesting age in the near future.

The growing stock of stands classified as overmature exceeded 600,000 m^3 in 2021 (Fig. 5). Stands are deemed overmature when their actual age surpasses the harvesting age set by the Forest Authority, allowing them to be harvested in accordance with legal regulations. However,

Table 2 Business-as-usual wood assortments based on historic wood assortment composition data (2017–2021 average, OSAP 2023) and increased industrial wood assortments determined by expert judgment considering an intensified wood industry

	Oaks	Turkey oak (*Quercus cerris* L.)	European beech (*Fagus sylvatica* L.)	Hornbeam (*Carpinus betulus* L.)	Black locust (*Robinia pseudoacacia* L.)	Other hard broadleaved	Hybrid poplars	Indigenous poplars	Willows	Other soft broadleaved	Conifers
Business-as-usual											
Sawlog	25%	2%	23%	2%	10%	10%	55%	38%	11%	20%	26%
Pulpwood for boards	6%	4%	16%	10%	10%	8%	31%	23%	54%	14%	39%
Pulpwood for paper	0%	1%	1%	0%	0%	0%	5%	20%	2%	1%	21%
Firewood	69%	93%	59%	88%	80%	82%	8%	18%	33%	65%	14%
Intensified wood industry											
Sawlog	50%	40%	40%	20%	40%	30%	55%	50%	20%	40%	40%
Pulpwood for boards	20%	20%	30%	30%	10%	30%	35%	30%	60%	30%	40%
Pulpwood for paper	5%	5%	5%	5%	0%	5%	5%	5%	5%	5%	10%
Firewood	25%	35%	25%	45%	50%	35%	5%	15%	15%	25%	10%

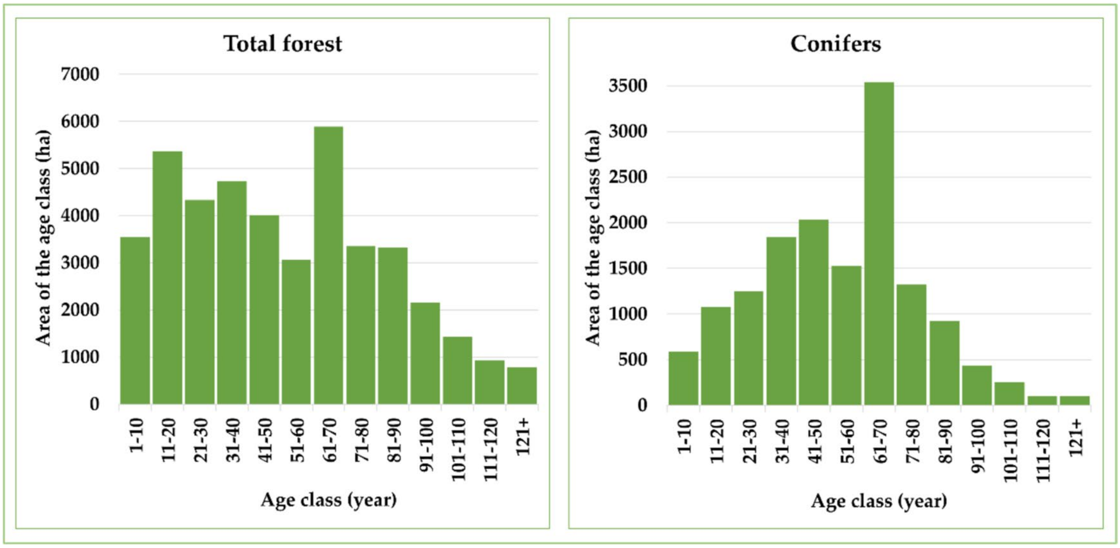

Fig. 4 Left: age-class distribution of forests managed by the Szombathely Forestry Company. Right: age-class distribution of coniferous forests managed by the Szombathely Forestry Company

it is important to note that stands with high nature conservation value, such as forest reserves, along with those managed under continuous cover forestry or non-production forest management, are not categorized as overmature. This is because the National Forestry Database does not assign a harvesting age to these stands. This means that the overmature standing volume could be harvested immediately without compromising the sustainability criteria laid down in Forest Management Plans.

Based on the harvesting age prescriptions of the Forest Management Plans, the total wood mobilization potential in the 2025–2055 period is 11.8 million m^3 (excluding already overmature stands). This represents the total timber available for harvest under the assumption that each stand is harvested upon reaching its harvesting age (Fig. 6, black dotted line). Including overmature stands increased the total available timber to 12.4 million m^3 (equivalent to an average of 400,000 m^3 annually) for the same period.

