World Conference on
Timber Engineering
Oslo 2023

MATERIAL FLOW ANALYSIS AND CARBON FOOTPRINT OF FOREST RESOURCES IN JAPAN: A CASE STUDY ON BUILDING MATERIALS

Hongjun Wang[1], **Atsushi Takano**[2]

ABSTRACT: The importance of wood products' environmental properties, such as renewability and carbon storage capacity, is well recognized in sustainable development. For the sustainable use of wood, the deeply linked supply and demand relationships are important. However, few studies have been conducted to develop a comprehensive understanding of the forest resource flow. The objectives of this study are to conduct holistic analyses on the material flow and carbon footprint of forest resources in Japan, focusing on building materials; draw holistic flowcharts on the basis of the inventory; and based on that, discuss problems and possibilities from resource and environmental points of view. In the material flow, a large amount of forest wood waste is unmanaged, and the replanting ratio is continuously low. Since major GHG emissions originate in manufacturing and waste management, attentions should be paid to the utilization of biomass energy and the choice of waste management.

KEYWORDS: Material Flow Analysis (MFA), Forest resources, Wood products, Carbon storage

1 INTRODUCTION

Due to a decrease in domestic wood supply and an increase in imports, the wood self-sufficiency rate in Japan dropped from 86.7% in 1960 to 18.8% in 2002. To improve this situation, the government has implemented measures to promote the use of domestic wood. As a result of such effort, the wood self-sufficiency rate recovered to 36.2% in 2017 and a goal of 50% or more has been set for 2025 [1]. Meanwhile, the importance of wood and forest product with environmental properties, such as renewability and carbon storage capacity, is widely recognized in the context of sustainable development nowadays. Carbon storage in forests and wood products is especially regarded as a key to tackling climate change. Since forest products such as timber and pulp are produced from the same resource, the linkage between the related industries: forestry, manufacturing, construction, and waste management is important.

Against such background, researchers in various countries have performed Material Flow Analysis (MFA) of forest resources. For instance, Lenglet et al. [2] have made an MFA of the French forest-wood supply chain to compensate for the absence of consistent accounts for wood product production and consumption. They have attempted to fill this gap and evaluate the potential consequences of raw wood export reduction policies in France. Gonçalves et al. [3] have developed an MFA of forest biomass in Portugal to clarify circularity and resource efficiency. They have created material circularity indicators and cascade factors for different product sectors and pointed out heterogeneity in the circulation of wood products in Portugal. For studies on a larger scale, Mantau [4] has assessed wood flow throughout Europe to produce a tool for setting policy targets. He has quantified resource potentials, cascades and carbon effects. In addition to MFA, the carbon footprint of forest resources has been assessed worldwide. For instance, Zhang et al. [5] have created the life-cycle carbon budget for Harvested Wood Products (HWP) in China to clarify the role HWP play in climate change mitigation. They have assessed carbon stock and emissions from HWP in China, considering production, end-use, post-service disposal stages, and pointed out that in-use HWP account for 73.7% of the life-cycle carbon stock. Head et al. [6] have developed a database of greenhouse gas (GHG) life cycle inventory, focusing on the wood used in Canadian buildings, to facilitate comparisons of climate change impact with non-wood materials. They suggested that most wood building products provide net negative climate change impact scores, but there is still a lack of data for the development of this modular database.

In Japan, there are not yet many studies related to MFA or the carbon footprint of forest resources. Kobayashi et al. [7,8] have developed material flow of forest resources and calculated the environmental loads during manufacturing. They have calculated the carbon footprint of timber,

---

[1] Hongjun Wang, Kagoshima University, Japan, Hongjun_Wang@protonmail.ch

[2] Atsushi Takano, Kagoshima University, Japan, takano@aae.kagoshima-u.ac.jp

https://doi.org/10.52202/069179-0112

plywood and wood waste, and the CO_2 emissions from building materials. They have pointed out the importance of reforestation and suggested that the utilization of wood waste may compensate for the emissions. To compensate for the insufficiency of emission factors, Nambu et al. [9] have developed an LCA database of wood materials, mainly focusing on imports. They have pointed out the lack of evaluation of imported wood materials and the insufficiency of unit values. In many cases, the assessment of forest resources ended with the accomplishment of the material flow or the database of emission factors, and few have gone on to discuss the issue from environmental perspectives. Emissions from the manufacturing sector have been assessed, while emissions from other processes such as forest management, construction, waste management, and so forth were not considered. Additionally, emissions from imported forest products have not been evaluated so far, though emission factors have already been calculated.

