Effects of Wood Product Utilization on Climate Change Mitigation in South Korea

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Abstract: Many countries, including South Korea, decided to suspend the inclusion of harvested wood products in their Nationally Determined Contributions, as part of the carbon inventory, in 2016. The inclusion of harvested wood products in the national greenhouse gases inventory must ensure the accuracy of carbon accounting and its conformity with the policy direction. The method used for harvested wood product carbon accounting can influence the accuracy of carbon account value, as well as policy direction based on greenhouse gas accounting. This research evaluated the utilization of domestic wood resources in South Korea in terms of carbon storage impacts from the perspective of the cascading use of wood products. The study also compared the two accounting methods (Tier 2 and Tier 3) of carbon storage for the period from 1970 to 2080, assuming the current pattern of wood resource utilization for the next sixty years. The results show that the current utilization of domestic wood resources is inefficient in terms of climate change mitigation. The analysis shows that there is a significant difference between the Tier 2 and Tier 3 methods in carbon storage effects, and the amount of harvested wood products carbon stock calculated by the Tier 2 method was found to be approximately double that of Tier 3. This result implies that there is a possibility of overestimating the carbon storage of harvested wood products when using the Tier 2 method in the case of net timber-importing countries, such as South Korea. The study can provide guidance for designing timber resource management from the perspective of the cascading use of wood products in order to contribute to sustainable development goals, including climate change mitigation.

Keywords: harvested wood products; carbon inventory; climate change mitigation; carbon accounting method

1. Introduction

Greenhouse gas (GHG) reduction by conserving carbon stocks in forests and increasing carbon uptake through improved forest management and reforestation are important tools for mitigating climate change [1]. Harvested wood products (HWPs) have been recognized for their contribution to the reduction in GHGs by storing carbon dioxide from the atmosphere in trees before decaying and combustion. When trees are harvested from forests, a significant amount of carbon is released, but will be continually stored in wooden products (e.g., in wood products as a building material, furniture, and paper) [2]. HWP, therefore, contributes to sequestering carbon dioxide over a period of time, rather than being immediately released into the atmosphere after harvesting [3].

HWPs as a carbon pool in the second Kyoto implementation period were ratified by the parties of the United Nations Framework Convention on Climate Change (UNFCCC) during the 17th Conference of the Parties (COP) in 2011. As a result, the parties were able to account for carbon stored in HWPs as a means to reduce GHG emissions and include them in their national carbon inventory. However, in the Nationally Determined Contributions (NDC) submitted by the parties to the UNFCCC under the Paris Agreement, many parties
decided not to include HWPs in their national carbon inventory due to the lack of scientific information on their climate change mitigation and socio-economic impacts. South Korea also decided to suspend the inclusion of HWPs in its carbon inventory as part of its 2016 NDC. Countries such as Australia, New Zealand, Canada, and the United States included HWPs in their NDC based on the result of research on carbon accounting approaches [3,4].

From the early 1990s, case studies have been conducted at the national level. Case studies on HWP carbon accounting inform the current status of each country regarding how much wood utilization of domestic wood resources can contribute to climate change. Case information provides an important basis to establish the strategies for climate change mitigation as well as sustainable wood utilization towards a sustainable society. Case studies have been conducted to estimate the amount of carbon stored in HWPs at the Tier 2 level [5–19]. The literature indicates that there is empirical research on HWP carbon stock accounting using the Tier 3 method in Japan [20], Ireland [21], UK [22], Portugal [23], Australia [24], the Czech Republic, and Lithuania [25,26]. Aleinikovas et al. in their work [26] stated that HWP carbon accounting values were estimated according to different data sources and methods of Tier 2 and Tier 3. South Korea established activity data at the Tier 2 level and applied default half-life according to IPCC 2013 guidelines [11,27]. A study comparing the three approaches prior to the decision of the seventh Conference of the Parties (CMP) was conducted at the Tier 2 level with the range of HWP carbon pool mixing both domestic and imported timber [11]. After the account scope was determined for domestic timber in the seventh CMP [28], carbon storage effects using the Tier 2 method were estimated with the scope of domestic timber according to the decision of the seventh CMP [27].

In order to include HWPs in the national GHGs inventory, the accuracy of the carbon accounting and its conformity with the policy direction must be ensured. The method for accounting carbon in HWPs influences the accuracy of carbon accounting and its alignment with the policy direction.

