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Article

Projection of the Carbon Balance of the Hungarian Forestry and Wood Industry Sector Using the Forest Industry Carbon Model

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Abstract: As forest-based climate change mitigation has become a crucial element of international climate policy it is of increasing importance to understand the processes leading to the carbon offsetting capacity of the sector. In our study, we assessed the climate benefits of contrasting forest management strategies: decreasing harvest and enlarging the forest carbon stock, or increasing harvest to increase carbon uptake, wood product carbon pools, and substitution effects. We developed the Forest Industry Carbon Model (FICM) which is a new carbon accounting tool covering forest biomass, dead organic matter, soil, and harvested wood product pools, as well as avoided emissions through product and energy substitution. We modeled the carbon balance of the Hungarian forest industry under three different scenarios. In the business as usual (BAU) scenario, we assumed no changes in the current harvest and afforestation levels. In the extensification scenario, we assumed that the harvest and afforestation levels drop to half, while in the intensification scenario, we assumed an increase in afforestation, improved industrial wood assortments, and a gradual increase in logging, reaching the highest level as per sustainability criteria by 2050. Our results show that the intensification scenario is characterized by the largest net removals and the maximized product and energy substitution effects. By 2050, the net forest industry carbon balance reaches −8447 kt CO_2 eq under the BAU scenario, while −7011 kt CO_2 eq is reached under the extensification scenario and −22,135 kt CO_2 eq is reached under the intensification scenario. Although substitution effects are not accounted for under the land-based (LULUCF) sector in the greenhouse gas inventory, the emission reductions in the industry and energy sectors have beneficial effects on the national carbon balance. Modeling results show that the 2030 LULUCF greenhouse gas removal target set by EU legislation for Hungary is reached under the intensification scenario. To achieve this outcome, widespread innovation is needed in the wood sector. The modeling results show that nonutilization of forests can only be a very short-term solution; however, its favorable effects will be reversed by 2050 resulting in additional emissions compared to the BAU scenario.

Keywords: carbon offset; forest industry; product and energy substitution; CO_2; HWP; forest management scenario

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1. Introduction

Forest-based climate change mitigation has become a crucial element of the Paris Agreement and EU climate law [1–3]. Reaching the net-zero target will be impossible unless unavoidable emissions are offset by nature-based and technical solutions [4–6]. While forests capture carbon dioxide (CO_2) from the atmosphere and provide onsite carbon storage, long-lived harvested wood products (HWPs) are seen as an offsite carbon storage pool and as an important means of substituting carbon-intensive products like concrete or steel [7,8]. The substitution of fossil energy with bioenergy is also an important step towards the EU-targeted circular bioeconomy [8,9]. This carbon capture, storage, and substitution framework creates the total carbon offset capacity of the forest-based sector.

Due to the important role of carbon stored as built-in timber as part of the technosphere and that of bioenergy, the forest-based sector is often referred to as the forest industry [10,11]. In this paper, we use the notion of "forest industry" to stress the joint nature of the forestry and wood industry. However, with this expression, we do not aim at industrializing the natural aspects of forests, as we acknowledge that a forest is far more than a carbon sink, pump, or stock; it is indeed the most complex terrestrial ecosystem with many functions and benefits far beyond the sole aspect of climate change mitigation.

In order to integrate the forest carbon sink in the broader ecological and economic context and promote business opportunities for enhancing forest industry-driven climate mitigation, a new set of policy instruments and legislative acts have been created [8]. The proposals for a nature restoration law [12], the new EU forest strategy for 2030 [13], and the upcoming proposals for a new soil health law [14,15] and a new framework for forest monitoring and strategic plans [16] together with the proposals for sustainable carbon cycles [17], carbon removal certification [18], and LULUCF regulation [19], cover the entire forest industry climate-mitigation framework.

However, despite the increasing political focus on forest-based mitigation, in recent years, the EU forest sink has developed counter to the climate objectives and is now showing a clear decreasing trend [8]. As Korosuo et al. [8] state, this trend is mainly driven by the ongoing aging process of European forests. An analysis carried out using the Carbon Budget Model to project the future forest sink development in the EU, shows that the decreasing trend of forest carbon sink will remain, progressively getting off track from the path towards the EU target for 2030 [8]. In this context, forest management can take two approaches—either decreasing harvest to enlarge the forest carbon stock or increasing harvest to increase carbon uptake and create HWPs for increasing long-term, offsite carbon storage and substitution effects [20].

