WOOD RESEARCH doi.org/10.37763/wr.1336-4561/69.1.7286
e-ISSN 2729-8906
69(1): 2024 72-86 pp.

CLIMATE CHANGE MITIGATION THROUGH CARBON STORAGE AND PRODUCT SUBSTITUTION IN THE HUNGARIAN WOOD INDUSTRY

ÉVA KIRÁLY, ZOLTÁN BÖRCSÖK, ZOLTÁN KOCSIS, GÁBOR NÉMETH,
ANDRÁS POLGÁR, ATTILA BOROVICS
UNIVERSITY OF SOPRON
HUNGARY

(RECEIVED NOVEMBER 2023)

ABSTRACT

In our study we estimated under two different scenarios the historic and future carbon balance of the Hungarian harvested wood product (HWP) pool using the HWP-RIAL model. We also estimated the effect of product and energy substitution and the magnitude of avoided emissions based on international substitution factors. According to our results in the period 1985–2021 the average of the HWP net emissions plus substitution effects was -3,800 kt CO_2. In this period the 49% of the forest industry-related climate benefits was attributable to carbon storage in forests, while 4% was attributable to carbon storage in wood products and 47% to product and energy substitution. According to our projection the HWP net emissions plus substitution effects could reach -14,994 kt CO_2 up to 2050 under an intensified domestic wood processing industry. This means that product substitution benefits could be tripled, while the net removals of the HWP pool could be 5 times higher than the historic values.

KEYWORDS: HWP, substitution factor, displacement factor, CO_2, forest industry.

INTRODUCTION

The European Green Deal relies on the forestry and wood industry sector (altogether also called forest industry) to achieve the European Union's climate neutrality by 2050 (Verkerk et al. 2022). Forest industry can contribute to climate change mitigation efforts through four means: carbon storage in forests, carbon storage in long-lived wood products, material substitution of emission-intensive products, and energy substitution of fossil fuels (Verkerk et al. 2022, Borovics 2022). These four climate mitigation pathways define conflicting goals of timber usage. Increasing wood harvests reduces the amount of carbon sequestered and stored in forests at least for decades, thus resulting in trade-off between carbon sequestration in forests and carbon storage in harvested wood products (HWP) and substitution (Helin et al. 2013).

In order to design the bets-fitting climate mitigation strategy for a region or country it is important to assess the results of different harvesting and wood processing scenarios and to quantify the climate benefits of HWP carbon storage as well as that of product and energy substitution.

Carbon storage and greenhouse gas (GHG) emissions from the HWP pool of a country can be modelled using different tools and approaches (Brunet-Navarro et al. 2016, 2018). The WoodCarbonMonitor model (Rüter 2016) is based on IPCC (2006, 2013) methodology, CO2FIX (Schelhaas et al. 2004), LANDCARB (Krankina et al. 2012) and CAPSIS (Fortin et al. 2012) models also handle recycling in wood product emission modelling. The HWP-RIAL model (Király et al. 2022, 2023a,b) was created in the frame of the ForestLab project (Borovics 2022). It combines IPCC methodology for HWP emission estimation (IPCC 2006, 2019) with the IPCC Waste model (IPCC 2006) and it is supplemented with a recycling and waste routing module.

While the positive role of forests in climate change mitigation is generally well perceived, the contribution of HWP to mitigation is much less understood (Leskinen et al. 2018). Current national reporting of GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC) does not attribute the substitution benefits of wood-based products directly to the forest sector. However, this information is important when developing optimal climate mitigation strategies (Leskinen et al. 2018).

A substitution factor describes how much GHG emissions would be avoided if a wood-based product is used instead of another product to provide the same function, be it a chemical compound, a construction element, a textile fibre, or energy service (Leskinen et al. 2018). GHG substitution effects can be estimated by combining information on the quantity of wood products that are produced or consumed, with product-specific substitution factors (Leskinen et al. 2018).

A meta-analysis with 51 studies conducted by Leskinen et al. (2018) provided information on 433 separate substitution factors. According to their review the large majority of studies indicate that the use of wood and wood-based products are associated with lower fossil and process-based emissions when compared to non-wood products (Leskinen et al. 2018). Leskinen et al. (2018) based on their review suggest an average substitution factor of 1.2, which means that for each kilogram of C in wood products that substitute non-wood products, there occurs an average emission reduction of approximately 1.2 kg C. According to Geng et al. (2017) substituting materials appears to be more effective in reducing GHG emissions than substituting fuels. According to Myllyviita et al. (2021) most of the energy substitution factors in the scientific literature are lower than 0.8, designating that all wood-based fuels do not replace fossil energy, or they replace fossil energy with low emissions. Knauf et al. (2015, 2016), Härtl et al. (2017) and Schweinle et al. (2018) suggest a substitution factor of 0.67 for energy substitution.

In our study we intended to estimate the historic and future emissions avoided through the product substitution effect of Hungarian wood products, as well as the carbon sequestration of the Hungarian HWP pool using the HWP-RIAL model. We supplemented the HWP-RIAL model with a substitution module and performed calculations under two different scenarios in order to get a picture on the climate mitigation potential inherent in the Hungarian wood industry.

MATERIALS AND METHODS

In order to calculate the carbon storage and emissions from the Hungarian HWP pool we used the HWP-RIAL model (Király et al. 2022, 2023a,b) which is based on IPCC (2006, 2019) methodology and also handles recycling of HWP (Fig. 1). We supplemented the existing model with a product and energy substitution module to estimate the avoided emissions attributable to using wood instead of other alternatives. In the modelling exercise we also estimated the carbon storage and end of life emissions of HWP. In our estimate we excluded HWP produced from imported timber.