The IPCC guidelines suggested default carbon accounting methods for assessing carbon stocks and stock changes of HWPs in use [29,30]. Based on the decisions of the Durban conference, the latest 2013 IPCC Guidelines [30] proposed methods for estimating carbon stocks for the three default HWP categories—paper and paperboard, wood-based panels, and sawn wood. However, carbon stocks can also be accounted in other HWP categories, developing country-specific accounting methods if reliable data are available. Parties can select one of the three accounting methodological levels, Tier 1, 2, or 3 [30]. The Tier 1 method assumes instantaneous oxidation when harvesting timber in the forest area. This method makes the simplistic assumption of no carbon stock in HWP. The Tier 2 method recommends using default categories of HWPs and activity data provided by the Food and Agriculture Organization (FAO). This method focuses on the availability of carbon accounting on HWP. There is room for improved reliabilities as to whether the default half-life of wooden products applied in the Tier 2 method reflects the actual utilization of wood resources. Due to its reliability issues, the IPCC guideline suggested the country-specific method Tier 3 rather than Tier 2. The Tier 3 method uses reliable country-specific HWP activity data, a coefficient, and a half-life for the decay rate. Additionally, because the Tier 3 method is a transparent method for estimating carbon stock changes in HWP, it can be applied to the stock method or the flux method according to a specific industry, such as construction, transportation, and paper or final wood products. Application of the Tier 3 method to account for carbon stock in the construction industry infers a policy direction to promote the supply of domestic wood for building materials. On the other hand, the material flow analysis method, which has been attempted in various developed countries, is a method that was developed for the purpose of sustainable resource use, suggesting a policy direction for circular resource utilization. Whereas the Tier 2 method simply accounts for the production of primary wood products, activity data using material flow analysis of the Tier 3 method provide information on circular resource use by identifying wood products, such as wood-based panels produced from recycled wood.
Natural resource utilization is a social process in which different interest groups, with diverse and often conflicting intentions, confront each other at local, regional, national, and global levels. The social relations of resource utilization are historically and politically constructed, and the concepts change over time and between different social and cultural actors [31]. It is important to determine the most influential actors who mobilize development in the direction of their own interests in terms of the utilization of nature resource utilization [32]. As a natural resource, wood has been used in various industries for centuries. In this regard, wood resource utilization has complex stakeholders and interests according to the social structural and cultural construction. The supply of and demand for wood in each country have thus affected sustainable wood resource utilization, since the pattern of supply and demand of wood resources varies according to the industrial composition of wood products by country. Wood supply is affected by factors, such as harvestable trees in the forests, accidental felling, wood stock from previous periods, ownership structure, own consumption, wood price, price of production factors, and legislation. In contrast, wood demand depends on the number and structure of the processing industry, the energy industry, wood stock from previous periods, economic development, demand of related industries, supporting programs and activities for wood promotion, wood and wood products prices, traditions, and consumer preferences [33]. Primary wood products require different raw materials. The quality of sawn wood and plywood depends on specific round wood conditions, such as the species and size, which leads to a difference in the quality and price of the sawn wood produced. On the other hand, fiberboards, such as medium-density fiberboard and particle boards, are produced using round wood as well as recycled wood, wood chips, and wood by-products as raw materials. As a substitute for sawn wood, fiberboard has a competitive advantage in price, and thus the price rather than the quality is the main condition for the supply of raw materials. In this context, depending on the current state of the wood product manufacturing industry in the country, the conditions of the required wood vary, and depending on the consumption factors, the form of use of the wood products varies. These differences have different determinants for the country’s sustainable use of wood.

Using wood products for as long as possible is a way to trap carbon in the HWPs in use and delay carbon dioxide emissions into the atmosphere, thereby contributing to greenhouse gas reduction. Sequestered carbon in used wood products, in effect, contributes to greenhouse gas reduction. To date, several practices have been proposed so as to expand the efficiency of wood products. One practice that has recently caught the attention of forestry experts is the cascading concept. The concept of cascading use has been presented for the sustainable use of wood resources and consists of a method to increase the usage time of wood resources and efficiently increase the carbon stock in HWP. It uses wood resources sequentially: (1) by producing raw wood as sawn wood, (2) using sawn wood as a building structural material, (3) recycling sawn wood into wood-based panel materials, and (4) using wood as fuel at the end of its life. The usage pattern of domestic wood resources helps to understand the country context. Understanding the detailed forms of domestic wood utilization from a carbon storage viewpoint can help comprehend the policy implications of increasing carbon stored in the HWP, thereby offering a direction for account method choices.

