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Changes in Carbon Balance of Harvested Wood Products Resulting from Different Wood Utilization Scenarios

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Abstract: The bioeconomy focuses on the production of renewable biological resources and the utilisation of these resources and waste streams into value added products. One of the most important aims of the forest industry is the sustainable production of wood. Improved utilization of available industrial wood assortments generates profit for all in the supply chain. At the same time, it may ensure the production of long-life harvested wood products (HWP), and consequently, increase the volume of carbon stored. The objective of this study is to compare different scenarios of industrial wood utilization in Slovakia and the resulting impacts on the national carbon balance. In the proposed scenarios, we aimed to evaluate changes in the current utilization of domestic wood resources through optimizing harvested wood assortments. Two inventory stock methods were applied to determine the potential quality of domestic wood and its utilization through appropriate distribution of outputs. The model scenario assumes that the higher share of industrial roundwood utilised to produce long-life HWP (sawnwood, wood-based panels) will increase carbon sequestration in HWP. Other scenarios quantify the differences between the carbon volumes stored in HWP using the modelled wood assortment supplemented with alternatives with and without export. The results confirmed that increasing the level of carbon stored in HWP can be achieved by changing the wood assortment structure, while maintaining the same level of volume felled. The highest level of carbon stock was observed in the scenario assuming the optimal structure of wood assortments and no wood export. The scenario that optimized wood assortments and excluded wood exports resulted in the highest level of predicted carbon stock, estimated at 4.87 million tons (mil. tons).

Keywords: bioeconomy; wood utilization; harvested wood products; carbon storage; CO_2 emission

1. Introduction

The bioeconomy is a key part of the solution to many of societies environmental challenges. According to Bugge et al. [1], there seems to be little consensus concerning what bioeconomy actually implies. The idea of bioeconomy deals with the production of renewable biological resources and the conversion of these resources and waste streams into value added products. Bugge et al. [1] further argue that it is possible to distinguish between three ideal visions of bioeconomy, biotechnology, bioresource, and a bioecology vision. The bioeconomy is an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources [2]. We can observe shifts from a fossil-based economy to a biomass-based economy, resulting from significant changes in the world economy. It is expected that the bioeconomy will play an important role in the low carbon economy [3]. Recently, integration of the bioeconomy strategy to national economies have developed.

In general, the main goal of the bioeconomy is to conduct the various production and consumption activities in a sustainable way. Some economic sectors traditionally use biological resources and processes, e.g., forestry, agriculture, food industry as well as the wood, paper, textiles and chemical. One option to promote sustainable development is to optimize the utilization of renewable resources in these sectors. In this context, the EU is the worldwide leader in terms of renewable utilization per capita [4,5].

The forest-based sector represents one of the most important parts of the European bioeconomy sector and positively affects atmospheric carbon balance. According to Kazulis et al. [6], air pollution monitoring readings across the globe rose at the highest rate on record in 2015 and 2016. Fossil resources used for energy have been the primary cause of the accumulation and increase of CO_2 in the atmosphere. If biomass resources were used as energy sources the amount of CO_2 in the atmosphere would increase. However, the total amount of carbon in the atmosphere would remain the same, because the carbon burned from the biomass can be brought back to Earth. The impacts of wood utilization for a bioeconomy have been described by many current European authors [7–10]. Harvested wood products (HWP) have many economic and environmental advantages over other alternatives. The increasing competitiveness of wood over other materials is notable when climate change impacts are considered. Carbon storage in HWP can be seen as a measure to mitigate climate change. By nature, wood is composed of carbon that is captured from the atmosphere during tree growth and the production of wood products requires less fossil fuel than substitute materials. These two effects - sequestration and substitution determine why the carbon impact of wood products is favourable from the bioeconomic point of view.

Carbon accounting models are a common tool for estimating, as well as, projecting carbon pools. After 2012, the research focused on the carbon sequestration in HWP reflected a new general accounting framework under the Kyoto Protocol [11]. This approach provides supplementary methods and good practice for estimating anthropogenic greenhouse gas (GHG) emissions by sources and removals by sinks resulting from land use, land-use change and forestry. Moreover, national carbon pools of HWPs are very dynamic, due to changing patterns of wood product consumption and trade [7]. Sikkema et al. [12] made a comparison between the cascaded use of HWP and the use of wood for energy. He considered different scenarios of wood utilization in the construction sector, paper products and pellets for power production. The results conclude that GHG emissions of all scenarios are substantially lower than the IPCC (Intergovernmental Panel on Climate Change) default. This research also confirmed the need for further investigations on an individual country basis. Sathre and Gustavsson [13] evaluated the energy and carbon balances of various cascade chains for recovered wood. They found that land use effects have the significant impact on energy and carbon balances, followed by substitution effects, while direct cascade effects are relatively minor. The carbon sequestration of HWP also plays an important role in climate mitigation.