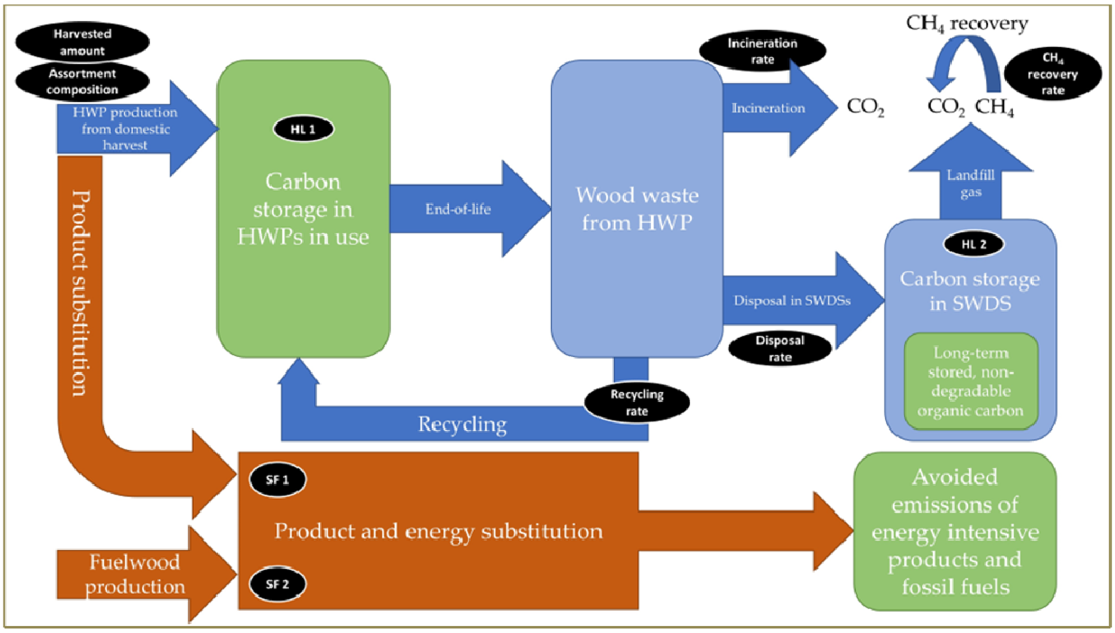

Fig. 1: Flowchart of the HWP-RIAL model (HL1 and HL2: half-life, SF1 and SF2: substitution factors, SWDS: solid waste disposal site).

We estimated substitution effects based on international literature and especially based on the Report of the European Forest Institute (Leskinen et al. 2018). As for Hungary no country specific substitution factors (SF) are available, we used the average SF given by Leskinen et al. (2018) for wood products, while for firewood we used SF as defined by Myllyviita et al. (2021), Knauf et al. (2015, 2016), Härtl et al. (2017), and Schweinle et al. (2018). For the calculation of the avoided emissions, we used the following equations (1-3):

$$\mathrm{SF} = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \qquad (1)$$

$$Avoided\ Emissions_{HWP} = Prod_{HWP} \times SF_1 \qquad (2)$$

$$Avoided\ Emissions_{firewood} = Prod_{firewood} \times SF_2 \qquad (3)$$

where: SF: substitution factor (unitless ratio), SF_1=1.2 (Leskinen et al. 2018), SF_2=0.67 (Myllyviita et al. 2021, Knauf et al. 2015, 2016, Härtl et al. 2017, Schweinle et al. 2018); $GHG_{non\text{-}wood}$: GHG emissions resulting from the use of non-wood alternatives (kt CO_2 eq); GHG_{wood}: GHG emissions resulting from the use of wood alternatives (kt CO_2 eq); WU_{wood}: the amounts of wood used in wood product alternatives (kt CO_2 eq); $WU_{non\text{-}wood}$: the amounts of wood used in non-wood product alternatives (kt CO_2 eq); Avoided Emissions: emissions avoided through product and energy substitution (kt CO_2 eq); $Prod_{HWP}$: production of harvested wood products expressed in the amount of carbon stored in the specific products (kt CO_2 eq); $Prod_{firewood}$: production of firewood expressed in the amount of carbon stored in the produced firewood amount (kt CO_2 eq).

In order to estimate the amount of carbon stored in a particular HWP commodity category and the amount of HWP reaching the end of its lifetime and going out of use a combination of the approaches recommended by the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) (herein after referred to as the Refinement) was used. In our estimate we excluded HWPs produced from imported wood in accordance with the IPCC guidelines (IPCC 2006, 2019). Tab. 1 shows the default half-life values and conversion factors which were taken from the Refinement. Default half-life values were used in the BAU scenario; however, half-life values were modified in the Intensification scenario.

Tab. 1: Default half-life values and conversion factors recommended by IPCC 2019 Refinement.