Figure 6 also shows the harvested volume and the net annual increment (NAI) across the five modeled scenarios. In the business-as-usual scenario, the harvested amount is consistently lower than the NAI throughout all projected years. In scenarios with increased harvesting intensities, the harvest level exceeds the NAI in certain projected years. Over the entire projection period, the ratio of actual harvest compared to NAI reaches 100% in the "+20% harvest" scenario (Fig. 7). Meanwhile, the ratio of the actual harvest compared to the maximum harvesting potential defined by Forest Management Plans is 96% in the "+30% harvest" scenario and 101% in the "+40% harvest" scenario (Fig. 7).

Under the business-as-usual scenario, the total standing volume of the company's forests increases from 12.4 million m^3 to 12.6 million m^3 by 2055. In contrast, in the "+40% harvest" scenario, the standing volume decreases to 10.7 million m^3 by 2055. The average age of the stands increases from 52 to 58 years in the business-as-usual scenario, while in the "+40% harvest" scenario the average age drops to 47.5 years (Fig. 8).

Our simulations indicate that, under the business-as-usual scenario, the forest biomass pool maintains moderate carbon sequestration, averaging −17 kt CO_2/year (Fig. 9, Table 3). In the "+10% harvest" scenario, the carbon sequestration in the forest biomass is almost zero, with an average carbon sink of −3 kt CO_2/year over the projection period. Increasing harvesting beyond 10% results in the forests becoming a carbon source. In the most intensified harvesting scenario ("+40% harvest"), the simulations result in an average emission of 41 kt CO_2/year for the projection period.

Regarding the carbon balance of the entire forest-based sector, our simulations indicate that increased harvest levels offer more favorable climate change mitigation effects as compared to the business-as-usual scenario (Fig. 9, Table 3). The annual average carbon sequestration in harvested wood products is −5 kt CO_2/year in the business-as-usual scenario, while it reaches −17 kt CO_2/year in the "+40% harvest" scenario, equivalent to the carbon sequestration from forest biomass under the business-as-usual scenario. Under intensified wood processing industry conditions, harvested wood product carbon sink can potentially increase further, up to a maximum of −90 kt CO_2/year. The largest portion of negative emissions comes from avoided emissions through product