Wood, as a building material in the construction sector, has a particular advantage in climate mitigation, due to the ability to bond carbon longer. Bergman [14] analysed savings of GHG emissions for wood products by comparing net wood product carbon emissions from the forest minus carbon storage over product use life with carbon emissions for substitute (non-wood) products. The results show notable carbon emissions savings when wood products are used in constructing buildings in place of non-wood alternatives. To some extent, the limited sources of non-renewable materials, growing environmental awareness and demand for wood could exceed its sustainable supply [15]. Recently, the idea of energy and carbon balances of wood supply chains has been frequently emphasised in climate mitigation [16–19].

Apart from the fact that there are several approaches and methods that may be used to analyse the contribution of HWP in terms of GHG emissions and removals at a national level, the results depend heavily on the availability, and aggregation, of input data. Several studies (e.g., [8,20–22]) use country-specific data and results of the national material flow analysis to cover only the domestic harvest and the primary and secondary wood products manufactured within the country. In some cases, unregistered data can also reveal and quantify material flows (e.g., waste streams) that could be evaluated in the analysis [23,24]. A documented increase of carbon storage might bring additional credits to reporting countries, and, more importantly, it could promote the use of long-life HWPs to mitigate climate change [22].

In Slovakia, there are very few studies focused on carbon balance in HWP. Raši et al. [25] concluded that the total amount of carbon stored in HWP in Slovakia have had an increasing trend in the latest five years and reached a volume of almost 15 Tg. The preliminary results of the production potential of wood in relation to its utilization were published by Moravčík et al. [26]. His variant models were based on the proposed changes of wood utilization to the current state resulting from the analysis of the factors affecting wood flows.

This study aims to compare different wood utilization scenarios in order to determine the impacts of different HWP output on the carbon balance at a national level. The current situation is represented by the scenario, which considers the actual structure of domestic wood supply assortments and actual level of foreign trade in industrial roundwood. On the other side, the model scenarios assume that the higher share of industrial roundwood will be utilised to produce long-life HWP (sawnwood, wood-based panels) that would increase carbon sequestration in HWP.

2. Materials and Methods

The methodological approach consisted of several phases involving scenario determination. The first included scenario framing and calculation of wood production data. Phases also included collection and processing of forest output production and trade data. Finally, a calculation of carbon emissions and removals from HWP is calculated.

2.1. Scenarios and Calculation of Input Production Data

In order to examine the effect of different wood utilization methods on the carbon emissions and removals from HWP scenarios considered (i) the production potential of forests and (ii) the utilization of domestic wood production.

Mathematical models were developed using domestic assortment tables to predict the volume of growing stock as a function of the tree diameter (d1,3), height (h) and stem quality (A—high, B, and C—below average). [27–29] The following species were included in the mathematical models: Beech, spruce, oak, hornbeam, pine, birch, fir, and spruce. Other tree species have been assigned to the mentioned trees in view of their similarity. The actual growing stock was derived from the following two information sources: (i) Summary information on forests (SIF)—annually updated within the Forest Management Information System governed by the National Forest Centre, and (ii) National Forest Inventory and Monitoring (NFIM) of the Slovak Republic. SIF represents information and data on the state and development of the forests that are obtained through describing forest stands as part of a detailed forest survey within the creation of forest management plans (FMP). The description is carried out for each forest stand separately (area, partial area, forest stand group) on forest land, using predetermined methods, with a significant predominance of the growth table method and ocular estimation. The obtained data serves to draw up the plan of management measures within the FMP. The data collection interval is generally 10 years, which complies with the validity period of FMP [30]. NFIM SR corresponds to the current national needs and it is in line with the general tendencies of a comprehensive survey of forest state and development in other countries. The first inventory cycle took place in 2005 and 2006; the second in 2015 and 2016 on the same network. The results of the sample survey are presented with a known degree of statistical accuracy or selection error, respectively. NFIM SR provides objective information on the state of the forests at the national level and in selected regions and the actual dynamics of changes during the last ten years. This information is particularly important in the current circumstances, when the condition of the forest is changing at an unprecedented rate due to climate change and a high proportion of accidental felling caused by harmful agents [31]. In this sense, accidental felling means felling occurred due to natural disturbance mostly caused by insects and windthrow.