This research set the following objectives: (1) evaluate the utilization of domestic wood resources in South Korea in terms of carbon storage effects from perspectives of cascading use; (2) compare the two methods (Tier 2 and Tier 3) of accounting climate change mitigation effects.

2. Methods

2.1. Utilization Flow of Domestic Wood Resources in South Korea

The current status of domestic timber use in South Korea was evaluated to confirm whether it follows the four sequential categories of cascading use, which is a carbon-efficient utilization process. For this purpose, the following factors were assessed: (1) the
ratio of domestic logs that are used in the production of sawn wood; (2) the use of recycled wood raw materials for wood-based panels (fiber and particle board); (3) the use of sawn wood and wood-based panels in long-lived industries; and (4) the use of fuel materials at the end of life.

The scope includes wood products (sawn wood, plywood, wood-based panels (particle board and MDF), preserved wood, wood chip, sawdust/wood powder, pulp, charcoal, and wood vinegar) produced from domestic roundwood and input to industries (construction, civil engineering, household, transportation, paper, and agriculture), as shown in Table 1.

Table 1. Main process of wooden material flow to HWP storage pool.

| Categories       | Main Process                                                                 |
|------------------|-----------------------------------------------------------------------------|
| Material         | Roundwood                                                                   |
| Manufacture      | Sawn wood, plywood, wood-based panels (particle board and MDF), preserved wood, wood chips, sawdust/wood powder, pulp, charcoal, and wood vinegar |
| Use (Industry)   | Construction, civil engineering, household, transportation, paper, agriculture, and others |

2.2. Methods of Accounting Carbon Stocks in HWPs

In the 2003 IPCC Guidelines, the types of carbon pools of HWPs were divided into HWPs in use and solid waste disposal sites (SWDSs). This study accounted for the carbon stored in domestic HWPs in use in accordance with an agreement of the seventh CMP. The researchers did not include the exported HWP, which accounts for a small proportion of the whole HWP and provides a limited understanding of its utilization pattern in exporting countries. In this study, data were collected for domestic wooden products, which was determined as the scope of HWPs in the seventh CMP and mentioned in the 2013 IPCC Guidelines. In South Korea, timber is harvested with logging permits. Most of the forests in South Korea have been recovered from deforested and degraded forests after the Korean War. Most of the lands conserved as natural forests have been designated as protected areas. Protected areas are strictly managed, and most of the logs in the country are legally harvested. There is an act for the effective implementation of sustainable wood utilization in South Korea.

Equation (1) was used for estimating carbon stocks in the HWP pool: \( C(i) \) = the carbon stock in the particular HWP category at the beginning of year \( i \), \( k \) = the decay constant for each HWP category, and \( \text{Inflow}(i) \) = the inflow to the specific HWP type during year \( i \) [30].

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C(i + 1) = e^{-k} \times C(i) + \left[ \frac{1 - e^{-k}}{k} \right] \times \text{Inflow}(i)
\] (1)

In order to track the flow of carbon stored in the HWP from the manufacturing process to the end use industry (the use stage), the flow of wood resources used was first calculated based on the material flow method and then converted into carbon units using the conversion factor. The researchers used the default conversion factors provided in the 2013 IPCC Guideline for HWP categories, as shown in Appendix A. Wood, prior to drying, contains moisture. The density coefficient was used to exclude the moisture content in the wood, thus determining the net wood content. By multiplying this value with the carbon fraction, the amount of carbon contained in wood can be computed. The \( C \) conversion factor, obtained by multiplying the density and the carbon fraction by each HWP, was then determined. In the IPCC Guidelines, a half-life was applied to estimate the carbon stock of HWPs in use. Half-life is the time required for a quantity to reduce the initial value by half. The original concept originated from nuclear physics. The term is currently used in several fields and is more commonly used to characterize exponential decay. It is assumed that the
lifespan of an HWP follows an exponential function, and each half-life is used to calculate the rate of disposal.

The HWP-specific half-life used in the study referred to IPCC reports [2] and prior studies, as shown in Table 2 below. Although the half-life used does not exactly match with the usage pattern in South Korea, it was applied with the assumption that the detailed usage pattern is similar for each industry. Differences between countries may be complemented by developing a half-life that fits national conditions in future studies.