The above-mentioned aging process is also characteristic of Hungarian forests. Kottek et al. [21] show increasing cutting ages in the case of most tree species. While the yearly felling volume in Hungary has remained within the range of 7 to 8 million m^3 for decades, Borovics et al. [9] found that more than 45 million m^3 standing volume in Hungarian forests is overmature. Stands are defined as overmature if their actual age is over the cutting age prescribed by the Forest Authority. If a stand is overmature, it can be harvested in accordance with legal requirements. However, stands with high nature conservation value, like forest reserves, as well as stands under continuous cover forest management and nonproduction forest management, are never regarded as overmature, as no cutting age prescription is recorded for those stands in the National Forestry Database. Borovics et al. [9] forecast an increasing wood mobilization potential for the 2024–2100 period due to the increasing number of stands reaching their cutting age [9]. Király et al. [22] show that increased harvesting and industrial wood utilization can significantly upscale HWP carbon sink and substitution effects in Hungary.

The aim of our study is to analyze the overall climate benefits of three contrasting forest industry strategies in Hungary. These strategies are (1) extensive conservation to enlarge onsite forest carbon stocks by nonutilization; (2) intensive forest management with increased harvest together with intensive afforestation and the establishment of new woody plantations, supplemented by the intensification of the Hungarian wood processing industry with new innovations; and (3) business as usual (BaU). We assess the net carbon benefits associated with the three strategies using the Forest Industry Carbon Model [21,23,24] and data from the National Forestry Database (NFD), the National Environmental Information System [25], and the Central Statistical Office [26].

2. Materials and Methods

2.1. Forest Data

In this study, we used the data of the NFD, which is the official database of the Forest Authority in Hungary and contains detailed dendrometrical data on each forest stand in the country. A thorough description of the database can be found in Tobisch and Kottek [27], Borovics et al. [9], and Kottek et al. [21].

The modeling covers the entire forest area of Hungary. The forest area of Hungary amounts to 2,072,186 hectares, representing 21% of the country's total area. Over 40% of the country's forests are characterized by a plantation-like composition of nonnative tree species. The forest land of the country consists predominantly of deciduous tree species, comprising 90.5%, and generally displays mixed-forest communities. State-owned Hungarian forests amount to 55%, with management responsibilities distributed among 21 state forestry companies. Private forests in Hungary are owned by 450,000 private persons, and administered by almost 32,000 private forest managers, typically dealing with small, disconnected areas [9].

2.2. Modeling Framework

The modeling of the carbon sequestration, storage, and emissions of the forest and HWP system under the three scenarios was performed using the Forest Industry Carbon Model (FICM, Figure 1), which is a substantially newly developed version of the spatially explicit DAS forest model [21,23] supplemented with soil and dead organic matter (DOM) submodules, and HWP plus substitution submodules [22,24]. The FICM model is a forest stand-based model suitable for projecting standing volume, increment, harvest, and carbon balance on the stand, regional, or country levels. Utilizing NFD data, including geospatial information, the model operates at the forest subcompartment scale and projects dendrometric parameters using country-specific yield tables. HWP carbon stock and decay projection is based on IPCC methodology [28–30], while wood waste management projections are drawn from the National Environmental Information System [25] and the Hungarian Greenhouse Gas Inventory [31]. Product and energy substitution effects are modeled in accordance with Leskinen et al. [32] as described by Király et al. [22]. The FICM model underwent validation against historical NFD data covering the period 2006–2015 and exhibiting a deviation of 1.1% from the historical volume stock data at the country level [23].

We developed three scenarios. The extensification (EXT) scenario is characterized by decreased harvest, minimal intervention management, and increased nature conservation ambitions (Figure 2). The intensification scenario (INT) is marked by intensive forest management with gradually increased harvest levels and intensive afforestation. We also assumed that new short-rotation industrial woody plantations would be established. The other main assumption in this scenario is the fast intensification of the Hungarian wood processing industry. We assumed that no timber would be exported from the country; instead, all raw material would be processed domestically, and the production of high-quality, durable HWPs would increase. For this the modeled assortment composition was also changed in a way that industrial wood assortments were increased (Table 1). Harvest levels in the INT scenario are based on the projection of Borovics et al. [9], and no stand is harvested before reaching the cutting age specified by the Forest Act [33] for the respective tree species. Under the third scenario (BAU), we assumed no changes in current forestry practices and management. In this scenario, we assume that the current assortment structure and wood processing capacities remain stable in the study period up to 2050. The used main model parameters are listed in Table 2. As regards harvesting patterns in the three modeled scenarios, it is important to underline that the modeling framework assures that forest reserves, as well as stands with high nature conservation value and stands under nonproduction forest management are excluded from harvesting. This guarantees that old-growth forests and areas of significant ecological importance are not disturbed in any of the modeled scenarios, thereby ensuring habitat preservation. Furthermore, soil protection and water management primary functions of stands are also considered, as forests having these primary functions are typically under nonproduction management in Hungary.