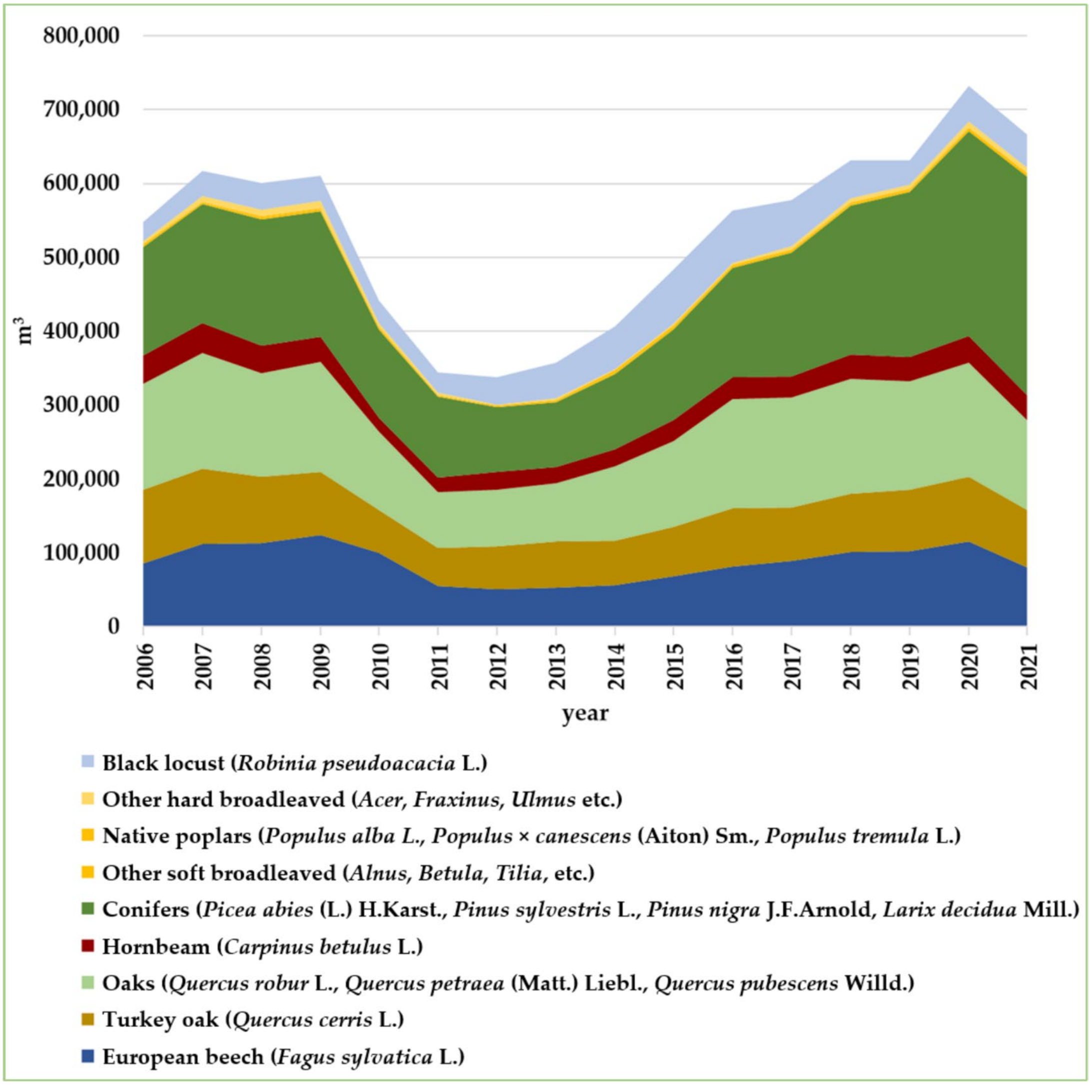

Fig. 5 Evolution of the growing stock of overmature forests within the Szombathely Forestry Company area from 2006 to 2021

and energy substitution, which are three to five times higher (in the business-as-usual and "+40% harvest" scenarios, respectively) than forest biomass plus harvested wood product net emissions.

Avoided emissions from product and energy substitution effects account for the largest share of the simulated negative emissions, meaning the uncertainties surrounding substitution factors significantly impact the modeling results. To assess how changes in substitution factors influence the outcomes, we conducted a sensitivity analysis (Fig. 10). The simulations using alternative substitution factors show that reducing the substitution factor by half or more alters the relative performance of the scenarios, making the business-as-usual scenario the most favorable, while the "+40% harvest" scenario becomes the least favorable.

4 Discussion

According to our analysis, the growing stock of stands classified as overmature exceeded 600,000 m^3 in 2021 in the area managed by the Szombathely Forestry Company. Stands are considered overmature when their age exceeds the cutting age set by the Forest Authority, making them eligible for harvest under legal regulations. Stands with high conservation value or managed under continuous cover or non-production forest management are excluded from the assessment. Thus, overmature standing volume can be harvested immediately without violating the sustainability criteria of Forest Management