Table 2. Applied discard rate and half-time for HWP carbon accounting.

| Sectors              | Discard Rate | Half-Time | Sources |
|----------------------|--------------|-----------|---------|
| Construction         |              |           |         |
| Building materials   | 0.012        | 50 years  | [34]    |
| Other building       | 0.043        | 16 years  | [34]    |
| materials            |              |           |         |
| Civil Engineering    |              |           |         |
| Temporal building    | 0.693        | 1 year    | [34]    |
| material             |              |           |         |
| Transportation       |              |           |         |
| Packing/Pallet       | 0.2          | 3.5 years | [35]    |
| Household            |              |           |         |
| Furniture            | 0.1          | 7 years   | [35,36] |
| Paper                |              |           |         |
| Paper products       | 0.35         | 2 years   | [29]    |
| Agriculture          |              |           |         |
| Mushroom bed log     | 0.33         | 2.1 years | [35]    |

The HWP categories used in this study are sawn wood and wood-based panels, as proposed by IPCC. Previous studies estimated wood domestically produced as a percentage figure in the input for the production of sawn wood and wood-based panels in South Korea [27]. The researchers collected and used the annual statistics for domestic roundwood production from 1970 to 2018 [37–39] and the input ratio into each wood processing industry from 2013 to 2017 [40–44]. The Tier 2 method used the data for the amount of sawn wood and wood-based panels produced. The Tier 3 method applied the average ratio of each type of wood product used in each industry for the last five years, while the amount of input to each industry was calculated from the production of sawn wood and wood-based panels applied in the Tier 2 analysis. The total amount of domestic sawn wood and wood-based panels produced is the same in both the Tier 2 and Tier 3 methods. The production amount of sawn wood and wood-based panels was used for the Tier 2 method, while Tier 3 used the amount of sawn wood and wood-based panels divided into each industry from the total amount of production.

2.3. Data

The wood resource data in the second category of Table 3 used national statistical data from two sources: the Statistical Yearbook of Forestry and the Survey of Wood Usage.

The researchers used the production of roundwood from the Statistical Yearbook of Forestry (1970–2018) [37–39], the production of sawn wood and wood-based panels from the Survey of Wood Usage (2013–2017) [40–44], and input to industries of sawn wood and wood-based panels from the Survey of Wood Usage (2013–2017) [40–44].

Since 2007, the Korea Forest Service has surveyed wood product manufacturers for their consumption of domestic and imported roundwood, and production and sales of wood products. They gradually expanded the number of items to be surveyed every year, and they are investigating most of all wood products produced from roundwood to date. Sawn wood has been surveyed since 2007, and wood-based panels have been included from 2012. The survey covers all manufacturers of wood products. They surveyed 635 sawmills in 2007 and 502 sawmills in 2017 as the number of sawmills gradually decreased in South Korea.
Table 3. Major characteristics of the methods for HWP carbon accounting applied in this study.

| Characteristics | Tier 2 Solid HWP: Primary Products | Tier 3 Solid HWP: Industry |
|----------------|-----------------------------------|---------------------------|
| HWP Categories | Sawn wood and wood-based panels according to IPCC 2013 [30] | Sawn wood |
| a. to construction |
| a.1. structural building material |
| a.2. other building material |
| b. to household |
| c. to civil engineering |
| d. to transportation |
| Wood-based panel |
| a. to construction |
| b. to household |
| c. to civil engineering |
| d. to transportation |

| Wood resource Data | Production of roundwood: Statistical Yearbook of Forestry (1970–2018) [37–39] |
|-------------------|-----------------------------|
| Production of sawn wood and wood-based panel: Survey of Wood Usage [40–44] |

| Carbon conversion factor | Density: Default value [30] |
|--------------------------|-----------------------------|
| Carbon fraction: Default value [30] |

| Half-life time | Default value [30]: Applied to primary products (Sawn wood and Wood-based panel) |
|----------------|--------------------------------------------------------------------------------|

| Note | Advantages: Easy accounting, focus on accounting |
|------|-------------------------------------------------|
|      | Disadvantages: Uncertainty to apply global average life–lifetime of primary products |