Against this background, this study aims to a create comprehensive overall image of the current state of forest resources in Japan through an examination of forestry, manufacturing, construction, and waste management. To fulfill this objective, this study:
1) presents a holistic flowchart of forest resources in Japan, mainly focusing on building materials.
2) performs MFA on the basis of the inventory.
3) analyses carbon footprint: processing GHG emissions and carbon content flow, on the basis of the inventory.
4) discusses the situation and points of improvement in terms of forest resources in Japan from material flow and environmental perspectives.

2 MATERIALS AND METHODS

2.1 SYSTEM BOUNDARIES

The system boundaries of this study are summarized in Figure 1. The life cycle stages studied are named according to the modularity principle of a building life cycle (EN 15978: 2011) [10], which consists of four main stages (module A1-3: product stage, A4-5: construction stage, B: use stage, and C: end-of-life stage) and an additional information module (module D: benefits and loads beyond the system boundary) has been added.

2.2 MFA

The inventory was carried out on the basis of statistical data published by relevant authorities, such as the Ministry of Agriculture, Forestry and Fisheries [11] and the Food and Agricultural Organization (FAO) [12]. The reference year is 2017. The definition of four sectors in the flowcharts are shown in Table 1, and the rules of flowcharts are explained in section 3.1. Most of the data are known in cubic meters, while data that are known in other units are converted by the following rules: data in “ton” are divided by the weight conversion factor from the Japanese Industrial Waste Information center [13], data in “square meter” are multiplied by the wood utilization conversion factors from the Japanese Ministry of Land, Infrastructure, Transport and Tourism [14]. Estimates were made using conversion factors and formulas referenced in the relevant publication by the Japanese Forestry Agency, the FAO and the Japanese Ministry of Environment [1, 12, 15].