	Half-life (Year)	**Density (oven dry mass over air dry volume) [Mg/m³]**	**Carbon Fraction**	**C conversion factor (per air dry volume) [Mg C/m³]**
Coniferous sawnwood	35	0.45	0.5	0.28
Non-coniferous sawnwood	35	0.56	0.5	0.225
Veneer sheets	25	0.505	0.5	0.253
Plywood	25	0.542	0.493	0.267
Particle board	25	0.596	0.451	0.269
HDF	25	0.788	0.425	0.335
MDF	25	0.691	0.427	0.295
Fibreboard compressed	25	0.739	0.426	0.315
Other board	25	0.159	0.474	0.075
	Half-life (year)	**Relative dry mass (oven dry mass over air dry mass) [Mg/Mg]**		**C conversion factor (per air dry mass) [Mg C/Mg]**
Paper and paperboard (aggregate)	2	0.9	-	0.386

To estimate the magnitude of the carbon stock in the HWP pool in use and its net changes a first-order decay function was used. The calculations were made separately for each product category. Concerning annual carbon stock change, Equation 12.2 of the Refinement was used:

$$\Delta\mathrm{C}(i) = C(i+1) - C(i) \tag{4}$$

$$\mathrm{C}\ (i+1) = e^{-k} \cdot C(i) + \left[\frac{(1-e^{-k})}{k}\right] \cdot \text{inflow}\ (i) \tag{5}$$

where: i: year; C(i): the carbon stock in the particular HWP commodity class i at the beginning of the year i, Mt C; k: decay constant of first-order decay for each HWP commodity class i given in units yr-1 (k = ln(2)/HL, where HL is the half-life of the particular HWP commodity in the HWP pool in years); inflow(i): the carbon inflow to the particular HWP commodity class i during the year i, Mt C yr-1; ΔC(i): carbon stock change of the HWP commodity class i during the year i, Mt C yr-1.

As a proxy, it was assumed that the HWP pool is in a steady state at the initial time (1963) from which the activity data started, and $\Delta C\ (t0)$ is assumed to be equal to 0. This steady-state carbon stock $C(t0)$ for each HWP commodity class 'i' is approximated based on the average of inflow(i) during the first 5 years (1964–1968), for which statistical data are available and are deemed reliable:

$$C_i(t0) = \frac{\text{inflow}_{i\ \text{average}}}{k} \tag{6}$$

For the estimation of annual carbon stock change and the outflow in year 'i' equations of the Refinement were used as follows:

$$\Delta\mathrm{C(i)} = \mathrm{C(i+1)} - \mathrm{C(i)} \tag{7}$$

$$\mathrm{C\ (i+1)} = \mathrm{e^{-k}} \cdot \mathrm{C(i)} + \left[\frac{(1-\mathrm{e^{-k}})}{\mathrm{k}}\right] \cdot \text{inflow (i)} \tag{8}$$

$$\text{outflow (i)} = \left(1-\mathrm{e^{-k}}\right) \cdot \mathrm{C(i)} + \left[1 - \frac{(1-\mathrm{e^{-k}})}{\mathrm{k}}\right] \cdot \text{inflow (i)} \tag{9}$$

where: ΔC(i): carbon stock change of the HWP commodity class i during the year i, kt C yr-1; outflow(i): the carbon content of the particular HWP commodity class i that goes out of use during the year i, kt C yr-1.

HWP reaching its end of life can be proceeded in three different ways in the HWP-RIAL model: it can be recycled, incinerated, or landfilled. The share of waste wood recycled and disposed of via incineration or solid waste disposal can be set as appropriate. In this study wood waste from HWPs going out of use was set as raw material for production of sawnwood (20%), particle board (50%), MDF (20%) and other board (10%). The share of wood waste recycled and disposed of was calculated with the following equations:

$$\text{recycled WW (i)} = \text{outflow (i)} \cdot F_{\text{recycled WW}} \quad (10)$$

$$\text{landfilled WW (i)} = \text{outflow (i)} \cdot F_{\text{landfilled WW}} \quad (11)$$

$$\text{incinerated WW (i)} = \text{outflow (i)} \cdot \left(1 - F_{\text{recycled WW}} - F_{\text{landfilled WW}}\right) \quad (12)$$

$$CO_2 \text{ Emissions from incineration (i)} = \text{incinerated WW (i)} \cdot 44/12 \quad (13)$$

where: recycled WW (i): the wood waste generated in year i from the particular HWP commodity class i and recycled thereafter, kt C yr-1; $F_{recycled\ WW}$*: the fraction of wood waste recycled (fraction); landfilled WW (i): the wood waste generated in year i from the particular HWP commodity class i and landfilled thereafter, kt C yr-1;* $F_{recycled\ WW}$*: the fraction of wood waste landfilled, fraction; incinerated WW (i): the wood waste generated in year i from the particular HWP commodity class i and incinerated thereafter, kt C yr-1; 44/12:* CO_2*/C molecular weight ratio.*

For estimating CH_4 and CO_2 emissions from waste wood disposed at solid waste disposal sites (SWDSs) the modified version of the Waste Model of the 2006 IPCC Guidelines (IPCC 2006) was used and parametrized for Hungary. The CH_4 generation potential of the waste that is disposed in a certain year decreases gradually throughout the following decades thus the CH_4 released from this specific amount of waste decreases as well. These decreasing CH_4 emissions are modelled with a first order decay pattern. The first order decay model is built on an exponential factor that describes the fraction of degradable organic material which each year is broken down into CH_4 and CO_2. CH_4 is generated under anaerobic conditions. One part of the CH_4 generated is oxidized in the cover of the SWDS. Other part can be recovered for energy or flaring. The percentage of CH_4 recovery can be set in the input sheet of the HWP-RIAL model. The basis for the calculation of CH_4 generated is the amount of Decomposable Degradable Organic Carbon (DDOCm) which is the part of the organic carbon that will decompose under anaerobic conditions in SWDSs. The amount of DDOCm available, and the accumulated and decomposed amounts of organic carbon were calculated using the following equations.