3. Results

3.1. Effects of Domestic Wood Resource Utilization on Climate Change Mitigation

Figure 1 below shows the flow of domestic roundwood as the raw material for primary wood products in South Korea. As a result of analyzing the use of domestic timber, in accordance with the proposed cascading use criterion to maximize the carbon storage of HWPs, approximately 72% of domestic roundwood was supplied to MDF and wood chips, crushing the wood resources directly to produce fiberboard and pulp (plywood, particle board, MDF, wood chips, and sawdust/saw powder). Only 14% of domestic roundwood was supplied to produce sawn wood, which is important in the cascading use of primary wooden products. Subsequently, the remaining roundwood resources were supplied with 12% of fuel materials, such as firewood, charcoal, and wood pellets, which were emphasized to be used at the end of the wood use cycle in cascading use and were immediately used as energy.
Sawn wood is not only important for its economic value, but also in terms of cascading use and climate change. It has the longest period of usage when used as a structural material since it stores carbon for the entire duration of its usage. In this regard, sawn wood stores the most carbon among other HWPs. Therefore, the use of sawn wood as a major material in the aforementioned industries has great potential for GHG reduction. Based on 2017 data, sawn wood was the most used wood resource in civil engineering and transportation, contributing approximately 58% of the materials in both sectors. Specifically, 33% and 25% of the wooden materials used, respectively, in civil engineering and transportation, which are both short-life industries, are sawn wood (Table 4).

Table 4. Input of sawn wood to industry and carbon flow.

| HWP Types       | Industry Sectors | Amount of Wood (m$^3$) | Percentage (%) |
|-----------------|------------------|------------------------|----------------|
| Sawn wood       | Construction     | 102,944                | 24.7           |
|                 | Civil Engineering| 137,022                | 32.9           |
|                 | Household        | 6281                   | 1.5            |
|                 | Transportation   | 104,438                | 25.1           |
|                 | Agriculture      | 6674                   | 1.6            |
|                 | Others           | 59,324                 | 14.2           |

As shown in Figure 2, most of the roundwood was used as material for fiberboard and wood chips. Only approximately 7% of roundwood was used for sawn wood in South Korea. Most of the low-quality domestic roundwood was supplied as raw material for wood-based panels (PB and MDF, etc.) and wood chips. More than two-thirds of the domestic roundwood were supplied for the production of primary wood products, in crushed form, of MDF, wood chips, particle boards, and sawdust/saw powder. Wood chips in South Korea are mainly used as materials for paper, PB, and biofuel.
Wood chips were mainly supplied to the paper industry (41%) and for the production of energy (40%). Wood chips were followed by MDF since it is the predominant wooden material used in manufacturing household products (71%) and in constructing buildings or infrastructure (28%). Particle boards are comparable with MDF given the fact that they were mostly supplied for the production of household goods (98%). In the field of agriculture, sawdust was the prominent wood resource, providing 80% of the sector’s materials. Finally, plywood was mainly used in civil engineering (63%) and the construction industry (34%).

With regard to the number of inputs by industry, most of the primary products produced using crushed wood resources were supplied to households, followed by the paper industry, the construction industry, and agriculture (Table 5).

Table 5. Input to industry and carbon flow (crushed form).

| HWP Types            | Industry Sectors | Amount of Wood (m$^3$) | Percentage (%) |
|----------------------|------------------|------------------------|----------------|
| Wood chips (2,088,762 m$^3$) | Particle board   | 277,901                | 13.3           |
|                      | Paper            | 861,587                | 41.2           |
|                      | Others           | 14,400                 | 0.7            |
|                      | Byproducts       | 100,375                | 4.8            |
|                      | Energy           | 834,499                | 40.0           |
| MDF (1,835,251 m$^3$) | Construction     | 517,754                | 28.2           |
|                      | Household        | 1,295,969              | 70.6           |
|                      | Transportation   | 21,528                 | 1.2            |
| Particle boards (865,241 m$^3$) | Household   | 845,917                | 97.8           |
|                      | Transportation   | 19,324                 | 2.2            |
| Sawdust/saw powder (93,764 m$^3$) | Sawdust charcoal(for energy) | 3824 | 4.1 |
|                      | Agriculture      | 74,272                 | 79.2           |
|                      | Others           | 15,668                 | 16.7           |
| Plywood (4223 m$^3$) | Construction    | 1429                   | 33.8           |
|                      | Civil Engineering| 2673                   | 63.3           |
|                      | Others           | 121                    | 2.9            |
The domestic roundwood used for energy production accounts for 12% of the roundwood and 18% of wood chip. In total, approximately one third of domestic wood resources were supplied for energy use. The use of wood for this purpose mostly directly used firewood without any manufacturing process. Some were consumed in the form of wood pellets and charcoal, as shown in Table 6 below.