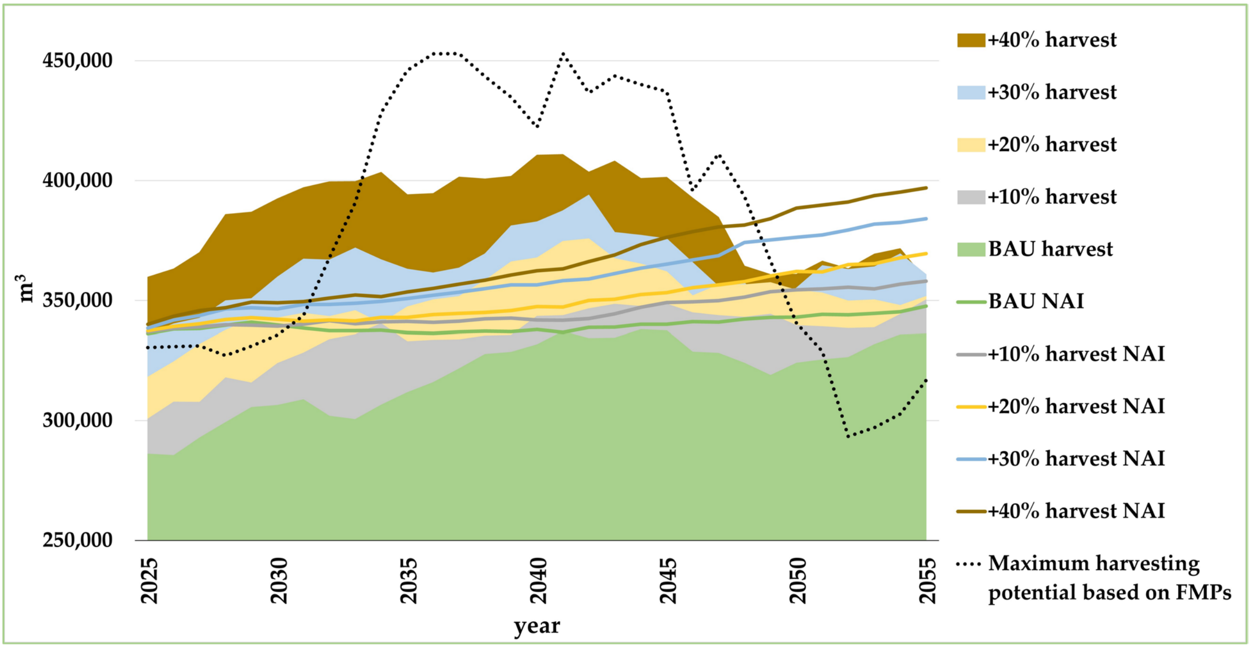

Fig. 6 Projected harvest and net annual increment (NAI) under the five scenarios modeled by the Forest Industry Carbon Model, alongside the maximum harvesting potential defined by Forest Management Plans

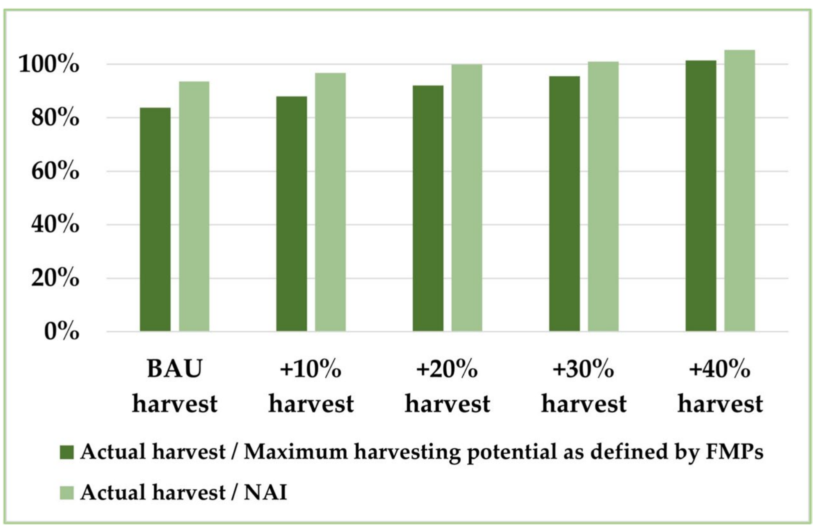

Fig. 7 Ratio of the projected harvest relative to the maximum harvesting potential defined by Forest Management Plans and relative to the scenario-specific NAI projected by the Forest Industry Carbon Model

Plans. Lerink et al. (2023) emphasize that aging forests and significantly high forest stock in many EU countries will inevitably increase the risk of natural disturbances in densely stocked forests. They estimate an additional harvest potential of 90 million m^3 annually across Europe. This highlights the importance of strategically managing overmature stands to balance sustainable timber production with minimizing the risks associated with aging forests and densely stocked areas prone to natural disturbances.

Our findings on age-class structure indicate that a crucial management decision is to be made by the Szombathely Forestry Company in the forthcoming years as an age-class covering a large area is about to reach its harvesting age. This is especially important considering the fact that climatic conditions in Hungary are no longer