$$DDOC_m = C \cdot DOC_f \cdot MCF \quad (14)$$

$$\text{DDOCm accum}_T = \text{DDOCmd}_T + \left(\text{DDOCmd}_{T\text{-}1} \cdot e^{-k}\right) \quad (15)$$

$$\text{DDOCm decomp}_T = \text{DDOCm accum}_{T\text{-}1} \cdot \left(1 - e^{-k}\right) \quad (16)$$

where: DDOCm: mass of decomposable degradable organic carbon deposited, kt C; C: degradable organic carbon deposited, kt C; DOCf: fraction of degradable organic carbon that can decompose (fraction); MCF: CH_4 *correction factor for aerobic decomposition in the year of deposition (fraction); DDOCm* $accum_T$*: DDOCm accumulated in the SWDS at the end of year T, kt C; DDOCm* $accum_{T-1}$*: DDOCm accumulated in the SWDS at the end of year (T-1), kt C;* $DDOCmd_T$*: DDOCm deposited into the SWDS in year T, kt C; DDOCm* $decomp_T$*: DDOCm decomposed in the SWDS in year T, kt C; k: reaction constant, given in units yr-1 (k= ln(2)/HL, where HL is the half-life of the particular waste category).*

Only a part of the degradable organic carbon in waste wood disposed in SWDS will decay into both CH_4 and CO_2, the part that will not decompose will be stored long-term in the SWDS (IPCC 2006). Long-term stored carbon was calculated as follows:

$$C_{\text{Long-term } T} = C \cdot (1 - DOC_f) \cdot MCF \tag{17}$$

where: MCF: CH_4 correction factor for aerobic decomposition in the year of deposition (fraction); DOCf: fraction of degradable organic carbon that can decompose (fraction); $C_{\text{Long-term } T}$: Long-term stored carbon in the SWDS in year T, kt C.

CH_4 generated and emitted was calculated as follows:

$$CH_4 \text{ generated}_T = \text{DDOCm decomp}_T \cdot F \cdot 16/12 \tag{18}$$

$$CH_4 \text{ Emissions } = [CH_4 \text{ generated}_T - R_T] \cdot (1 - OX_T) \tag{19}$$

where: CH_4 generated$_T$: amount of CH4 generated from decomposable material in year T, kt; DDOCm decomp$_T$: DDOCm decomposed in year T, kt C; F: fraction of CH_4 by volume in generated landfill gas (fraction); 16/12: CH_4/C molecular weight ratio; CH_4 Emissions: CH_4 emitted in year T, kt; R_T: recovered CH_4 in year T, kt; OX_T: oxidation factor in year T (fraction).

The amount of CH_4 recovered was calculated from the amount of the CH_4 generated and the percentage of methane recovery set on the input sheet. There was no differentiation between CH_4 recovered for energy and CH_4 flared as in both cases CH_4 is oxidized and released to the atmosphere in the form of CO_2. Carbon dioxide emissions from SWDS were calculated as the sum of CO_2 directly emitted from the landfill and CO_2 generated and emitted during the energetic utilization or flaring of the CH_4 component of the landfill gas:

$$R_T = CH_4 \text{ generated}_T \cdot CH_4 \text{ recovery\%} \tag{20}$$

$$CO_2 \text{ Emissions from landfills } = \left(CH_4 \text{ emissions} \cdot \frac{44}{16}\right) + \left(R_T \cdot \frac{44}{16}\right) \tag{21}$$

where: CH_4 recovery%: fraction of CH_4 recovered from landfill (fraction); 16/12: CO_2/CH_4 molecular weight ratio.

The solid waste disposal model was parametrized taking into account data of the Hungarian GHGI and data of the National Environmental Information System (OKIR 2023), as well as IPCC (2006) default data (Tab. 2). In order to get a realistic initial stock for HWP in SWDS the starting year of the waste sub-models was set to 1940, and a constant HWP waste outflow to SWDS was assumed for years 1940-1964 which was set equal to the average historic 1965-1969 outflow.

Tab. 2: Parameters used in the waste sub-model (Hungarian GHGI and IPCC 2006).

Waste Model Parameters	
DOCf (fraction of DOC dissimilated)	0.5
k (methane generation rate constant, years^{-1}) wood	0.02
k (methane generation rate constant, years^{-1}) paper	0.04
Half-life of wood waste (years)	35
Half-life of paper waste (years)	17
OX (oxidation factor, fraction), managed SWDS	0.1
OX (oxidation factor, fraction), unmanaged SWDS	0
MCF (methane correction factor for aerobic decomposition in the year of deposition, fraction), managed SWDS	1
MCF (methane correction factor for aerobic decomposition in the year of deposition, fraction), unmanaged, shallow	0.4
MCF (methane correction factor for aerobic decomposition in the year of deposition, fraction), unmanaged, deep	0.8
F (fraction of methane in developed gas)	0.5

We used historic HWP production data as defined by Király et al. (2022) and as used also in the Hungarian Greenhouse Gas Inventory (NIR 2023). In order to project future HWP net emissions and substitution effects we used harvest projections in two scenarios (Fig. 2). The business as usual (BAU) scenario assumed unchanged harvest level in the entire projection period (up to 2050), while in the Intensification scenario we used the estimate of Borovics et al. (2023) on the maximum wood mobilization potential. In Tab. 3 we define the modelling parameters used in the two scenarios.