Table 6. Input to industry and carbon flow (fuel wood and mushroom bed log).

| HWP Types                        | Industry Sectors | Amount of Wood (m$^3$) | Percentage (%) |
|----------------------------------|------------------|------------------------|----------------|
| Fuel wood (356,113 m$^3$)        | Energy           | 181,613                | 100            |
| Wood pellet (118,126 m$^3$)      | Energy (in household) | 35,564                | 30.1           |
|                                  | Energy (in agriculture) | 770                  | 0.7            |
| Charcoal/hardwood vinegar (89,778 m$^3$) | Energy     | 8519                   | 100            |
| Mushroom bed log (53,328 m$^3$)  | Agriculture      | 53,328                 | 100            |

3.2. Carbon Storage Effects of HWPs by Different Accounting Methods (Tier 2 and Tier 3) in Climate Change Mitigation

The results show that there are significant differences between the Tier 2 and Tier 3 methods in carbon storage impacts. The amount of HWP carbon stock, in the context of usage patterns of domestic wood resources, is much higher when using the Tier 2 method compared to the Tier 3 method. The obtained value of the prior is approximately more than double the value of the latter (Table 7). The large disparity was due to the usage gap between the primary products and the industry level. Tier 2 uses the activity data of primary wood products and the default half-life of the IPCC Guidelines, which takes into account the international average usage time of primary wood products. On the other hand, Tier 3 established activity data for each industry for sawn wood and wood-based panels and half-life according to each industry in the country context. This also reflects the differences between the usage pattern of domestic wood resources and the average usage pattern worldwide. In the case of sawn woods, most are currently used in short-lived industries.

Table 7. Carbon dioxide stored in pool of HWPs according to Tier 2 and Tier 3 (unit: Gg tCO$_2$).

| Year | Total Tier 2 | Tier 3 | Sawn Wood Tier 2 | Tier 3 | Wood-Based Panel Tier 2 | Tier 3 |
|------|-------------|--------|------------------|--------|-------------------------|--------|
| 1970 | 222         | 1654   | 40               | 317    | 137                     | 317    |
| 1990 | 11,579      | 18,768 | 2196             | 1992   | 28,354                  | 17,575 |
| 2010 | 34,076      | 47,123 | 10,070           | 2484   | 39,380                  | 20,932 |
| 2080 | 60,536      | 30,291 | 12,682           | 2693   | 46,299                  | 21,042 |

When comparing by primary wood product, the carbon stock amount of sawn wood using the Tier 2 method is five times higher than that of Tier 3. Activity data and half-life may influence the amount of HWP carbon storage effects. The largest amount of sawn wood was input for civil engineering, which is a short-lived industry, and the smallest input was for the structural materials industry, which is a long-lived industry. The domestic
usage patterns of sawn wood resulted in a substantial difference between Tier 2 and Tier 3 in the carbon stock of sawn wood (Figure 3).

![Figure 3. Carbon stock within the sawn wood by accounting method (unit: Gg t CO₂).](image)

In total, wood-based panels applying the Tier 2 method have more than double the amount of carbon stock compared to Tier 3 (Figure 4). This shows that South Korea has a large gap of half-life between Tier 2 and Tier 3 with the different usage patterns of domestic wood-based panels. Domestic wood-based panels did not input into building structural materials, which is a long-lived industry. Many wood-based panels inputted to furniture materials, and this was followed by other building materials, which are medium- and short-term industries. The half-life of building materials was longer than that of furniture materials, indicating that more carbon dioxide was accumulated in other building materials.

![Figure 4. Carbon stock within wood-based panels by accounting method (unit: Gg t CO₂).](image)

In terms of the industry sector, carbon stocks were the highest in construction and household sectors (Table 8). Although the industrial input of wood-based panels was the largest in the household sector, the half-life of building materials was longer than that of wood-based panels used as wood furniture; thus, the amount of carbon accumulated was the highest in the construction sector.
Table 8. Carbon dioxide stored in pool of harvested wood products by industry (unit: Gg t CO$_2$).

| Year | Building Structure | Other Construction | Temporal Material for Construction | Wood Pallet/Packings | Furniture |
|------|-------------------|--------------------|---------------------|---------------------|-----------|
| 2010 | SW 231 WP 52 WP 3204 | SW 105 WP 4 | SW 383 WP 227 | SW 7 WP 2691 |
| 2030 | SW 803 WP 161 WP 9873 | SW 170 WP 6 | SW 810 WP 481 | SW 17 WP 6932 |
| 2050 | SW 1246 WP 208 WP 12778 | SW 170 WP 6 | SW 819 WP 487 | SW 19 WP 7561 |
| 2080 | SW 1719 WP 233 WP 14311 | SW 170 WP 6 | SW 820 WP 487 | SW 19 WP 7657 |

Note: SW: sawn wood; WP: wood-based panels.