Scenario S0, referred to as a basic model, considered the actual structure of timber assortments and actual level of foreign trade in industrial roundwood (thus reflecting current processing in the domestic forest-based sector). Scenario S1 incorporated the modelled structure of wood assortments and actual level of foreign trade. The next scenario S2 assumed the actual structure of wood assortments and domestic wood consumption at the level of domestic production (without foreign trade) and scenario S3 considered the modelled structure of wood assortments and domestic wood consumption.

Based on these two methods, the total growing stock in Slovakia was classified into the categories of timber quality grades as defined by the Slovak Technical Standards for classification of softwood and hardwood round timber [32,33] as follows: (a) Logs of grades I., II. (veneer logs), IIIA. and IIIB. (sawlogs), (b) other industrial roundwood (IV. grade), (c) pulpwood (V. grade), (d) energy and fuelwood (VI. grade) and e) waste (Tables 1 and 2). For the purposes of this analysis, the pulpwood category also incorporated the category of other industrial roundwood (due to its insignificant production volume).

Table 1. Model distribution of coniferous growing stock by quality grades of timber assortments.

Inventory Method	Quality Grade						
	I	II	IIIA	IIIB	IV+V	VI	Waste
	%						
SIF	2.27	5.07	43.49	26.53	20.85	1.76	0.02
			Total III: 70.02				
NFIM	3.0 ± 0.6	4.6 ± 0.6	40.1 ± 2.6	29.1 ± 1.9	21.3 ± 1.1	1.8 ± 0.1	0.1 ± 0.0
			Total III: 69.2				

Table 2. Model distribution of broadleaved growing stock by quality grades of timber assortments.

Inventory Method	Quality Grade						
	I	II	IIIA	IIIB	IV+V	VI	Waste
	%						
SIF	1.73	7.64	19.39	25.67	40.46	5.02	0.10
			Total III: 45.06				
NFIM	1.8 ± 0.3	6.1 ± 0.5	15.1 ± 0.9	25.9 ± 1.4	43.5 ± 1.6	7.3 ± 0.9	0.2 ± 0.0
			Total III: 41				

In order to determine the volumes of the available production potential for the scenarios the shares of model distribution of quality grades in the forests in Slovakia were compared with their real shares in wood supply in 2017.

2.2. Production and Trade Data

Input data on the production of, and trade in, wood products used in the model to estimate carbon emissions and removals from harvested wood products in Slovakia were acquired from the public Forestry Production and Trade database of the Food and Agriculture Organization of the United Nations [34]. In particular, FAO data on production, import and export quantities of sawnwood (coniferous/non-coniferous), wood-based panels, paper and paperboard, industrial roundwood (coniferous/non-coniferous) and wood pulp were obtained for the period 1989–2017. Due to the fact that the data for Slovakia and Czechia were aggregated before the splitting of Czechoslovakia in 1993 the shares of Slovakia and Czechia on each HWP category in the period 1989–1992 had to be additionally calculated by multiplying the Czechoslovakia figures by an average country specific share on the sum of figures for both countries in the period of five years 1993–1997. The proposed method was published earlier by Cienciala and Palán [35]. Table 3 shows the share of Slovakia on each HWP category in the period 1993–1997.

Table 3. The share of Slovakia on harvested wood products categories in the period 1993–1997.

HWP Category	FAO Code	Production	Import	Export
Sawnwood	1872	0.166	0.132	0.277
Coniferous sawnwood	1632	0.122	0.114	0.219
Non-coniferous sawnwood	1633	0.467	0.169	0.808
Wood-based panels	1873	0.284	0.281	0.149
Paper and paperboard	1876	0.345	0.228	0.402
Industrial roundwood	1865	0.295	0.196	0.245
Coniferous industrial roundwood	1866	0.223	0.036	0.190
Non-coniferous industrial roundwood	1867	0.650	0.405	0.475
Pulp wood	1875	0.316	0.118	0.159

2.3. Calculation of Carbon Emissions and Removals from Harvested Wood Products

In order to account for the HWP contribution from forest management (FM) activities a spreadsheet model within Microsoft Excel was created. Carbon accounting in the HWP pool followed the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* [36] based on three aggregate commodities of semi-finished wood products, i.e., sawnwood, wood-based panels, paper, and paperboard. We applied the default first order decay (FOD) method provided by the Intergovernmental Panel on Climate Change (IPCC)–Tier 2 method. More detailed information regarding the FOD method is provided by Pingoud and Wagner [37]. It is assumed that all HWP are derived from domestic harvest under FM activities. The Tier 2 method was considered as scenario S0.