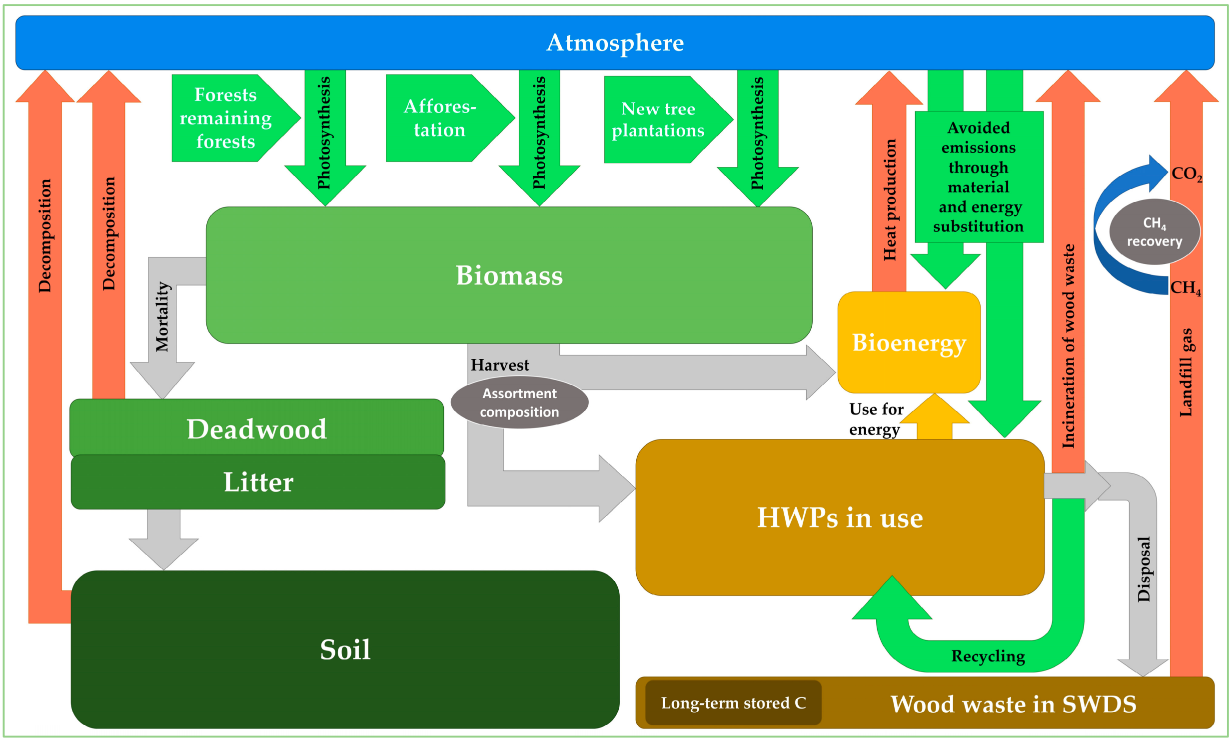

Figure 1. Flowchart of the Forest Industry Carbon Model (FICM). (SWDS stands for solid waste disposal sites).

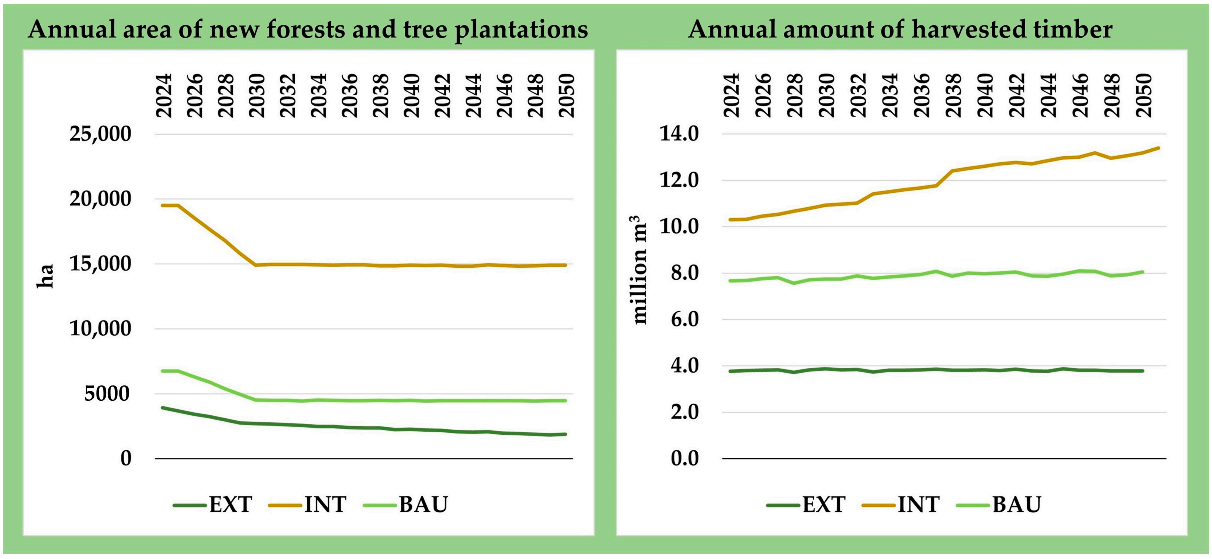

Figure 2. Annual area of afforestation and new forest plantations (**left**) and the annual amount of harvested timber (**right**) as used in the three examined scenarios.