4. Discussion

The amount of HWP carbon storage in South Korea varies greatly depending on the accounting method, i.e., Tier 2 or Tier 3. The carbon storage effects of HWPs using the Tier 2 method were found to be approximately double those of the Tier 3 method. This is opposite to the results from the existing literature, for example, in case studies of the Czech Republic and Lithuania [25,26].

The activity data and assumed half-life time of wood products used for carbon accounting of HWPs in use have a significant impact on the amount of carbon stocks [45]. Activity data and decay rate can vary between Tier 2 and Tier 3, and accuracy of the carbon accounting in HWPs should be a matter of concern [6,16]. Activity data applied to Tier 2 and Tier 3 methods were different as the assumed utilization pattern of domestic wood resources in the Tier 2 and Tier 3 method is quite different in South Korea. The utilization pattern of South Korea is different from the usage patterns of other countries. In South Korea, the ratio of roundwood input to sawn wood and the use of sawn wood to building sector are significantly lower compared with other industrial countries. For example, most roundwood is consumed for the production of sawn wood in Switzerland [46]; half of sawn wood in Finland is used for structural building [47]. Regarding the industrial sector, carbon stocks were the highest in wood products used for construction and household commodities, such as furniture, in South Korea. Although the production input of wood-based panels was largest in the household commodity sector, the half-life of building materials was longer than that of wood-based panels used as wood furniture; thus, the amount of carbon stocks was highest in the construction sector in South Korea. By contrast, carbon stocks in the building sector gradually increased over time in Japan, indicating the greatest potential for carbon reduction to mitigate climate change [17].

The domestic sawn wood in South Korea is mostly used in the civil engineering and transportation industries, where the lifetime of sawn wood is relatively short. This is due to the low quality of domestic roundwood in South Korea, as most timber is cut at young ages for reforestation with more productive species, since most current forest stand were established for rapid restoration of once deforested lands [48–51]. In order to efficiently increase carbon stock in HWPs with current short-lived usage, the extension of the usage duration of wood resources by increasing HWPs in long-lived industries, such as building, has been suggested [52].

In the case of wood-based panels, the production rate using domestic wood was high, and the difference in the carbon stock value by different accounting methods was more than double. The carbon storage amount of wood-based panels was higher than that of sawn wood. This is similar to the Portuguese case, which had about twice as much storage than sawn wood [23]. In South Korea, the number of wood-based panels produced was about four times higher than sawn wood in the Tier 2 method and eight times higher in the Tier 3 method in 2020 (see Table 8). This indicates any policy measures affecting the carbon stocks of HWPs in South Korea.
It was found that there is a possibility of overestimating when using the Tier 2 method as a timber-consuming country that relies on imported timber. Imported timber is traded in the market at the highest price [53,54], and the share of imported timber used to produce sawn wood was 83.2%, comprising 16.8% of domestic timber in South Korea [44]. The sawn wood industry in South Korea was centered on imported timber. In this situation, the Tier 3 method can realistically reflect the current status of carbon stocks. The Tier 3 method has lower uncertainty compared to Tier 2, since it can specifically reflect the state of wood utilization in the countries, applying half-life and activity data for each industry [55].

In order to ensure the feasibility of including HWPs in the national carbon inventory, it is pertinent to ensure the accuracy of carbon accounting and establish the reliability of the accounting results. The Tier 3 method used country-level data, making it possible to obtain more accurate calculations and specific account values. However, establishing data and country coefficients remains a challenge. On the other hand, the Tier 2 method, despite offering a more straightforward accounting procedure, sets the half-life of sawn wood and wood-based panels to the level of the international average. This implies a risk of having carbon accounts that diverge from the actual value that are based on the current status of domestic wood resource utilization in each country.