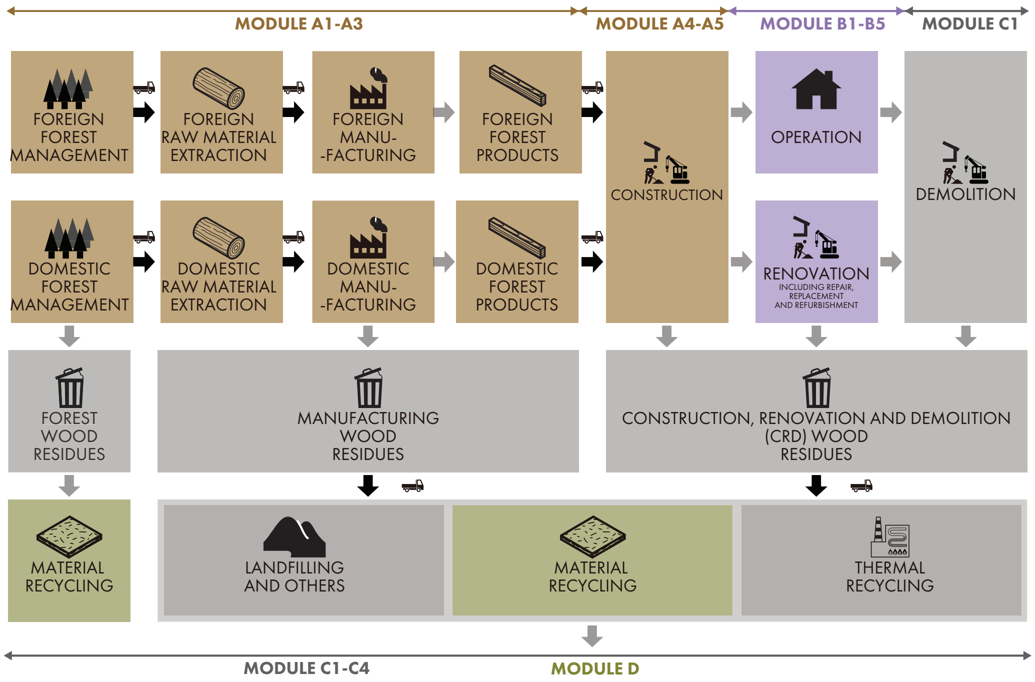

Figure 1: *System boundaries of this study.*

Table 1: Definition of sectors in this study.

Sectors	Contents of each sector
Forestry	Forest management, growing stock (by forest type and age class) and the annual increment of it, forest wood waste
Manufacturing	Production, imports, exports and consumption of forest products, manufacturing wood waste
Building	Wood stock in existing buildings (by construction method) and the annual increment/decrement of it
Disposal	Construction, renovation and demolition (CRD) wood waste, wood waste management

2.3 CARBON FOOTPRINT

2.3.1 Processing GHG emissions

On the basis of the inventory, GHG emissions generated during forest management, forest product processing, construction, demolition, selection, and waste management are assessed. Carbon release from incineration of post-use wood was not counted as processing GHG emissions. Emissions associated with domestic forest product processing, construction, demolition and wood waste management were calculated in accordance with the unit values from the Inventory Database for Environmental Analysis [16]. GHG emissions of imported forest products were calculated using the LCA database created by Nambu et al. [9]. The calculations were carried out by multiplying the unit values by the amount of each product.

2.3.2 Carbon content flow

The carbon content flow of the entire process was also assessed based on the inventory. Carbon content in forest resources was quantified based on the National Greenhouse Gas Inventory Report [15] and Intergovernmental Panel on Climate Change's guidelines for national GHG inventories [17]. In the carbon content flow, "stock" refers to the trees in forests and wood used in buildings; "carbon storage" refers to the carbon in the stock; "carbon uptake" refers to the annual increment of carbon in forests, forest products and wood used in buildings; "carbon release" refers to carbon released after disposal and carbon in exported products. The carbon content related to forests and forest products was calculated using relevant equations and carbon factors [16]. The carbon storage in the existing building stock and carbon uptake in new construction were calculated using relevant carbon fractions [17]. The carbon release was assessed for exported forest products and wood waste by multiplying either the volume or mass according to their carbon fractions [16, 17].

3 RESULTS AND DISCUSSION

3.1 MFA

The result of MFA in Japan is summarized in Figure 2 as a flowchart. Volume of four sectors: forestry, manufacturing, building, and disposal are shown from left to right. In the forestry sector, each tree icon represents 1x10^8 m^3 of wood volume in growing stock and the dotted circle shows the annual increase of the wood volume. Gradational colors of tree icons represent trees of different age classes, in which trees from young to old are classified by colors from light to dark respectively. In the manufacturing sector, the area of ring is in proportion to the volume of each type of forest product. Each ring with two different colors shows the direct material input (DMI, equals production plus imports): production is shown in the darker color and imports are shown in a lighter color. The lighter ring above the two-color ring shows the exports of forest products. In the building sector, each house icon represents 1x10^8 m^3 of wood stock in buildings and the dotted circle shows the annual increase of the wood stock. In the disposal sector, the area of the ring is in proportion to the volumetric data. Gradational gray colors from light to dark represent wood waste disposed of by material recycling, thermal-recycling, incineration without electricity production, landfill or other disposal methods.