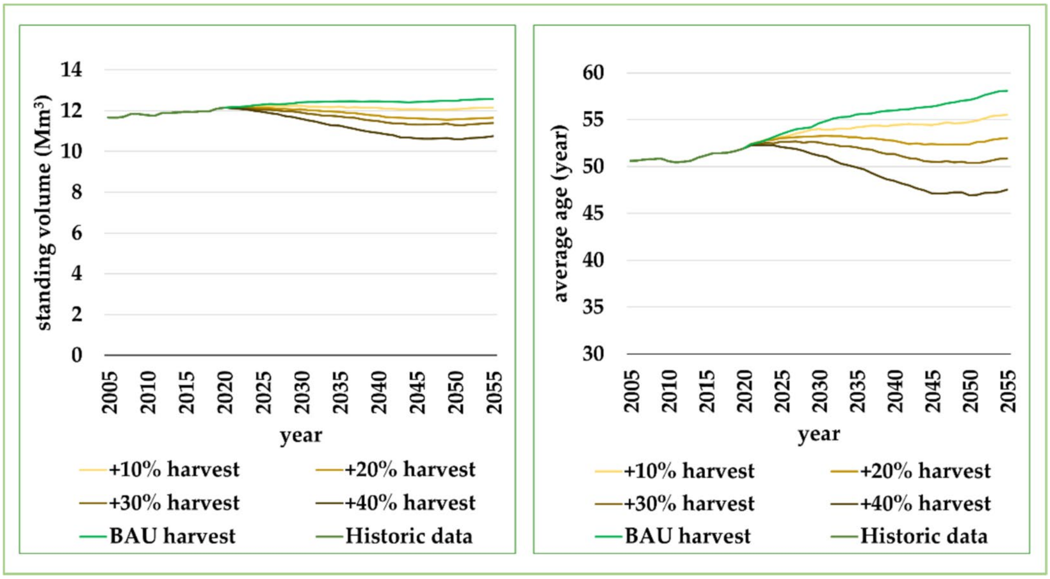

Fig. 8 Left: standing volume projection across the five scenarios. Right: projection of average age across the five scenarios

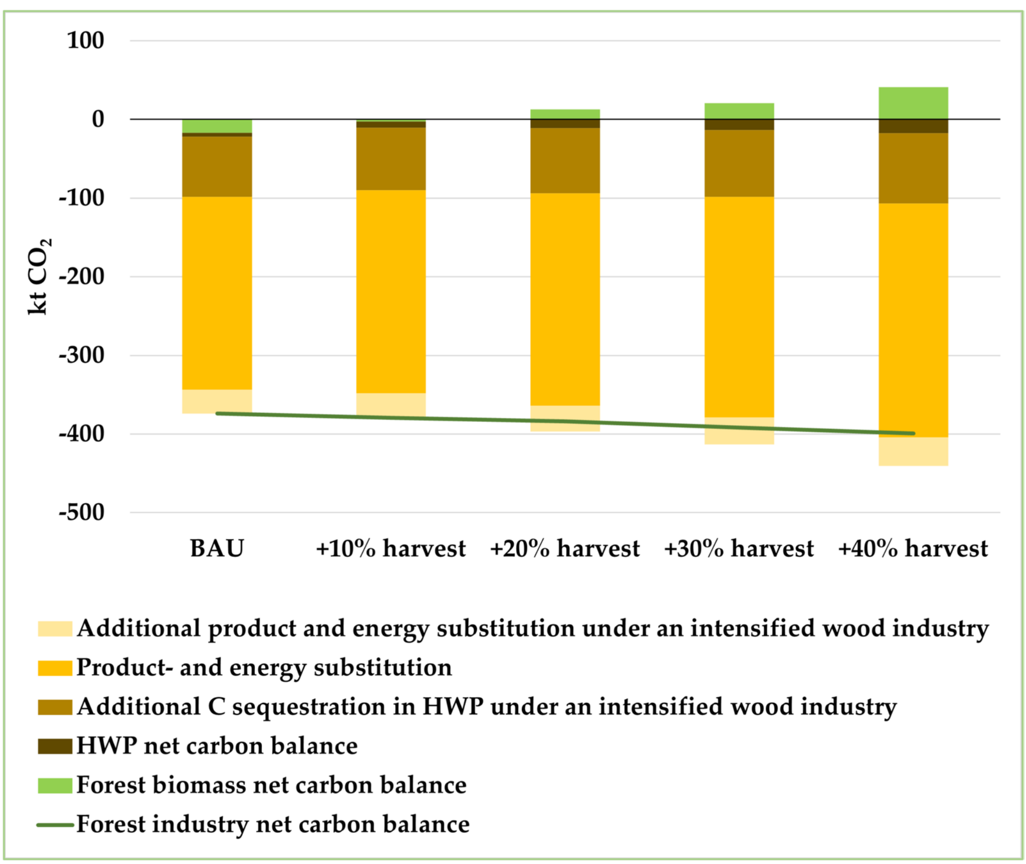

Fig. 9 Average annual carbon balance of the forest biomass pool and the harvested wood products pool, and substitution effects across the five scenarios

Table 3 Simulated annual carbon balance of the forest biomass pool and the harvested wood products pool as well as avoided emissions through product and energy substitution under the five examined scenarios

	Business-as-usual	+10% harvest	+20% harvest	+30% harvest	+40% harvest
Forest biomass net carbon balance (kt CO_2/year)	−17	−3	13	21	41
Harvested wood products net carbon balance (kt CO_2/year)	−5	−8	−11	−13	−17
Additional carbon sequestration in harvested wood products under intensified wood industry (kt CO_2/year)	−76	−80	−83	−85	−90
Product and energy substitution (kt CO_2/year)	−246	−258	−270	−280	−298
Additional product and energy substitution under intensified wood industry (kt CO_2/year)	−30	−31	−33	−34	−36
Forest industry net carbon balance (kt CO_2 /year)	−374	−379	−384	−392	−399