To estimate the carbon stock and the annual changes for each of the HWP categories: Sawnwood (coniferous/non-coniferous), wood-based panels, paper and paperboard we used the following FOD function with default half-lives of 35, 25 and two years, respectively ([36], Equation 2.8.5):

$$C_{i+1} = e^{-k} \times C_i + \left[\frac{1-e^{-k}}{k}\right] \times Inflow_i \tag{1}$$

$$\Delta C_i = C_{i+1} - C_i \tag{2}$$

where:

I—year
C_i—the carbon stock in the particular HWP category at the beginning of year *i*, Gg C
K—decay constant of FOD for each HWP category (HWPj) given in units year^{-1} (*k* = ln(2)/HL, where HL is the half-life of the HWP pool in years
Inflow_i—the inflow to the particular HWP category (HWPj) during year i, Gg C yr^{-1}
ΔC_i—carbon stock change of the HWP category during year i, Gg C yearr^{-1}

According to the Tier 2 method, the initial carbon stock in the HWP pool at $t = t_0$ was estimated by means of Equation (2) ([36], Equation 2.8.6):

$$C(t_0) = \frac{Inflow_{average}}{k} \tag{3}$$

$$Inflow_{average} = \sum_{i=t_0}^{t=4} Inflow_i/5 \tag{4}$$

In addition, the estimates of the HWP carbon pool by means of Equation (1) starts with *i* = 1990 and C(1990) = 0.

For the conversion of wood volume or weight into carbon the default conversion factors and half-lives stipulated by IPCC shown in Table 4 were used.

Table 4. Carbon conversion factors and half-lives used in modelling.

HWP Categories	C Conversion Factor	Half-Life
	[Mg C·m^{-3}]	[years]
Sawnwood	0.229	35
Coniferous sawnwood	0.225	35
Non-coniferous sawnwood	0.280	35
Wood-based panels	0.269	25
	[Mg C·Mg^{-1}]	
Paper and paperboard	0.386	2

The carbon stock change is then converted into Gg CO_2 year^{-1} by multiplying by −44/12. Resulting values of annual changes in carbon stocks and associated CO_2 emissions and removals from the HWP pool were calculated separately for each defined scenario thus allowing us to evaluate the effect of different ways of wood potential utilization on carbon balance in HWP.

3. Results

3.1. Analyses of the Production Potential and Its Utilization

The Slovak Republic is among the most forested countries in Europe. Forests, as one of the most important sources of renewable materials, cover more than 45% (including forests on non-forest land) of total land area in the country. According to NFIM 2015–2016 [31], the total volume of growing stock in forests was about 628 million m^3 (mil. m^3), out of which 583 mil. m^3 were on forest land. Alternatively, according to SIF the volume of growing stock was estimated at 480 mil. m^3 just on forest land. The current growth increment has reached about 12 mil. m^3 annually, resulting in an increase in the volume of growing stock by 8.3% (mostly non-coniferous species) during the last ten years and the average volume of growing stock per hectare was about 248 m^3.

Several factors contribute to the current state and development of forests in Slovakia. First, the permanent increase in the planned felling volume can mainly be attributed to the significant increase in the total growth increment. Second, a significant increase in the share of accidental felling. Third, changes in the tree species composition within the forests. In Slovakia, the total supply of roundwood was 9.36 mil. m^3 in 2017, of which domestic wood supplies were about nine mil. m^3. The sale of wood is the most important source of earnings and it provides approximately 80% of the revenues in the forestry sector [38]. Shares of real and modelled quality grades were calculated to determine the differences amongst utilization of the available production potential (Table 5).

Table 5. Comparison of the actual and model shares of quality grades.