3.1.1 Forestry

Japan has 25.05x10^6 ha of forest, of which 51.02% is covered by coniferous trees and the remaining 48.98% is covered by non-coniferous trees. In 5,242x10^6 of growing stock, 71.08% is coniferous and 28.92% is non-coniferous. Of all the coniferous forest, 52.96% of trees is aged 41~60 years, followed by 21.76% aged 61~80 years and 12.81% aged more than 80 years. There is an average annual increase of 68.26x10^6 m^3 or 1.40% in growing stock, including 78.26% in planted forests and 21.74% in natural forests. 84,226 ha of forest are harvested, but only 22,069 ha or 26.20% of the harvested area is replanted. The composition of Japanese forest by area is different from the composition by volume, since the density of conifer trees in planted forests is much higher than that of trees in natural forests. As for the age class, of all the coniferous forests, more than 30% is aged 61+ years and ready for harvesting. The non-coniferous forests are generally older than coniferous forests since non-coniferous forests depend on natural regeneration and very few areas are replanted.

3.1.2 Manufacturing

Japan produces 28.68x10^6 m^3 of roundwood, 9x10^6 m^3 of timber, 2x10^6 m^3 of Glulam (Glued Laminated Timber) and CLT (Cross-Laminated Timber), 3.57x10^6 m^3 of veneer sheets, 3.06x10^6 m^3 of plywood, 0.18x10^6 m^3 of LVL (Laminated Veneer Lumber), 5.19x10^6 m^3 of wood chips, and 1.89x10^6 m^3 of wood-based panels. Among all roundwood production, 42% is Japanese cedar, 10% is Hinoki cypress, 23% is Japanese larch, Yezo spruce and