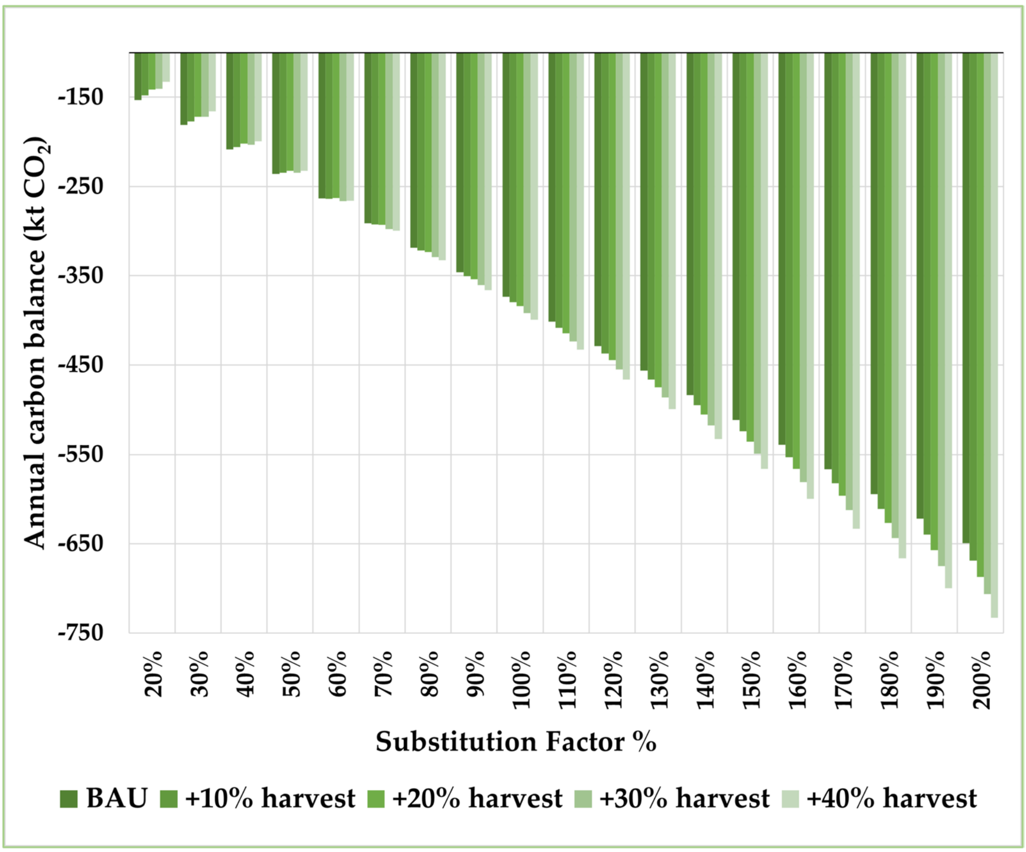

Fig. 10 Sensitivity analysis results showing the impact of varying substitution factors on the relative performance of the analyzed scenarios. Substitution factors were adjusted from 20 to 200% of their original values

optimal for Norway spruce, and in the future Scots pine may also face increasing damage (Mátyás et al. 2018; Ujvári-Jármay et al. 2016, Lakatos et al. 1999). The harvesting and regeneration (or replacement) of the stands in the overrepresented age-class will be impossible without increasing the current business-as-usual harvest levels. If the harvesting intensity remains unchanged, the overrepresented age-class will persist, and average stand age will continuously increase according to the model simulations.

Our simulations evaluated three criteria for determining forest management sustainability: Forest Management Plans, the ratio of harvest to net annual increment (NAI), and carbon balance. Among these, Forest Management Plans are the most normative and the only one applicable at the forest stand level. Forest Management Plans in Hungary are prepared by the Forest Authority in consultation with the Nature Protection Authority and ensure the sustainability of forest stand management in accordance with the Hungarian Forest Act. Forest Management Plans specify the harvesting age for each stand, indicating that stands can be harvested above this age without compromising sustainability (Borovics et al. 2023). At the forest estate level, sustainability may be defined by stipulating that harvest levels should not exceed NAI, or by maintaining forests as carbon sinks or at least carbon–neutral each year. Achieving a forestry company-level positive carbon balance involves ensuring that the combined level of harvest and mortality always remains below NAI.