Indicator		Coniferous			Non-Coniferous		
		Actual	Model	Difference	Actual	Model	Difference
Share of quality grades (%)	I	0.12	2.64	−2.52	0.14	1.77	−1.63
	II	0.12	4.84	−4.72	0.61	6.89	−6.28
	III	60.16	69.66	−9.50	37.52	43.11	−5.59
	IV+V	33.84	21.08	12.76	54.62	42.05	12.57
	VI	5.76	1.78	3.98	7.11	6.18	0.93

It follows from the table, that the potentially available share of high quality log grades (I., II. and III.) is higher compared to the real sales of these assortments, both for coniferous and non-coniferous species. On the other hand, more wood is sold as lower quality pulpwood (grades V. and VI.) compared to the modelled potential. There are also significant differences between particular quality grades and wood species categories. Coniferous wood is mainly represented by sawlogs (III. quality grades) accounting for almost 70% of the standing volume and more than 60% share on the actual wood supply resulting in a negative difference of 9.5%. Similar negative differences between the real supplies and potential standing volume structure were observed for non-coniferous high quality veneer logs and sawlogs of II. and III. quality grades (about 6% each). Obviously, these differences are consequently reflected in a higher share of pulpwood (quality grade IV. and V.) in the wood supplies compared its potential representation in the forest (12.6%).

This analysis reveals that there are differences in the potential structure of assortments and actual utilization of this available potential. For both coniferous and non-coniferous wood, it is apparent that available potential of high quality veneer logs and sawlogs is higher compared to the supplied volumes, in particular by 16.7% for coniferous and 13.5% for non-coniferous wood, respectively.

3.2. Estimation of Carbon Stocks and Annual Carbon Stock Changes in Harvested Wood Products

This analysis evaluates the annual changes of the carbon stock in HWP within the domestic consumption and allows for its comparison with defined theoretical models. The differences between gains and losses of CO_2 from domestically produced and used HWP for the period 1990–2017 (Tier 2 method) are shown in Figure 1 (S0 scenario). In the depicted figure the positive values represent the greenhouse gas emissions; the negative values represent the removals of carbon from the atmosphere. All values are expressed in Gg CO_2.year^{-1}.

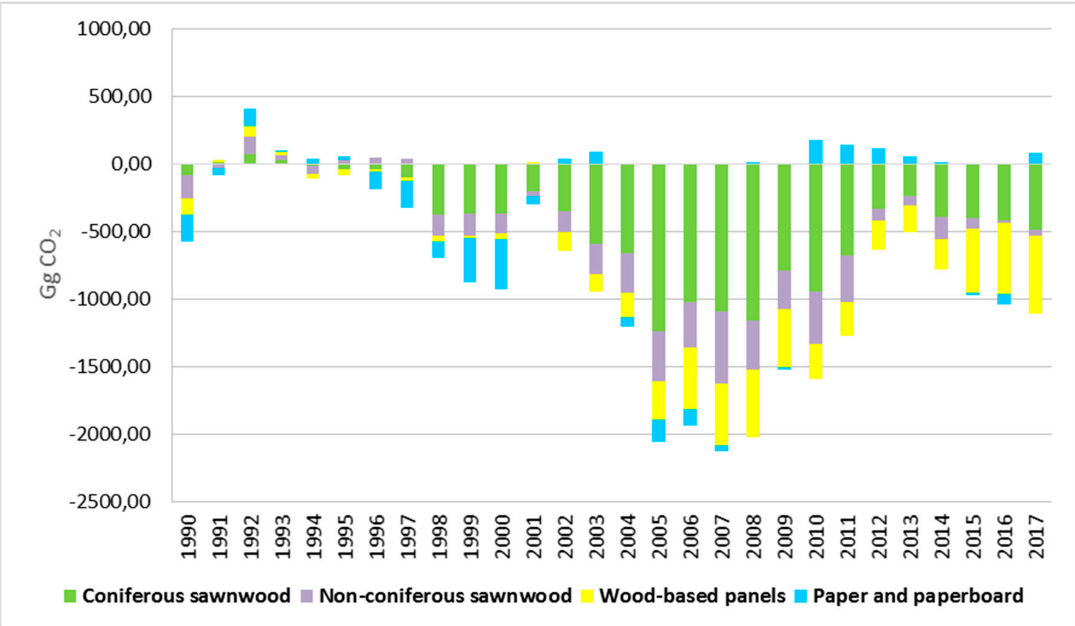

Figure 1. The balance of CO_2 from domestically used harvested wood products (S0 scenario). Note: Positive values indicate CO_2 emissions released into the atmosphere from consumed wood products. Negative values indicate amount of CO_2 stored in harvested wood products.

Over the entire examined period (except from 1992 and 1993), the amount of CO_2 stored in HWP exceeded the CO_2 emissions released into the atmosphere from consumed wood products. The opposite trend in carbon bonding in HWP could occur if the volume of wood products was reduced, by increasing the share of short-life products.