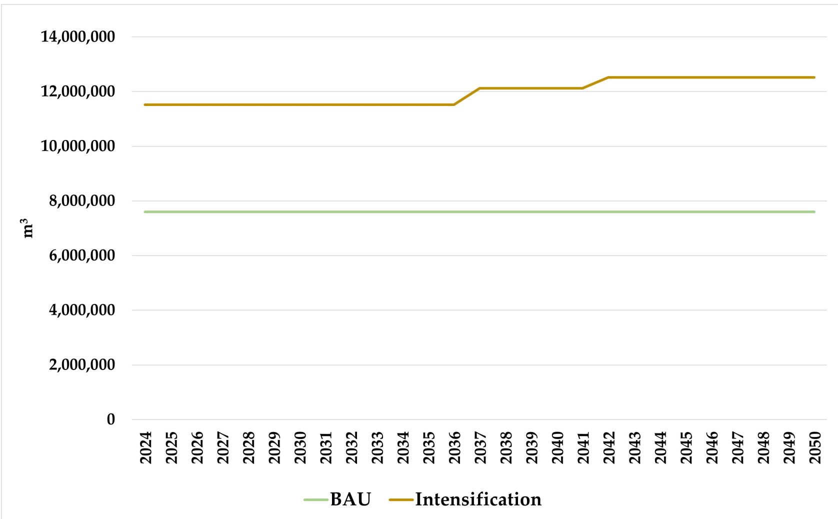

Fig. 2: Harvest projection used for HWP modelling under the BAU and the Intensification scenario.

Tab. 3: Scenario parametrization.

Parametrization of the scenarios		
		2050
BAU	HWP production	Average of the last five historic years.
	Half-life sawnwood	35
	Half-life wood panels	25
	Half-life paper and paperboard	2
	Landfilled wood %	6

	Landfilled paper %	10
	Recycled sawnwood %	25
	Recycled wood panel %	25
	Recycled paper and paperboard %	71
	Methane recovery %	7

Intensification	HWP production	Increased production due to increased harvest and increased industrial wood assortment.
	Half-life sawnwood	50
	Half-life wood panels	35
	Half-life paper and paperboard	2
	Landfilled wood %	2
	Landfilled paper %	2
	Recycled sawnwood %	60
	Recycled wood panel %	60
	Recycled paper and paperboard %	90
	Methane recovery %	60

Note: For the year 2022, BAU parameters were used in both scenarios. In the Intensification scenario the parameters were gradually changed between the years 2022 and 2050.

We estimated HWP production under the BAU scenario based on historic data on assortment composition (OSAP 2022), while in the Intensification scenario we used increased industrial wood assortments based on expert judgement (Tab. 4). In the Intensification scenario we assumed that all timber harvested domestically is processed domestically and that no export takes place. In order to estimate the rate of manufacturing by-products and waste we used the values given by Németh (2012).

Tab. 4: BAU (2017-2021 average) and increased industrial wood assortments.

	Oaks	**Turkey oak**	**Beech**	**Hornbeam**	**Black locust**	**Other hard broadleaved**	**Hybrid poplars**	**Indigenous poplars**	**Willows**	**Other soft broadleaved**	**Pines**
BAU scenario											
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%
Intensification scenario											
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%

RESULTS AND DISCUSSION

According to our estimate the average net emissions of the HWP pool in the 1985-2021 period were -327 kt CO_2 eq, while the average avoided emissions through substitution were equal to -3,474 kt CO_2 eq (Fig. 3). Negative numbers on the vertical axis indicate carbon dioxide removals or avoided emissions, while positive numbers indicate emissions.

According to the Hungarian GHGI (NIR 2023) the average net emissions of the Hungarian Forest Land (including land converted to forest land, forest land remaining forest land, and forest land converted to other land uses) were -3,597 kt CO_2 in the same period. The average of forest and wood sector net removals and avoided emissions was -7,398 kt CO_2. This means that 49% of the forest industry-related climate benefits was attributable to carbon storage in forests, while 4% was attributable to carbon storage in wood products and 47% was attributable to product and energy substitution.

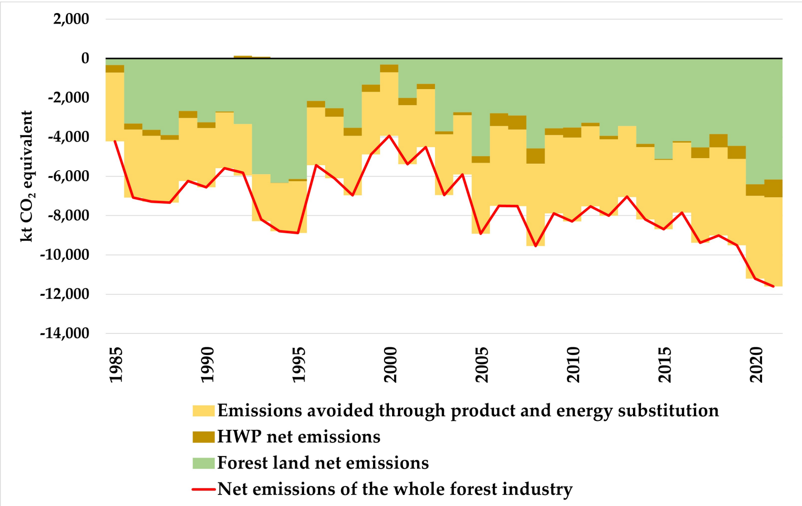

Fig. 3: Historic net emissions from Forest Land as reported in the GHGI, modelled HWP net emissions, and emissions avoided through product and energy substitution.