However, when decisions are made at the forest stand level, it becomes evident that achieving carbon neutrality every single year is not feasible. For instance, in the year of final harvest, the stand becomes a carbon source, and carbon neutrality is achieved over the entire rotation cycle. From a broader perspective, considering the forest industry as a whole, prioritizing carbon neutrality in the forest biomass pool may not always represent the most effective strategy for climate change mitigation. Under some circumstances, maintaining harvest levels below the NAI is no suitable solution. According to Böttcher et al. (2008), a landscape with a right-shifted age-class distribution (fewer stands in young age-classes) results from temporarily reduced disturbances (including harvest plus natural disturbances), which is transient and unsustainable. Canadell et al. (2007) highlight that past forest management practices leave a legacy that can persist for decades, influencing future regional carbon dynamics in the Northern Hemisphere. Böttcher et al. (2008) also note that while management changes affect the magnitude and timing of emissions or removals, they do not alter the fundamental direction of carbon stock changes driven by the legacy effect of age-class structure.

In the specific case of forests of the Szombathely Forestry Company, the aforementioned age-class legacy effect is quite determining. This means that in order to be able to regenerate or replace overmature pine and Norway spruce forests in time it is to be accepted that the forest biomass pool turns into a carbon source for some decades. The regeneration period of a stand is crucial in climate change adaptation as it gives space to adaptation via natural genetic diversity as well as via using preadapted propagation material and tree species replacements (Borovics et al. 2023; Borovics and Mátyás 2013). Postponing harvesting and regeneration slows down the adaptation process and increases the risk of carbon emissions caused by natural disturbances. As shown in Fig. 6, increasing harvest levels also leads to higher NAIs, which contribute to increased atmospheric CO_2 removal.

According to the Helsinki Resolution H1, sustainable forest management is "the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems" (MCPFE 1993). This means that the maintenance of forest productivity, vitality, and regeneration capacity are key components of management sustainability. These aspects however could be compromised when strictly adhering to the positive carbon balance of the biomass pool under a right shifted age-class structure. Prins et al. (2023) emphasize that the scope of the concept of sustainable forest management needs to be expanded to include the aspects of climate change mitigation, energy supply, rural development, and related policy areas to which forest management contributes, and this necessitates a new understanding of the system boundaries of sustainable forest management. Hurmekoski et al. (2022) point out that evaluating the overall climate impact of the forest-based sector requires simultaneous consideration of carbon stock changes in standing trees, soil, and harvested wood products, as well as the avoided fossil emissions from the substitution impacts of wood use. This would mean that the system boundaries of sustainable forest management are much broader than those of the forest itself and include the whole forest industry (Borovics et al. 2023) as well as long-term stored timber stocks of the technosphere (Hurmekoski et al. 2022).

As in our study no land use change was simulated, soil carbon pool was considered to be in equilibrium in accordance with the assumption used in the Hungarian Greenhouse Gas Inventory (NIR 2023). According to our simulations in the case of the Szombathely Forestry Company, the carbon sequestration of harvested wood products and the product substitution effects are much higher than the biomass net emissions. This suggests that the "+40% harvest" scenario offers the most favorable overall mitigation effect at the forest industry level among the scenarios analyzed. Scenarios with further intensified harvest levels were not considered, as a +40% increase was identified as the maximum realistically achievable level. As illustrated in Fig. 7, a +40% increase leads to a harvest level exceeding (101%) the maximum harvesting potential defined by the Forest Authority in Forest Management Plans. In Hungary, these plans are legally binding and stands can only be harvested upon reaching their designated harvesting age. Exceeding the maximum harvesting potential would violate both sustainability requirements and the Forest Act. Therefore, testing scenarios with harvest increases beyond + 40% would be unreasonable, as this scenario already fully utilizes the wood mobilization potential that is available without compromising legal or sustainability constraints.

Our findings are in accordance with those of Fiorese and Guariso (2013) who conducted a regional modeling of forest-based sector carbon balance in Italy and concluded that the scenario with maximized annual harvest was optimal in the case of three out of four forest macrocategories. According to their results, the net carbon emissions of forests were one order of magnitude lower than the emissions avoided through energy substitution (Fiorese and Guariso 2013). Their findings underscore that in the studied region forests' role as bioenergy suppliers outweighs their function as carbon sinks, and without active harvesting, if forests are left to evolve naturally under complete protection policies, their impact on the regional carbon budget is negligible (Fiorese and Guariso 2013). Pukkala (2014) confirmed that the carbon balance of forestry is usually positive if the harvested volume is close to NAI, although without substitution effects the balance would be near zero or even negative, depending on whether the soil and harvested wood product carbon pools are increasing or decreasing. This emphasizes the critical role of substitution effects in shaping the carbon balance of the forest industry.