As the Tier 2 method uses data of primary wood production, it will be instrumental in developing a policy that will boost the production of specific primary wood products, increasing the production of roundwood from the forest. In fact, in 2016, the South Korean government established a plan to reduce GHG emissions through an increased HWP carbon stock highlighted by a policy that increases sawn wood and roundwood production [56]. Meanwhile the Tier 3 accounting method can provide more detailed policy information with regard to the industry of sawn wood. Specifically, the Tier 3 method supports the establishment of policy measures that support GHG reduction, by increasing the production of sawn wood for building structural materials. The half-life of sawn wood applying the Tier 2 method is 35 years, which is the global average duration. The global average of sawn wood’s half-life could be applied; however, the actual lifetime of wood products in each country may be divergent from the world average depending on the conditions and utilization pattern of domestic wood resources.

The Tier 3 method derives more accurate account values according to the state of the country and provides policy information for the sustainable use of wood [53,54]. The introduction of these methods, along with the response to greenhouse gases, promotes recycling and leads to a longer utilization of wood resources. As a timber consumer country that relies on imported timber, South Korea has indirectly affected the illegal logging of tropical forests at the global level. The sustainable consumption of wood resources in South Korea will affect the supply side at the global level, contributing to solving the issues of global deforestation and climate change.

5. Conclusions

In this study, the researchers evaluated the carbon accounting accuracy of HWPs, following the Tier 2 and Tier 3 methods, as well as the sustainability of domestic wood resources in South Korea. The results were based on the analysis of the uncertainty of carbon accounting from the differences of carbon stock calculated using the two aforementioned methods. Additionally, this study investigated whether domestic wood resources have a sustainable utilization from the perspective of the HWP carbon storage impacts. In order to examine sustainability in domestic wood utilization, the researchers analyzed usage patterns with reference to the concept of cascading use described in the second section. For the sustainable use of wood resources following the cascading use concept, the raw materials must be used for the production of the sawn wood and then be recycled for wood-based panels, such as particle boards or MDF. The results of carbon stock accounting demonstrate the current status of GHG reduction through the HWP carbon pool. Moreover, it can provide a reference for policy recommendations on how governments could increase the amount of GHG reduction through HWPs.
In the context of the utilization of domestic wood resources in South Korea, adopting the Tier 3 method is likely to be appropriate in terms of accuracy and policy direction, since account values are currently small, but show the potential for carbon increase through the cascading use of wood. Promoting the cascading use of domestic wood resources can improve our society’s climate change mitigation, and thus the transition towards a sustainable society.

At the time the study was conducted, there was a limitation in the available data for the application of the Tier 3 method. The industry-specific half-life has not yet been developed in South Korea; thus, there may be slight differences in accounting carbon storage effects by using half-life values of similar timber-consuming countries. These limitations are expected to be overcome once South Korea has developed its industry-specific half-life in the future.

The researchers propose the establishment of a database for the Tier 3 method through further research on the construction of activity data, a half-life, and a coefficient. It will be necessary to promote step-by-step efforts to use sustainable wood resources and respond to climate change, rather than including HWPs in the national carbon inventory.

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**Appendix A**

Table A1. Default conversion factors for the HWP.

| Harvested Wood Products | Density (mg/m³) | Carbon Fraction (%) | C Conversion Factor (mg C/m³) |
|-------------------------|----------------|---------------------|-----------------------------|
| Sawn wood               |                |                     |                             |
| Sawn wood (aggregate)   | 0.458          | 0.5                 | 0.229                       |
| Coniferous sawn wood    | 0.45           | 0.5                 | 0.225                       |
| Non-coniferous sawn wood| 0.56           | 0.5                 | 0.28                        |
| Wood-based panels       |                |                     |                             |
| (aggregate)             | 0.595          | 0.454               | 0.269                       |
| Hardboard               | 0.788          | 0.425               | 0.335                       |
| Insulating board paper  | 0.159          | 0.474               | 0.075                       |
| Fiberboard compressed   | 0.739          | 0.426               | 0.315                       |
| Medium-density fiberboard (MDF) | 0.691 | 0.427 | 0.295 |
| Particle board          | 0.596          | 0.451               | 0.269                       |
| Plywood                 | 0.542          | 0.493               | 0.267                       |
| Veneer sheets           | 0.505          | 0.5                 | 0.253                       |
| Paper and paperboard (aggregate) | 0.9 | - | 0.386 |

Source: [30].
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