https://doi.org/10.52202/069179-0112

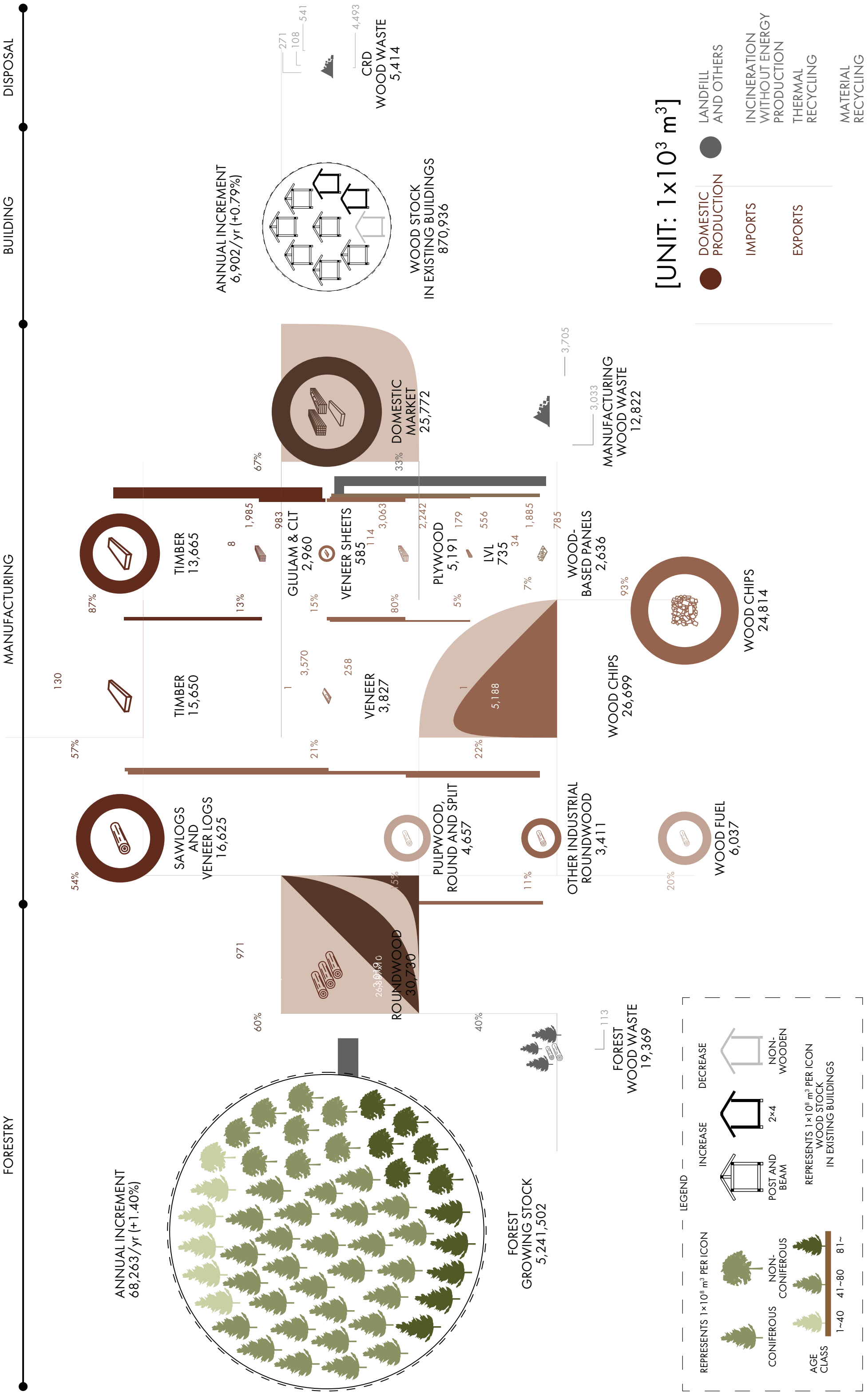

Figure 2: *Material flow of forest resources in Japan (Reference year 2017)*

https://doi.org/10.52202/069179-0112

others, the remaining 25% is unclassified. To meet domestic consumption, approximately 10% of roundwood DMI, 40% of timber DMI, 33% of Glulam & CLT DMI, 7% of veneer sheet DMI, 42% of plywood DMI, 76% of LVL DMI, 81% of wood chip DMI, and 29% of wood-based panel DMI is imported. As for the main source of imports, 85.66% of roundwood imports is from North America, 78.88% of timber imports is from Europe and North America, 81.18% of Glulam imports is from Europe, 83.53% of veneer sheet imports is from Russia, and 92.95% of plywood imports is from Southeast Asia. Of all roundwood consumption, 54% is consumed as sawlogs and veneer logs, 15% is consumed as pulpwood, round and split, 11% is consumed as other industrial roundwood, and 20% is consumed as wood fuel. Of all timber consumption, 13% flowed to glulam and CLT manufacturing, and 87% is used directly in construction and other industries. 25.77x10^6 m^3 of forest products flowed to the domestic market and an average of 1.19% of domestic production is exported. For the composition of the domestic market, 53.02% is timber, 11.48% is glulam and CLT, 2.27% is veneer sheets as the final product, 20.14% is plywood, 2.85% is LVL and 10.23% is wood-based panels. For the sustainability of harvesting, although the increase of most forest types is greater than removals, since the harvesting-replanting ratios are different by forest type, the sustainability of roundwood from different forest types should be evaluated separately and the harvesting should be controlled. For the inflow of forest products, Japan has tried to lower the volume of material imports but still has a great dependency on foreign products. For most types of forest product, the majority of imports are from particular regions, which throws more doubt on the reliability of forest product DMI. For the consumption of forest products, the majority of timber production is still being used directly in construction and other industries. Since the demand for Glulam is increasing because of the recovery of new housing construction and the utilization of CLT is being promoted by the Japanese government, the demand for EWP (Engineered Wood Products) will probably increase in the near future.