Carbon stock (CO_2 released into the atmosphere with a delay has negative values in the balance sheet) as well as emission volumes (CO_2 released into the atmosphere from consumed wood products have positive values in the balance) for particular HWP categories in 2017 are calculated for respective scenarios (Table 6).

Table 6. Different scenarios of the balance of CO_2 from domestically used harvested wood products in 2017.

		Coniferous Sawnwood	Non-Coniferous Sawnwood	Wood-Based Panels	Paper and Paperboard	Total [1]
S0	Carbon stocks	−1034,18	−375,39	−1003,09	−684,25	3096,91
	Emissions	549,6	325,68	427,37	768,56	2071,21
	Annual change	−484,58	−49,71	−575,72	84,31	1025,71
S1	Carbon stocks	−1373,89	−640,91	−1057,43	−519,68	−3591,9
	Emissions	552,94	328,29	428,12	743,07	2052,42
	Annual change	−820,95	−312,61	−629,31	223,39	1539,48
S2	Carbon stocks	−1508,86	−422,61	−1325,76	−713,42	3970,65
	Emissions	554,27	326,15	431,8	773,08	2085,29
	Annual change	−954,59	−96,47	−893,96	59,65	1885,36
S3	Carbon stocks	−2002,81	−721,54	−1610,52	−537,09	4871,95
	Emissions	559,13	329,09	435,71	745,76	2069,69
	Annual change	−1443,68	−392,45	−1174,81	208,68	2802,26

[1] thousand metric tons of CO_2 equivalent.

Scenario S0 considers the actual structure of domestic wood supply assortments and actual level of foreign trade in industrial roundwood (thus reflecting the actual processing capacities of domestic forest industry). In 2017, the domestic wood supply was about 8.72 mil. m^3, of which coniferous logs (3.33 mil. m^3) and non-coniferous pulpwood (2.09 mil. m^3) accounted for over 62%. In spite of the fact, that additional, 1.23 mil. m^3 of coniferous logs were exported, the sawmilling industry, as the key wood processing sector, produced approximately 1.3 mil. m^3 of coniferous sawnwood, followed by the production of paper (0.73 mil. tons). From scenario S0, as the real basic model, it was estimated that approximately 3.10 mil. tons of CO_2 were stored in HWP, but at the same time 2.07 mil. tons of CO_2 were emitted to the atmosphere from consumption of HWP in 2017. The overall balance was positive because the volume of CO_2 stored in HWP was increased by 1.03 mil. tons.

Scenario S1 incorporated the modelled structure of assortments and the actual level of foreign trade. The model assumes the optimal utilization of wood potential in the forests (larger share of higher quality grades), while maintaining the total volume of domestic wood supply. The analysis assumes the increase in the production of coniferous logs to more than 3.79 mil. m^3 and non-coniferous logs to about 2.10 mil. m^3. On the other side, the production of pulpwood (both coniferous and non-coniferous) decreased relative to the scenario S0 level and was about 2.74 mil. m^3. These changes in the composition of roundwood quality grades were reflected in the volumes of production of HWP, as the production of coniferous sawnwood increased to 1.74 mil. m^3 and production of paper decreased to 0.62 mil. tons. These changes would have an impact on the carbon sequestration in HWP. For the S1 scenario, HWP were able store more than 3.59 mil. tons of CO_2 and consumption of HWP emits 2.05 mil. tons of CO_2. Following these calculations, the overall carbon balance is almost 1.54 mil. tons.

The next scenario S2 assumed utilization of the actual structure of timber assortments and excluded the foreign trade. In this case, the volume of supplied I.–III. quality grade logs increased to 4.8 mil. m^3 and the volume of pulpwood to 3.9 mil. m^3. Utilising these available volumes would result in the enhanced production of HWP, when the production of sawnwood would increase to 2.45 mil. m^3 and production of paper to 0.64 mil. tons. The utilization of domestic resources in this manner would have a positive impact on the carbon sequestration in HWP, when HWP would be able to store more than 3.97 mil. tons of CO_2 and consumption of HWP would emit 2.08 mil. tons of CO_2. At the same time, the carbon balance would be almost 1.89 mil. tons.