During the modeling exercise we also examined whether the 2030 land-based sector (LULUCF) target set by the EU for Hungary (i.e., −5724 kt CO_2 eq) is reached. For this, we considered only the forest and HWP carbon balance, as product and energy substitution are not part of the LULUCF accounting [20]. Although the LULUCF target is to be reached by the entire LULUCF sector, including croplands, grasslands, wetlands, settlements, forests and HWPs, we examined only the forest and HWP net emissions against the target value. This simplification was used as, currently, the only LULUCF sink in Hungary is the forest-based sector, thus, it is most likely that when the forest-based sector does not reach the target, it will not be reached at all.

Table 1. Wood industry and waste management-related scenario parametrization. (For the year 2024 BAU parameters were used in all scenarios. In the intensification scenario, the parameters were gradually changed between 2024 and 2050).

	BAU, 2050	**EXT, 2050**	**INT, 2050**
HWP Production	**Average of the Last Five Historic Years**	**Half of the Last Five Historic Years**	**Increased Production Due to Increased Harvest and Increased Industrial Wood Assortment**
Half-life sawnwood	35	35	50
Half-life wood panels	25	25	35
Half-life paper and paperboard	2	2	2
Landfilled wood %	6	6	2
Landfilled paper %	10	10	2
Recycled sawnwood %	25	25	60
Recycled wood panel %	25	25	60
Recycled paper and paperboard %	71	71	90
Methane recovery %	7	7	60
Substitution factor for wood products	1.2	1.2	1.2
Substitution factor for bioenergy	0.67	0.67	0.67

Table 2. Wood assortments under the three examined scenarios. BAU and EXT assortments are based on the 2017–2021 average wood assortment [26], while INT assortments are based on expert judgment.

	Oaks	**Turkey Oak**	**Beech**	**Hornbeam**	**Black Locust**	**Other Hard Broadleaved**	**Hybrid Poplars**	**Indigenous Poplars**	**Willows**	**Other Soft Broadleaved**	**Pines**
BAU and EXT											
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%
INT											
Sawlog	50%	40%	40%	20%	40%	30%	50%	50%	20%	40%	40%
Pulpwood for boards	20%	20%	30%	30%	10%	30%	40%	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%

3. Results

According to our results, the age class structure develops differently under the three scenarios (Figure 3). In the BAU scenario, the ongoing aging process continues unchanged, while in the EXT scenario, the average age of Hungarian forests increases radically, from the current 45.5 years, it goes up to 66.1 years by 2050. On the other hand, under the INT scenario, the aging process is reversed, and the average age of forests would decrease to 39.5 years by 2050.

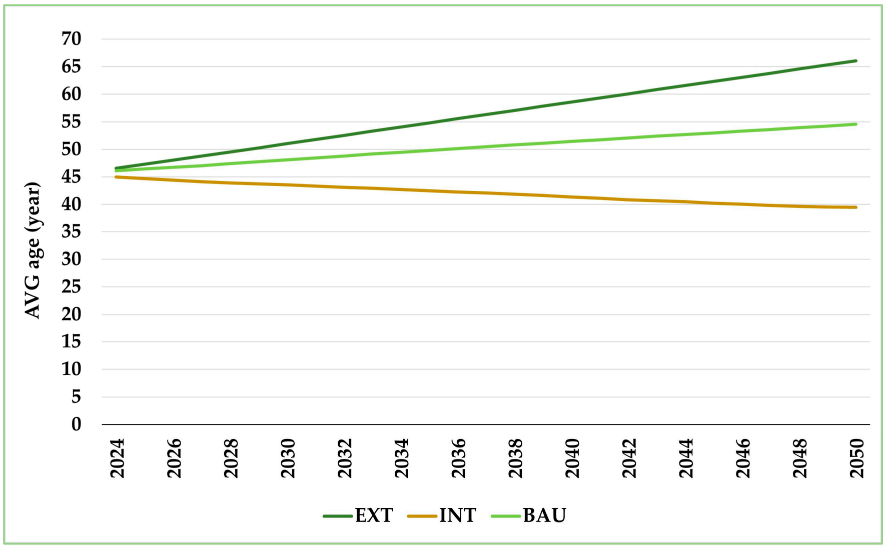

Figure 3. Average age of the Hungarian forest stands under the three examined scenarios.