3.1.3 Building

Of 81.71x10^6 m^2 of new housing construction, 63.59% is wooden construction (W), 19.66% is reinforced concrete construction (RC), and 16.14% is steel construction (S). Among 52.97x10^6 m^2 of new non-housing construction, 71.85% is S, 15.60% is RC, and 8.64% is W. The volume of the wood stock in total new construction is 12.32x10^6 m^3. Wood stock in new construction is composed of 87.68% in W, 6.72% in RC, and 5.41% in S. Japan has 8,381x10^6 m^2 of existing building stock, which 48.93% is W, 30.52% is S, and 18.51% is RC. The volume of wood stock in existing buildings is 870.94x10^6 m^3, containing 89.94% in W, 6.06% in RC, 3.82% in S, and tiny in SRC and CB. Most of the wood is stocked in wooden housing, while 12% is stocked in non-dwelling buildings using other construction methods because of their large area. Thus, wood stock used in non-wooden constructions should also be accounted for. The composition of the wood stock in new construction are similar to that in existing buildings, but the share of wood stock in wooden constructions in new construction in 2017 is 2.26% smaller than that in existing buildings. Despite the promotion of wooden construction and wood for furnishing these years, the share of it is still lower than in the past.

3.1.4 Disposal

Japan generates 19x10^6 m^3 of forest wood waste, which is 40.31% of the volume of harvested roundwood. Of 5x10^6 m^3 of CRD wood waste, 40% is generated during construction and 60% is generated during demolition. Wood waste generated during renovation is minor. 99% of forest wood waste is unmanaged and less than 1% is material-recycled as wood chips. 47% of manufacturing wood waste is landfilled or disposed of by other waste management, 29% is material-recycled and 24% is thermal-recycled. 83% of CRD wood waste is thermal-recycled, 10% is material-recycled, 5% is incinerated without electricity production, and 2% is landfilled or disposed of by other management method. Although GHG emissions and energy payback ratio in utilization of forest wood waste may be higher than that of fossil fuel [18], the majority of forest wood waste is still unmanaged due to reasons such as the difficulty of collection and the greater cost. Moreover, due to the high water-content ratio very little waste is estimated to be recycled and less than 1% is actually accounted for. Together with the promotion of forest wood waste recycling, methods raising the mechanization rate of collection and lowering the expense should be considered. Since most of the manufacturing wood waste is small particle and ideal as a source of composting material for agricultural purposes, half of the amount is disposed or used by agriculture without recycling. CRD wood waste is usually combined with metals and other matters, which makes the selection time-consuming, so most of it is incinerated for energy use.

3.2 PROCESSING GHG EMISSIONS

The assessments result of processing GHG emissions are summarized in Figure 3 in the same manner as Figure 2. The darker grey line represents processing emissions from domestic production and the lighter grey line represents emissions associated with imported products. The width of each line is relative to the amount of GHG emissions.

3.2.1 Emissions from forest management and roundwood manufacturing

Of 486,306 t-CO$_2$eq of GHG emissions during roundwood processing, domestic production accounts for 36.80% and importation accounts for 63.20%. Half of the GHG emissions during domestic roundwood manufacturing come from Japanese cedar, followed by 25.51% from unclassified trees and 12.29% from Hinoki cypress.