The last scenario S3 could be considered as the most appropriate model from the viewpoint of effective utilization of domestic wood resources, i.e., based on the maximization of wood quality as well as the volume of domestic resources. This theoretical model assumes the modelled structure of timber assortments and timber consumption at the level of domestic wood production. If this option was undertaken the production of logs would increase to almost 5.9 mil. m^3 and production of pulpwood to more than 2.7 mil. m^3. In this case, the production of sawnwood would reach the theoretical maximum to 3.3 mil. m^3. However, the production of paper would decrease to 0.55 mil. tons (mostly due to the elimination of imported pulpwood). Such an optimal utilization of domestic resources would be reflected in a higher production of the long-term HWP, which would have a positive influence on the carbon sequestration. HWP would be able to store more than 4.87 mil. tons of CO_2, while emission would be only 2.07 mil. tons of CO_2. Such a model occurs as the most efficient from the carbon balance point of view (2.8 mil. tons).

It follows from the results that all the three model scenarios (S1–S3) result in more favourable balances in comparison to the basic scenario S0. These gains are obtained either from the foreign trade exclusion and along with the growth of material inflow entering the production of HWP with higher added value and longer lifetime (S2 and S3 model).

4. Discussion

Rather than study the effects of different IPCC modelling methods on the carbon stock level, this study aims to estimate the effect of better utilization of available wood resources on the level of carbon stored in HWP. In this study, the significant positive results are achieved without intensifying roundwood production and findings show that changes in wood assortments can positively influence the carbon pool in HWP. In some other studies (e.g., [7]) the level of carbon stock in HWP is resulting from either an increased production of industrial roundwood or changed structure of HWP considering a higher proportion of the long-life HWP (sawnwood, wood-based panels, and cross laminated timber). In particular, ours deals with the comparison of the actual wood assortments structure and its utilization by the domestic wood processing industry in Slovakia, with the modelled situations assuming both the optimal use of available wood quality grades and the possibility of a domestic market to consume wood from domestic resources only.

The current state and development of forests in Slovakia are determined by a gradual increase of planned, and permanently higher total annual, felling volumes. Naturally, there are some underlying factors affecting this situation. First of all, currently there is an uneven age composition of forest stands with the prevailing standing volumes in matured and overmatured [38] age classes and, secondly, there is a high volume of incidental felling, mainly in coniferous forests. Both factors are interrelated and have a direct negative impact on the resulting quality mix of produced and supplied wood assortments.

With over 30% share of beech forests, the wood quality is declining with trees aging over the rotation period [38]. At the same time, natural disturbances such as windthrown and bark beetle damages directly decrease the quality of raw wood material.

Taking into account the requirements of sustainable forest management, the increased volumes of accidental felling have an impact on postponing other planned felling, which may lead to further aging of already matured forest stands. This has an effect on the existing wood material flows (material and waste), as well as, changing structure of HWP production [23]. Moreover, increasing felling volumes in the latest years are reflected in an increasing trend of the total amount of carbon stored in the HWP in Slovakia [25]. It is, however, expected that in the future the volume of coniferous wood supply will be gradually decreasing [39] that may have a negative impact on the carbon sequestration in HWP.

Calculations of the model distribution of wood quality grades in the forest in Slovakia are based on the results of two different methods (SIF and NFIM). These results were compared with the real shares of quality grades supplied to the market. It follows from the analysis that the potential of high-quality grades, especially veneer and sawlogs of I.–III. quality classes is higher compared to their use. If this potential was utilized, for non-coniferous industrial wood, there would be an increase in the volume of logs by almost 924,000 m^3 and for coniferous logs by 704,000 m^3 at the expense of the pulpwood category. Petráš and Paluš [40] state that this potential from domestic resources can be efficiently utilized only if there were sufficient wood processing capacities available. Taking into account the average price of wood assortments in 2017 [41] the income generated by these shifts would result in additional 35.83 mil. EUR and 94.99 mil. EUR in the case of coniferous and non-coniferous wood, respectively. The key reasons for these differences are manifold. In addition to those mentioned above, windthrown wood, as well as, the structure and production capacities of the domestic wood processing industry which is not able to able to efficiently (effectively) distribute (utilize) the available wood outputs. The wood processing industry has the sufficient production capacities to process the whole volume of coniferous wood, however, currently only 40% of these capacities are used [41]. In Slovakia, it is mostly the sawmilling industry playing an important role in the domestic forest product market. Except for a couple of large mills, there is a large number of small sawmills in the market due to the nature of coniferous sawnwood products (limited number of tree species and low products differentiation), [42]. The low competitiveness of sawmills is due to the lack of innovation, own financial resources and investments (especially small and medium-sized companies), which is reflected in the use of obsolete technologies with a low degree of product finalization. Domestic sawmilling and plywood capacities for high quality non-coniferous logs are limited, and their consumption is estimated at no more than 500,000 m^3 annually [41]. In contrast, the pulp and paper industry is focused on the processing of low quality non-coniferous wood and is more diversified (in terms of product specialisation) with a more homogenous structure in terms of company size [43]. According to Parobek, et al. [23], the most significant consumers are sawmills, with a volume of 2.5 million m^3 of processed wood. The total consumption of the pulp and paper industry was almost 2.9 m^3 and the volume of waste produced in the wood processing industry was about 1 million m^3, which can be further processed for industrial or energy purposes. The total cascade coefficient of wood utilization in Slovakia was 1.48. Owing to the present structure and specialisation of the industry, a significant part of coniferous logs production is being exported and non-coniferous pulpwood is being imported. Without the additional production and innovation investments, and government support, the wood processing industry in Slovakia will not be able to utilise the available domestic wood potential and produce value added products and eliminate the export of roundwood and intermediate products [44].