The modelled carbon stock stored in HWPs in use was 12,511 kt C, while HWPs in SWDSs stored 1,168 kt C in 2021. Under the BAU scenario carbon stored in HWPs in 2050 is projected to be 15,930 kt C, and carbon stored in SWDSs is projected to be 1,695 kt C (Fig. 4a). Under the Intensification scenario carbon stored in HWPs in 2050 is projected to be 46,112 kt C, and carbon stored in SWDS is projected to be 1,395 kt C (Fig. 4b). This means that under the Intensification scenario carbon stored in HWPs is 289% higher than under the BAU scenario in 2050.

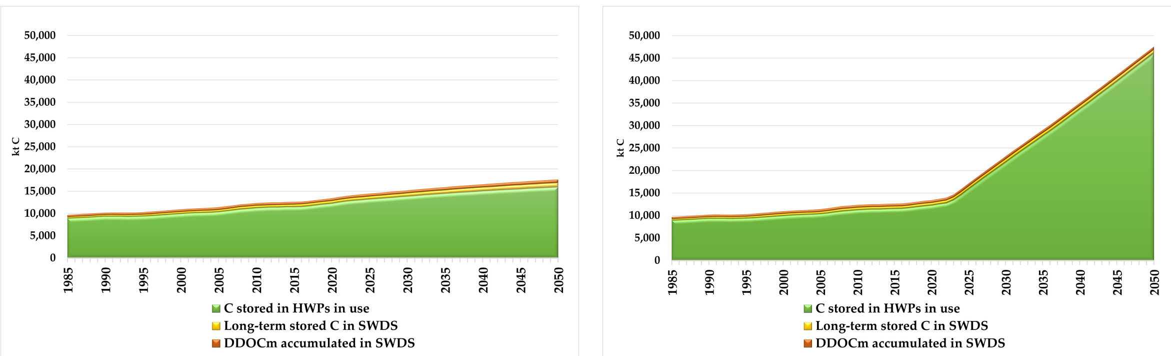

Fig. 4. Historic and projected carbon stock stored in HWPs in use and HWPs in SWDS under a) the BAU scenario, b) the Intensification scenario.

Under the BAU scenario projected net removals of the HWP pool drop from -905 kt CO_2 eq to -242 kt CO_2 eq up to 2050. Avoided emissions in the projection period are in a range between -4,529 kt CO_2 eq and -4,566 kt CO_2 eq. The projected net emission reduction of the Hungarian wood industry under the BAU scenario is in total -4,809 kt CO_2 eq in 2050 (Fig. 5a). Under the Intensification scenario HWP net emissions reach -4,607 kt CO_2 eq up to 2050, while emissions avoided through product and energy substitution increase from -4,529 kt CO_2 eq to -10,387 kt CO_2 eq (Fig. 5b). This means that the projected net emission reduction of the Hungarian wood industry under the Intensification scenario is in total -14,994 kt CO_2 eq in 2050.

Our results are in line with the estimates of Parobek et al. (2019) who concluded that increased industrial wood assortments and favouring domestic timber processing can significantly increase carbon sequestration and storage of HWPs even without increased harvests. In their study an increase of 273% was reached in HWP net emissions without increased harvests. In our estimate a 275% increase is reached together in HWP net emissions and substitution effects due to increased industrial wood assortments, domestic processing, and increased harvests. We estimate that product substitution benefits can be increased to 299% up to 2050. Furthermore, the projected increase in HWP net removals in year 2050 is even higher, net removals of the HWP pool under the Intensification scenario are 5 times higher than under the BAU scenario.

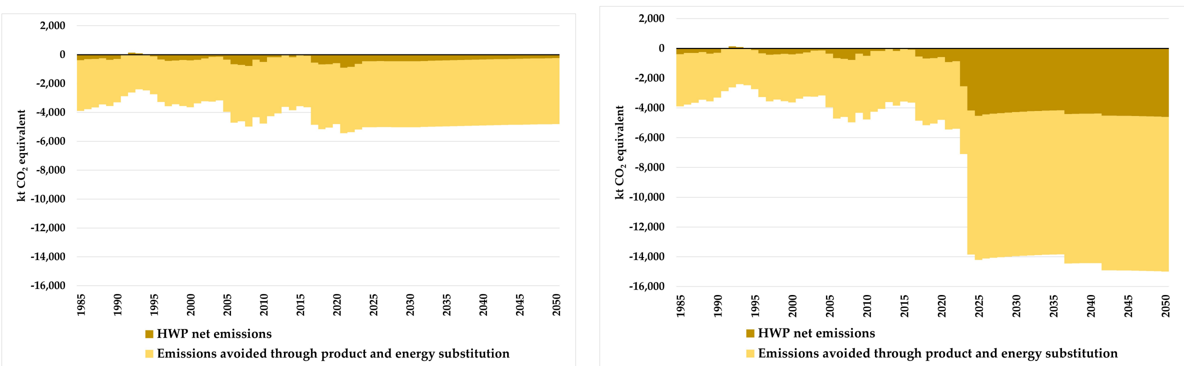

Fig. 5 Historic and projected net emissions of the HWP pool and avoided emissions under a) the BAU scenario, b) the Intensification scenario.