https://doi.org/10.52202/069179-0112

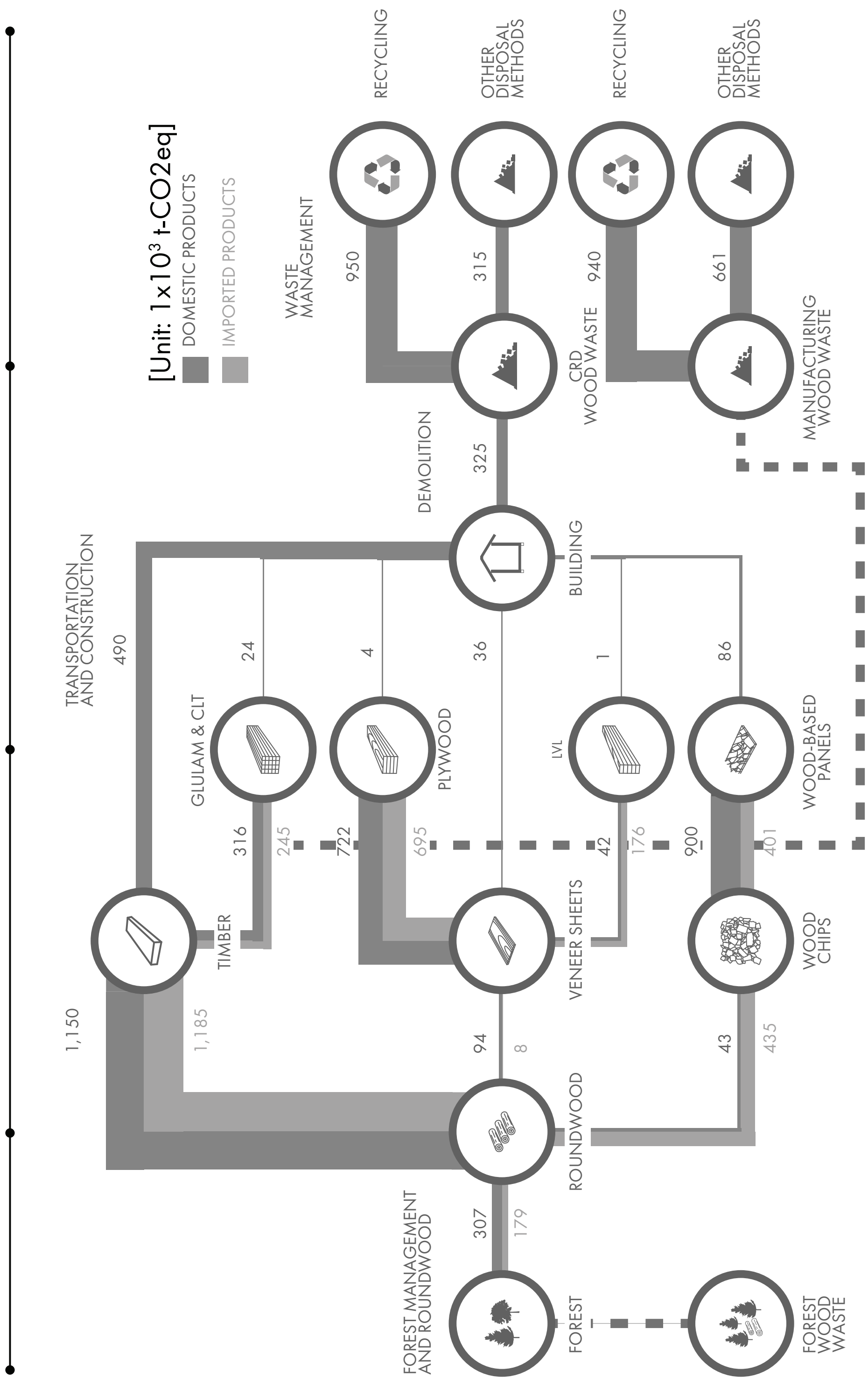

Figure 3: *Processing GHG emission flow of forest resources in Japan (Reference year 2017)*

3.2.2 Emissions from forest product processing

Of 6.41x10^6 t-CO_2eq of GHG emissions during forest product processing, 51% is from domestic production, 21.40% from Southeast Asia, followed by 10.05% from Europe, 5.90% from North America, 5.79% from Russia and 5.90% from other regions. Of 3.27x10^6 t-CO_2eq of GHG emissions from production, 35.21% come from timber processing, followed by 27.56% from wood-based panel processing, 22.09% from plywood processing, 9.66% from glulam & CLT processing, and the remaining 5.47% from other processes. Of 3.15x10^6 t-CO_2eq of GHG emissions from imports, 37.67% come from timber processing, followed by 22.08% from plywood processing, 13.83% from wood chip processing, 12.75% from wood-based panel processing, and the rest 13.77% from other processes.

3.2.3 Emissions from construction and demolition

0.97x10^6 t-CO_2eq of GHG emissions come from building material transportation, construction and demolition, of which 66.29% is from building material transportation and construction, 30.20% is from demolition and 3.51% is from the selection of CRD waste. 76.63% of GHG emissions resulting from these processes is from timber, followed by 13.43% from wood-based panels and 9.93% from other forest products. 76.72% of the GHG emissions related to the utilization of forest products come from wooden construction, followed by 12.79% from steel construction, 9.59% from reinforced concrete construction, and less than 1% from others.