As regards the carbon balance of the three scenarios, we observed that in the BAU and EXT scenarios, the most important carbon sink is the living forest biomass (above- and below-ground), while in the INT scenario, in addition to the living biomass, HWPs represent a sink of the same order of magnitude (Figures 4–6). Under the BAU scenario, substitution effects are of comparable magnitude to the forest carbon sink (Figure 4). Under the EXT scenario, substitution effects are less pronounced (Figure 5), while under the INT scenario, substitution effects represent the largest carbon benefit (Figure 6).

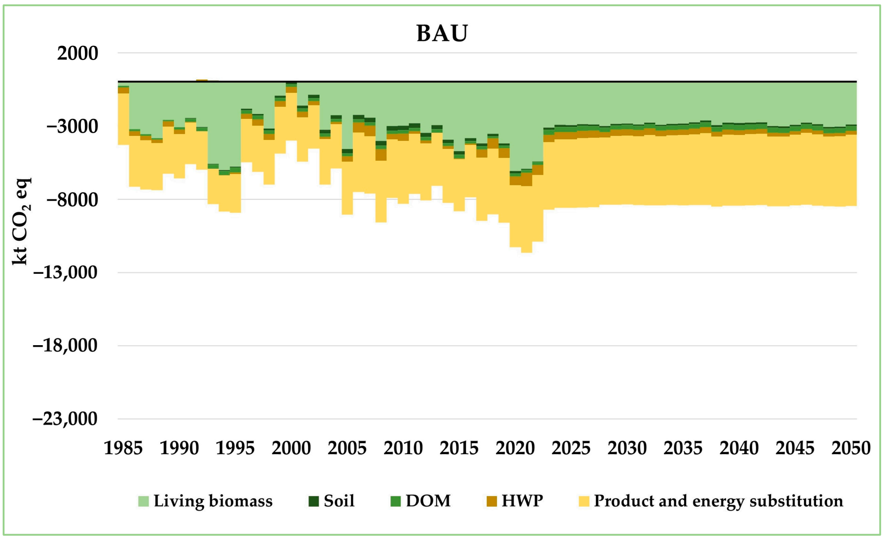

Figure 4. Historic and projected carbon balance of the living biomass, DOM, soil, and HWP pools, as well as product and energy substitution effects under the BAU scenario. (Historic forest and HWP net emission values are taken from the Hungarian Greenhouse Gas Inventory [31]. Negative numbers indicate carbon sequestration according to the IPCC conventions).

Figure 7 represents the net forest plus HWP carbon sink performance of the three scenarios as compared to the 2030 LULUCF target of Hungary (i.e., −5724 kt CO_2 eq). Under the BAU scenario, the 2030 net carbon removal of the forest-based sector is −3659 kt

CO_2 eq, which means that the target will not be reached unless extensive carbon removals occur in the cropland, grassland, settlement, or wetland subsectors. Under the EXT scenario, the modeled 2030 carbon sink reaches −7121 kt CO_2 eq, while under the INT scenario, the 2030 removal is projected to be −5754 kt CO_2 eq, meaning that the target is reached in both scenarios.

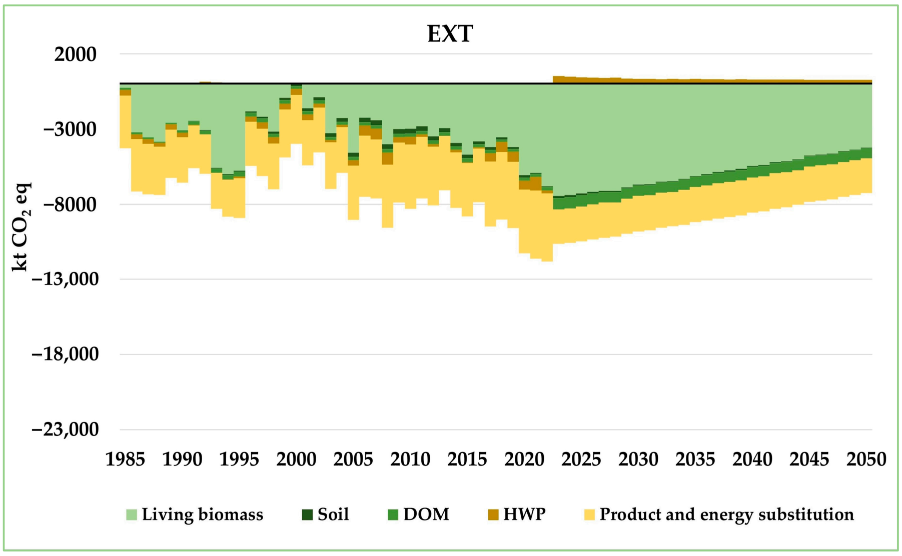

Figure 5. Historic and projected carbon balance of the living biomass, DOM, soil, and HWP pools, as well as product and energy substitution effects under the EXT scenario. (Historic forest and HWP net emission values are taken from the Hungarian Greenhouse Gas Inventory [31]. Negative numbers indicate carbon sequestration, while positive numbers indicate emissions according to the IPCC conventions).