However, quantifying these substitution benefits is complex and involves many uncertainties. A substitution factor typically represents the amount of greenhouse gas emissions avoided when a wood-based product replaces another product serving the same function (Leskinen et al. 2018). These effects vary significantly depending on factors such as the type of wood product, the non-wood product it substitutes, differences in operating lifespans, end-of-life management, and the use of harvest and processing residues (Leskinen et al. 2018). As a result, substitution factors reported in the international literature show considerable variability. Leskinen et al. (2018) reviewed 51 studies suggesting substitution factors ranging between − 0.7 and 5.1 kg C/kg C. However, over 90% of the reviewed substitution factors that included two or more life cycle stages had a value greater than zero. In our study, we applied the average product substitution factor of 1.2 kg C/kg C suggested by Leskinen et al. (2018) and an energy substitution factor of 0.67 kg C/kg C, as recommended by Myllyviita et al. (2021), Knauf et al. (2015, 2016), Härtl et al. (2017), and Schweinle et al. (2018). A notable limitation of our modeling approach is the lack of country-specific substitution factors for Hungary. To explore alternative outcomes, we conducted a sensitivity analysis by varying the substitution factors from 20 to 200% of the originally used values. The simulations revealed that reducing the substitution factor to 50% or lower significantly alters the relative performance of the scenarios. Specifically, the business-as-usual scenario becomes the most favorable for climate change mitigation, while the "+ 40% harvest" scenario emerges as the least favorable.

Verkerk et al. (2022) emphasize in their review that the additional climate change mitigation potential of wood use in the EU-27, Norway, Switzerland, and the UK largely depends on changes in wood utilization. Their analysis estimates an average mitigation potential of 13 $MtCO_2eq$/year, though individual studies and scenarios report a wide range of values, from − 70 to 391 $MtCO_2eq$/year. This significant variability is primarily driven by differing assumptions across the analyzed studies, particularly between two EU-level studies by Brunet-Navarro et al. (2021) and Jonsson et al. (2021), which adopt contrasting assumptions. These differences underscore the critical role that substitution factors play in determining the outcomes of such simulations and highlight the need to derive country-specific substitution factors representative of Hungary to minimize uncertainties in modeling. Nonetheless, it is essential to note that the substitution factors we selected are conservative and based on EU-wide analyses of multiple studies. For instance, Köhl et al. (2020) report a factor of 1.9 kg C/kg C for lignite substitution. Given that Hungary's second-largest thermal power plant relies on lignite, the energy substitution factor used in our study is likely underestimated.

In our study, we also examined the potential impacts of increased industrial wood processing and an upscaled wood industry. Our simulations suggest that the wood industry has considerable potential for climate change mitigation, with a large part of this potential tied to product and energy substitution, which should be investigated and described in greater detail. Increasing industrial wood assortments and processing of drought tolerant species which are currently less commonly used for industrial purposes can further contribute to climate change mitigation (Borovics et al. 2023; Király et al. 2023a,b). Thus, it is recommended to assess the possibilities and elaborate procedures to use a wider range of tree species to produce long-lived wood products.

5 Conclusions

In this study, we assessed the age-class structure, maximum wood mobilization potential, and current and future carbon balance of forests managed by the Szombathely Forestry Company to identify the most suitable harvesting intensity considering the carbon balance of the living biomass as well as harvested wood products and product and energy substitution effects. Our results on age-class structure indicated that an important management decision is to be made by the company in the forthcoming years as an age-class with an extremely high area is about to reach its harvesting age. Carbon balance modeling highlighted the effects of this age-class legacy, as we found that the forest biomass pool would turn into a source of carbon emissions if the harvesting intensity increased by more than 10%. On the other hand, our simulations show that the scenario with a harvesting intensity increased by 40% is the most favorable in terms of carbon balance considering the whole forest-based sector. We conclude that management decisions for the Szombathely Forestry Company are to be made considering Forest Management Plan prescriptions and the overall carbon balance of the forest-based sector. Efforts should be made to increase industrial wood assortments and use timber for long-lived wood products in accordance with the goals of the circular bioeconomy. Overmature forests need to be harvested and regenerated with specific consideration given to climate change adaptation.

Authors' contributions
Conceptualization: A.B.; methodology: A.B., P.K., and É.K.; validation: A.B.; formal analysis: P.K and É.K.; investigation: P.K. and A.B.; data curation: P.K.; writing—original draft preparation: A.B. and É.K.; writing—review and editing: A.B. and P.K.; visualization: É.K.; supervision: A.B.; project administration: A.B.; funding acquisition: A.B. All authors have read and agreed to the published version of the manuscript.

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Data availability
The data and codes cannot be made freely available due to legal constraints; however, they will be made available upon reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare no conflict of interest.

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