According to Hurmekoski et al. (2021) the quantification of the potential impact of large-scale material substitution at the market level remains challenging and is subject to assumptions and system boundary considerations. To get a more reliable estimate on the substitution effects in the Hungarian forest industry country-specific substitution factors should be derived from related life cycle assessments. The studies of Polgár (Polgár 2023, Polgár et al. 2023) can be a basis for the development of country-specific substitution factors, however further research is also needed in the field of product substitution in Hungary.

Myllyviita et al. (2021) emphasize that substitution factors including only fossil emissions should be applied together with a coherent assessment of changes in forest and HWP carbon stocks. Thus, in order to get a comprehensive overall picture on the impacts of different forest industry-related climate change mitigation strategies it is essential to assess the net removals of the wood industry together with the carbon balance of Forest Lands. In the framework of the ForestLab project, we are planning to model the joint impact of climate change mitigation measures using the HWP-RIAL model and the DAS forest model (Kottek 2017, Kottek et al. 2023) to project substitution effects and net emissions arising from Hungarian forests and wood products up to 2050.

CONCLUSIONS

In our study we assessed the climate change mitigation potential of the Hungarian wood industry which is realised by carbon storage in wood products and avoided emissions through product and energy substitution. According to our results the net removals of the Hungarian HWP pool can be significantly increased by increasing industrial roundwood removal, increasing industrial wood assortments and processing all timber domestically.

ACKNOWLEDGMENTS

This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

REFERENCES

1. BOROVICS A. – MERTL T. – KIRÁLY É. – KOTTEK P. (2023): Estimation of the overmature wood stock and the projection of the maximum wood mobilization potential up to 2100 in Hungary. Forests 14(8):1516.
2. BOROVICS A. (2022): ErdőLab: a Soproni Egyetem erdészeti és faipari projektje: Fókuszban az éghajlatváltozás mérséklése (ErdőLab: forestry and wood industry project of the University of Sopron: Focus on mitigating climate change). Erdészeti Lapok 157: 4 pp. 114–115.
3. BRUNET-NAVARRO P. – JOCHHEIM H. – KROIHER F. – MUYS B. (2018): Effect of cascade use on the carbon balance of the German and European wood sectors. Journal of Cleaner Production. 170, 137-146.
4. BRUNET-NAVARRO P. – JOCHHEIM H. – MUYS B. (2016): Modelling carbon stocks and fluxes in the wood product sector: a comparative review. Global Change Biology. 22, 2555-2569.
5. FORTIN M. – NINGRE F. – ROBERT N. – MOTHE F. (2012): Quantifying the impact of forest management on the carbon balance of the forest wood product chain: a case study applied to even-aged oak stands in France. Forest Ecology and Management. 279, 176-188.

6. GENG A. – YANG H. – CHEN J. – HONG Y. (2017): Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. Forest Policy and Economics. 85:192–200.
7. HÄRTL F.H. – HÖLLERL S. – KNOKE T. (2017): A new way of carbon accounting emphasises the crucial role of sustainable timber use for successful carbon mitigation strategies. Mitigation and Adaptation Strategies for Global Change. 22(8):1163–1192.
8. HELIN T. – SOKKA L. – SOIMAKALLIO S. – PINGOUD K. – PAJULA T. (2013): Approaches for inclusion of forest carbon cycle in life cycle assessment–a review. GCB Bioenergy 5(5):475–486.
9. HURMEKOSKI E. – SMYTH C.E. – STERN T. – VERKERK P.J. – ASADA R. (2021): Substitution impacts of wood use at the market level: a systematic review. Environmental Research Letters, Volume 16, Number 12.
10. IPCC (2006): IPCC Guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).
11. IPCC (2013): Revised supplementary methods and good practice guidance arising from the Kyoto protocol. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Pp. 268.
12. IPCC (2019): Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A.; Baasansuren, J.; Fukuda, M.; Ngarize, S.; Osako, A.; Pyrozhenko, Y.; Shermanau, P. and Federici, S. (eds).
13. KIRÁLY É. – BÖRCSÖK Z. – KOCSIS Z. – NÉMETH G. – POLGÁR A. – BOROVICS A. (2022): Carbon sequestration in harvested wood products in Hungary an estimation based on the IPCC 2019 refinement. Forests. 13(11):1809.
14. KIRÁLY É. – BÖRCSÖK Z. – KOCSIS Z. – NÉMETH G. – POLGÁR A. – BOROVICS A. (2023b). A new model for predicting carbon storage dynamics and emissions related to the waste management of wood products: introduction of the HWP-RIAL model. Acta Agraria Debreceniensis, 1, 75-81.
15. KIRÁLY É. – KIS-KOVÁCS G. – BÖRCSÖK Z. – KOCSIS Z. – NÉMETH G. – POLGÁR A. – BOROVICS A. (2023a): Modelling carbon storage dynamics of wood products with the HWP-RIAL model—projection of particleboard end-of-life emissions under different climate mitigation measures. Sustainability 15(7):6322.
16. KNAUF M. – JOOSTEN R. – FRÜHWALD A. (2016): Assessing fossil fuel substitution through wood use based on long-term simulations. Carbon Management. 7(1-2):67–77.
17. KNAUF M. – KÖHL M. – MUES V. – OLSCHOFSKY K. – FRÜHWALD A. (2015): Modeling the CO_2-effects of forest management and wood usage on a regional basis. Carbon Balance and Management. 10(1):13.
18. KOTTEK P. – KIRÁLY É. – MERTL T. – BOROVICS A. (2023b): The re-parametrization of the DAS model based on 2016-2021 data of the national forestry database: New results on cutting age distributions. Acta Silvatica & Lignaria Hungarica. 19(2), 61–74.
19. KOTTEK P. (2017): National Forest Projection–2050; University of Sopron, Faculty of Forestry, VI. Faculty Scientific Conference Book of Abstracts; Bidló, A., Facskó, F., Eds.; Publishing Office of the University of Sopron: Sopron, Hungary, 59 p.