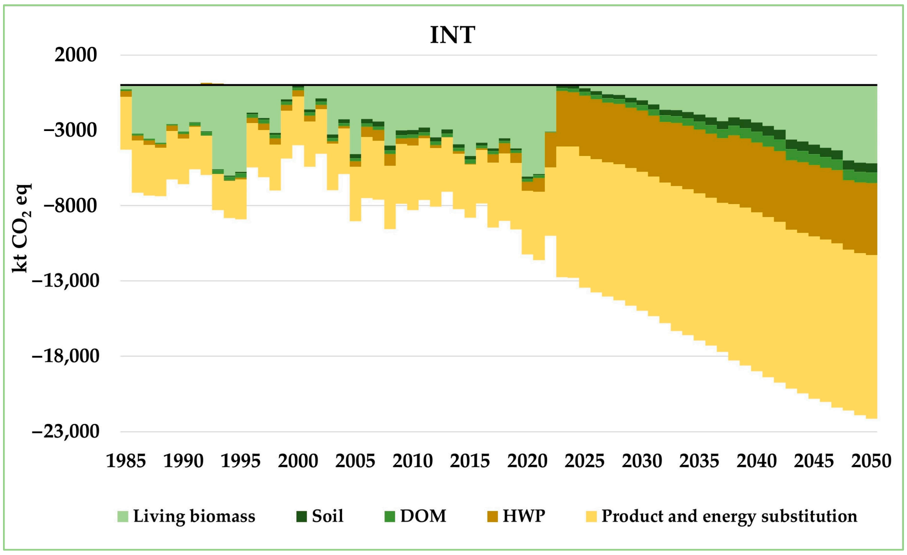

Figure 6. Historic and projected carbon balance of the living biomass, DOM, soil, and HWP pools, as well as product and energy substitution effects under the INT scenario. (Historic forest and HWP net emission values are taken from the Hungarian Greenhouse Gas Inventory [31]. Negative numbers indicate carbon sequestration according to the IPCC conventions).

We assessed the climate change mitigation potential of the INT and EXT scenarios compared to the BAU net emission levels (Figure 8). From 2024 to 2030, the projected average annual mitigation potential of the EXT scenario is 1347 kt CO_2 eq, while under the INT scenario, it reaches 5520 kt CO_2 eq. In the 2031–2050 period, the EXT scenario performs a negative average mitigation potential of −206 kt CO_2 eq, which means that compared to the BAU scenario, additional emissions occur in the EXT scenario. In the same period under the INT scenario, the intensified forest industry reaches a mitigation potential of 10,606 kt CO_2 eq compared to BAU net emission levels. In the EXT scenario, in both periods, HWPs and substitution effects produce additional emissions compared to BAU, while forests perform extra sink. On the other hand, in the INT scenario in 2024–2031, forests sequester less carbon than under the BAU scenario, while HWPs and substitution effects generate additional sinks. In the 2031–2050 period, all carbon pools as well as substitution, perform additional removals under the INT scenario.

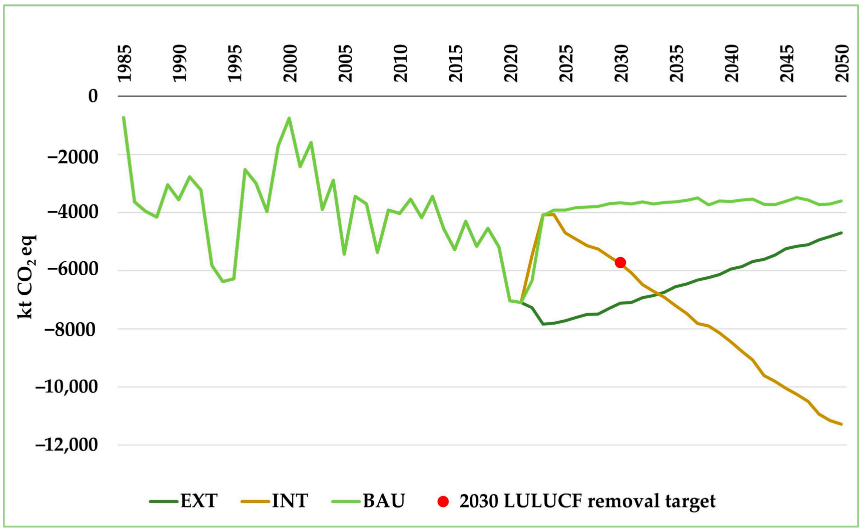

Figure 7. Historic and projected net emissions of the forest and HWP sectors under the three examined scenarios and the 2030 LULUCF removal target. (Historic forest and HWP net emission values are taken from the Hungarian Greenhouse Gas Inventory [31]. Negative numbers indicate carbon sequestration according to the IPCC conventions).