These circumstances have a direct impact on the level of carbon stock in HWP. In the proposed scenarios we aimed at the evaluation of changes in the current level of production and utilization of domestic wood resources through assuming the optimal structure of wood assortments and maximized domestic wood consumption that allowed for quantification of the contribution of such changes to carbon stock in HWP. Scenario S0 represents the actual structure of domestic wood supply assortments and actual level of foreign trade with a final level of 3.1 Gg t carbon stored in HWP in 2018. Scenario S1 represents the state where the quality structure of supplied wood has increased. If the wood was used more efficiently with respect to the appropriate way with respect to the growth potential of forests in Slovakia, the ratio of longer half-life products would increase. As the study by Brunet-Navarro [45] reports, the longevity and recycling rate are two determining factors that influence the carbon stock in wood products. Moreover, the carbon stock in wood products increases linearly when increasing the average lifespan of wood products and exponentially when improving the recycling rate. Scenario S1 yields 3.6 Gg t carbon stored in HWP in 2017. This resulted from shifts of wood volumes from the lower value quality grades to the higher quality grades of wood mainly used for production of sawnwood and solid wood products. At the same time, this scenario results in lower volumes of fuelwood produced due to a shift of its portion to the category of industrial wood (primarily puplwood). This has a positive effect on carbon stock level, as the direct burning of fuelwood releases the carbon directly to the atmosphere. Additional volumes of wood resulting from higher domestic consumption are assumed under scenario S2. An increase in domestic consumption would result from the change in the structure and capacity of the Slovak wood processing industry induced by improved innovation investments and expansion of the existing production potential. The production of HWP from these additional wood resources would increase the carbon stock to 4 Gg t. Finally, the highest amounts of stored carbon (4.9 Gg t) occur in scenario S3 that represents the situation where under the unchanged production volumes of wood, its quality as well as its domestic wood consumption would increase. Some studies [7,8] show that the carbon stock level determination varies with different input data or computing methods used. The more detailed input information about the material flow is available the more specific are the results of carbon stock level. Donlan [46] supports this idea and mentions that countries are advised to include as much detail as possible, according to data availability, because as detail increases, so should accuracy. In order to improve the resulting values of annual changes in carbon stocks and associated CO_2 emissions and removals from the HWP pool, Pingoud et al. [47] suggest using direct stock inventories of wood products in order to reduce the uncertainty of the carbon pool estimates resulting from uncertainty on methods, parameters and activity data used.

5. Conclusions

The study compared different scenarios of industrial wood utilization and pointed out the contribution of alternatively produced HWPs to the carbon balance. The following conclusions can be drawn:

- the current state and development of forests in Slovakia are determined by gradual increase of planned felling, and currently higher volume of annual felling due to an uneven age composition of forest stands and high volume of accidental felling,
- based on the results of the two stock inventory methods used, namely SIF and NFIM, there is a difference in quality structure of the available domestic wood potential and its utilization when the available volumes of high-quality wood assortments are not utilized for their intended uses,
- positive changes in the level of carbon stored in HWP can be achieved by the changes in utilization of wood while maintaining the same level of volume felled,
- to improve domestic utilization of available wood potential there is a need to scale up the innovation process and increase investments to the wood processing sector,
- better utilization of the available assortment structure may ensure the production of the long-life HWP and consequently increase the carbon stored in HWP,
- the expected changes in the felling structure in the future can result in a higher share of products with a shorter life cycle and thus negatively influence the carbon stock in HWP.

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