20. KRANKINA O.N. – HARMON M.E. – SCHNEKENBURGER F. – SIERRA C.A. (2012): Carbon balance on federal forest lands of Western Oregon and Washington: the impact of the Northwest forest plan. Forest Ecology and Management 286, 171-182.
21. LESKINEN P. – CARDELLINI G. – GONZÁLEZ-GARCÍA S. – HURMEKOSKI E. – SATHRE R. – SEPPÄLÄ J. – SMYTH C. – STERN T. – VERKERK P.J. (2018): Substitution effects of wood-based products in climate change mitigation. From Science to Policy 7. European Forest Institute. Pp. 28.
22. MYLLYVIITA T. – SOIMAKALLIO S. – JUDL J. ET AL. (2021): Wood substitution potential in greenhouse gas emission reduction–review on current state and application of displacement factors. Forest Ecosystems. 8, 42.
23. NÉMETH G. (2012): Fafeldolgozási hulladékok kezelése, felhasználhatósága (Management and usability of wood processing waste). University of West Hungary Press, Sopron, 160 p.
24. NIR (2023): National Inventory Report for 1985–2021. Hungary. Chapter: Land-Use, Land-Use Change and Forestry; Somogyi, Z., Tobisch, T., Király É., Hungarian Meteorological Service: Budapest, Hungary, 486 p.
25. PAROBEK J. – PALUŠ H. – MORAVČÍK M. – KOVALČÍK M. – DZIAN M. – MURGAŠ V. – ŠIMO-SVRČEK S. (2019): Changes in carbon balance of harvested wood products resulting from different wood utilization scenarios. Forests. 10(7):590.
26. POLGÁR A. (2023): Carbon footprint and sustainability assessment of wood utilisation in Hungary. Environment Development and Sustainability. https://doi.org/10.1007/s10668-023-03571-9.
27. POLGÁR A. – SZAKÁLOSNÉ MÁTYÁS K. – HORVÁTH A.L. – KOVÁCS Z. – VITYI A. – VÁGVÖLGYI A. – KOCSIS Z. – KIRÁLY É. – BIDLÓ A. – BÖRCSÖK Z. ET AL. (2023): Életciklus elemzés. A faalapú biomassza energetikai célú felhasználásának szénlábnyoma és modellje, tűzifával való égetés CO_2-lábnyom elemzése. Sopron, Hungary, 104 p.
28. RÜTER S. (2016): Der Beitrag der stofflichen Nutzung von Holz zum Klimaschutz; Das Modell WoodCarbonMonitor. Technische Universität München, Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt Holzforschung München, Lehrstuhl für Holzwissenschaft. München, 270 p.
29. SCHELHAAS M.J. – ESCH P.W. – GROEN T.A. – JONG B.H.J. – KANNINEN M. – LISKI J. – MASERA O. – MOHREN G.M.J. – NABUURS G.J. – PALOSUO T. – PEDRONI L. – VALLEJO A. – VILEN T. (2004): CO2FIX V 3.1-A modelling framework for quantifying carbon sequestration in forest ecosystems. In: Alterra. ALTERRA, Wageningen, Netherlands, 122 p.
30. SCHWEINLE J. – KÖTHKE M. – ENGLERT H. – DIETER M. (2018): Simulation of forest-based carbon balances for Germany: a contribution to the ‘carbon debt’ debate. WIREs Energy Environ 7(1): e260.
31. VERKERK P.J. – DELACOTE P. – HURMEKOSKI E. – KUNTTU J. – MATTHEWS R. – MÄKIPÄÄ R. – MOSLEY F. – PERUGINI L. – REYER C. P. O. – ROE S. – TRØMBORG E. (2022): Forest-based climate change mitigation and adaptation in Europe. From Science to Policy 14. European Forest Institute. Joensuu, Finland. Pp. 76.

ÉVA KIRÁLY*, ATTILA BOROVICS
UNIVERSITY OF SOPRON
FOREST RESEARCH INSTITUTE
VÁRKERÜLET 30/A, H-9600 SÁRVÁR
HUNGARY
*Corresponding author: kiraly.eva.ilona@uni-sopron.hu

ZOLTÁN BÖRCSÖK, ZOLTÁN KOCSIS, GÁBOR NÉMETH
UNIVERSITY OF SOPRON
FACULTY OF WOOD ENGINEERING AND CREATIVE INDUSTRIES
BAJCSY-ZSILINSZKY STR. 4, H-9400 SOPRON
HUNGARY

ANDRÁS POLGÁR
UNIVERSITY OF SOPRON
FACULTY OF FORESTRY
BAJCSY-ZSILINSZKY STR. 4, H-9400 SOPRON
HUNGARY