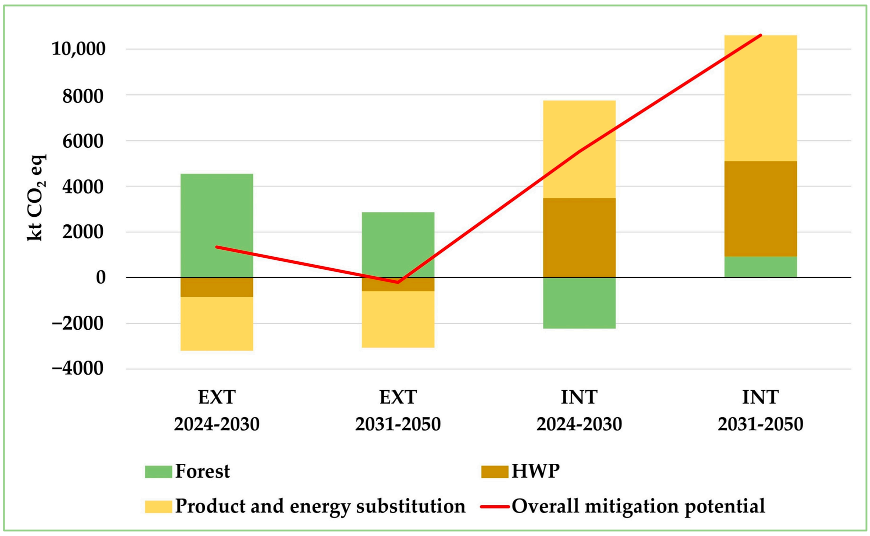

Figure 8. Average annual mitigation potential of the EXT and INT scenarios compared to the BAU scenario calculated for the periods 2024–2030 and 2031–2050. (Positive numbers indicate additional carbon sequestration compared to the BAU level, while negative numbers indicate additional CO_2 emissions).

4. Discussion

Under the BAU scenario, assuming the continuation of current Hungarian forest management practices and harvest levels, our projection shows a decreasing forest-based carbon sink, with constant product and energy substitution benefits. This is most likely attributable to the age class structure of Hungarian forests leading to a decreasing gross annual increment over time. This result is significant as it stresses the fact that without urgent further action, the 2030 LULUCF target set for Hungary is not likely to be reached.

The results of the climate benefit assessment of the INT scenario underline that in Hungary, the amount of harvested timber can be increased reaching net climate benefits. This is in line with the findings of Köhl and Martes [7], who state that the forest-based sector can make a much greater contribution to climate neutrality by harvesting their wood and supplying it to low-emission processing operations, and by long-term carbon storage in HWPs. Moreau et al. [34] used the spatially explicit forest landscape model LANDIS-II and its extension Forest Carbon Succession, in conjunction with the Carbon Budget Model for harvested wood products framework to model the carbon balance of a northern temperate forest. They found that the productivity of the area was mainly stimulated by forest harvesting, with the most intensive management scenarios showing the highest net growth, net ecosystem productivity, net primary productivity, and net carbon sequestration. These findings are in line with our results; however, we note that in the case of their study, substitution effects were negligible, while according to our modeling results, substitution effects give a major part of the climate mitigation potential projected under the INT scenario. Our results align with the conclusions drawn by Fiorese and Guariso [35], who conducted a regional analysis of carbon balance within Italy's forest-based sector. They determined that maximizing harvest proved to be the optimal scenario for three out of four forest macrocategories. In contrast, Heinonen et al. [36] demonstrated in the context of Finland that the overall cumulative carbon balance of the forest-based sector was the most favorable when applying low cutting levels. However, they also emphasized that scenarios with higher cutting targets displayed better HWP carbon balance values due to enhanced substitution effects and increased carbon accumulation in wood-based products. Pukkala [37] also highlights that integrating substitution effects into carbon balance modeling significantly boosts the carbon offset capacity of the forest-based sector.

As regards the EXT scenario, our projection shows that after a rapid and significant increase in the forest carbon sink, the projected net biomass carbon sequestration shows a decreasing trend, which will be reduced almost to the BAU level by 2050. This tendency is worsened by the fact that under the EXT scenario, substitution effects are much lower than under the other two scenarios due to decreased harvest levels. Martes and Köhl [20] used the BEKLIFUH model to assess six management scenarios in the Hamburg Metropolitan Area. In line with our results, they found that while conservation led to a higher above-ground carbon pool, including HWPs, and material and energy substitution resulted in more carbon offsets under management scenarios with increased timber harvesting.

The significant aging of Hungarian forests under the EXT scenario, with the average age reaching more than 66 years up to 2050, anticipates that these overmature forests may become more vulnerable and severely exposed to natural disturbances. In view of the ongoing climate change, this may cause a significant problem and extensive forest damage. In our modeling framework, we did not consider the effects of climate change due to the related high uncertainty, the short projection period, and the current limitations of the used model. Nevertheless, it is forecast that many tree species will see reductions in their suitable ranges in Hungary [38], especially populations near their xeric limit are likely to be affected [39]. Following all this, it is likely that net forest carbon sink would decrease in all scenarios under increasing climate forcing. Still, forest management can have a significant role in adapting the land to its future characteristics [40,41]. For example, under an intensified management scenario, harvest operations could target stands that are most susceptible to insect outbreaks, fire, or productivity decline, thus reducing the impacts of such events while maintaining the harvest level [34,42,43] and allowing for regeneration of stands. The regeneration period 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 [9]. Postponing harvesting and regeneration slows down the adaptation process and increases the risk of carbon emissions caused by natural disturbances. Under an intensified management scenario, foresters could actively manage species composition to increase forest resilience and sustainability in the face of a changing climate [34].

The harvest level in Hungary has remained stable at approximately 7.5 million m^3 for decades. Our results show that the harvested amount could be significantly increased without having negative impacts on climate change mitigation and without harvesting stands younger than the cutting age prescribed. However, significant investments and innovation are needed in the wood industry sector to enable the processing of an extra 2–4 million m^3 of timber. Excess availability of timber from drought-tolerant species like Turkey oak (*Quercus cerris*) and indigenous poplars (*Populus alba*, *Populus* × *canescens*, *Populus tremula*) is expected in Hungary in the forthcoming decades [9]. Thus, it is advisable to design novel product types and establish innovative production processes to effectively utilize the available timber from these tree species currently underutilized for industrial purposes. One of the primary challenges for the Hungarian forest industry in the forthcoming decades will be the mobilization of the unused wood stock reserve and the optimal utilization of additional harvesting possibilities. To unlock harvesting potential, there is a need for professional integration and technical support provided to forest managers and wood industry enterprises through GIS applications. Accurate and geographically explicit data regarding the quantity and value of harvestable wood stocks could serve as a foundation for fostering a novel entrepreneurial culture and devising innovative approaches for offering forest-related services [9].

The limitation of our study is the fact that the effects of climate change on future carbon sinks are not modeled. We plan to develop our model in the framework of the ongoing ForestLab project and include processes that allow us to carry out model runs under different projected scenarios of climate forcing up to 2100.

5. Conclusions

Based on our findings, we conclude that a significant part of the forest industry-related climate change mitigation potential is inherent in HWP carbon storage and product and energy substitution effects. Thus, increasing or sustaining forest carbon stocks by nonutilization for climate change mitigation is a misconception that arises from missing a crucial element of the forest industry by not considering processes occurring offsite in the technosphere. A comprehensive and coherent understanding of forestry and the wood industry, as well as innovations in wood processing of underutilized tree species, are essential to achieving the most favorable carbon trajectory. Climate neutrality can be reached through the joint implementation of forest-based climate mitigation actions and active adaptation combined with wood industry innovations and intensification. Deadwood accumulated in unmanaged forests or forests managed with a decreased harvesting intensity is decomposed by microorganisms. During this slow-burning, the same amount of carbon dioxide is released to the atmosphere as if timber was used as firewood to substitute fossil fuels. Sustainable forest management channels the captured carbon into wood products, not letting it be decomposed by microorganisms, and leaves only the necessary amount of deadwood in forests for biodiversity protection. Postponed harvests and extended rotation cycles reduce atmospheric carbon dioxide concentrations only temporarily in the short term, meanwhile hindering adaptation actions such as tree species replacements, the use of preadapted propagation material in forest regenerations and enrichment plantings, and the implementation of precommercial harvests, which could form a less dense stand structure leading to decreased water demand. Thus, decreased timber utilization can lead to increased carbon sequestration only in the short term, undermining long-term mitigation and adaptation goals and compromising forest productivity, vitality, and regeneration capacity. Mobilizing the unused wood stock reserve leads to increased carbon sequestration in wood products and an increased level of avoided emissions resulting from product and energy substitutions. Forest industry intensification, together with new wood processing innovations, can produce higher carbon sequestration levels up to 2050. To achieve this, the introduction of new economic instruments for green investments is essential. In addition, broad social consultation and the development of training and communication materials are needed to facilitate the effective presentation of the process leading to the successful achievement of climate change mitigation objectives. In the meantime, recognizing the diverse and unique ecosystem of forests, along with their various functions and services beyond carbon sequestration, is also indispensable.

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Data Availability Statement: All data that are necessary for the reconstruction of this study can be found in this paper and in the referenced sources.

Conflicts of Interest: The authors declare no conflicts of interest.

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