3.2.4 Emissions from wood waste management

1.60x10^6 t-CO_2eq of GHG emissions come from manufacturing wood waste management, of which 58.71% is from recycling and 41.29% is from other disposal methods. 71.29% is from collection and transportation, followed by 21.14% from thermal-recycling, 7.37% from landfilling and others. 1.26x10^6 t-CO_2eq of GHG emissions come from CRD wood waste management, of which 75.13% is from recycling and 24.87% is from other disposal methods. 39.62% is from thermal recycling, followed by 38.18% from collection and transportation, 2.39% from pure incineration, and 19.81% from landfilling and others.

3.2.5 Total GHG emissions

The amount of GHG emissions associated with all forest products is 10.67x10^6 t-CO_2eq, of which 68.84% is from domestic processing and 31.16% is from foreign processing. Of the total GHG emissions resulting from forest resource processing, 59.71% is from forest product processing, followed by 26.85% from wood waste management, 9.05% from CRD activities, and 4.39% from forestry. The most (21.80%) is generated during timber processing, specifically 11.60% from timber imports and 10.70% from domestic timber construction. This amount is tremendous mainly because of the great volume, and the use of fossil fuel during the wood-drying process. To reduce the GHG emissions during timber processing, methods such as biomass substitution during the subprocess of drying should be brought into the discussion. The second largest (15.00%) is generated during manufacturing wood waste management, and as much as 11.86% is from CRD wood waste management. Wood waste in Japan is difficult to collect or select, which transforms into high unit values. The transportation distance and the choice of wood waste management methods may have a great influence on total GHG emissions.

3.3 CARBON CONTENT FLOW

The assessment results of carbon storage, uptake and release (defined in section 2.3.2) are summarized in Figure 4 in the same manner as Figure 2. Most of the rules are the same as for the material flow, while values of carbon storage in forests and buildings are represented by rings with two layers, which are proportionally 25 times larger than single-layer rings.

3.3.1 Carbon storage and uptake

Of 7,268x10^6 t-CO_2eq of carbon storage, 90.11% is stored in the growing stock and 9.89% is stored through wood utilization in existing building stock. More specifically, 55.17% is stocked in coniferous forests, 34.94% in non-coniferous forests, 8.89% in wooden construction buildings, and 1% in other construction. Of 104x10^6 t-CO_2eq of carbon uptake, 78.56% is from growing stock and 21.44% is from forest products. 45.44% of carbon uptake in forest products is stored in buildings, while the remaining 54.56% is discarded during construction or flows to other industries. Similar to the volumetric composition, 22.36x10^6 t-CO_2eq of carbon uptake in forest products flowed to the domestic market, with 51.33% being from timber, followed by 22.75% from plywood, 12.71% from wood-based panels, and a combined 26.44% from others. 39.48% is stored in imports and 60.52% is stored in production.

3.3.2 Carbon release

1.08x10^6 t-CO_2eq is exported in forest products and 17.69x10^6 t-CO_2eq is released through wood waste management. Carbon loss consists of 60.36% in forest wood waste, 25.84% in manufacturing wood waste and 13.81% in CRD wood waste. Since the majority of forest wood waste is unmanaged and industrial wood waste is mostly treated through thermal recycling, almost all the carbon in wood waste is released.

4 SCENARIO ANALYSIS

4.1 GOAL OF WOOD SELF-SUFFICIENCY RATE

Although the demand for wood was predicted to decline from 82x10^6 m^3 in 2017 to 79x10^6 m^3 in 2025, the goal of wood self-sufficiency has been increased from 36.2% in 2017 to 50% in 2025 [1]. Thus, the amount of self-sufficient wood is assumed to increase from 29x10^6 m^3 in 2017 to 40x10^6 m^3 in 2025. This variation may trigger impacts on the sustainability of forest resources.

https://doi.org/10.52202/069179-0112

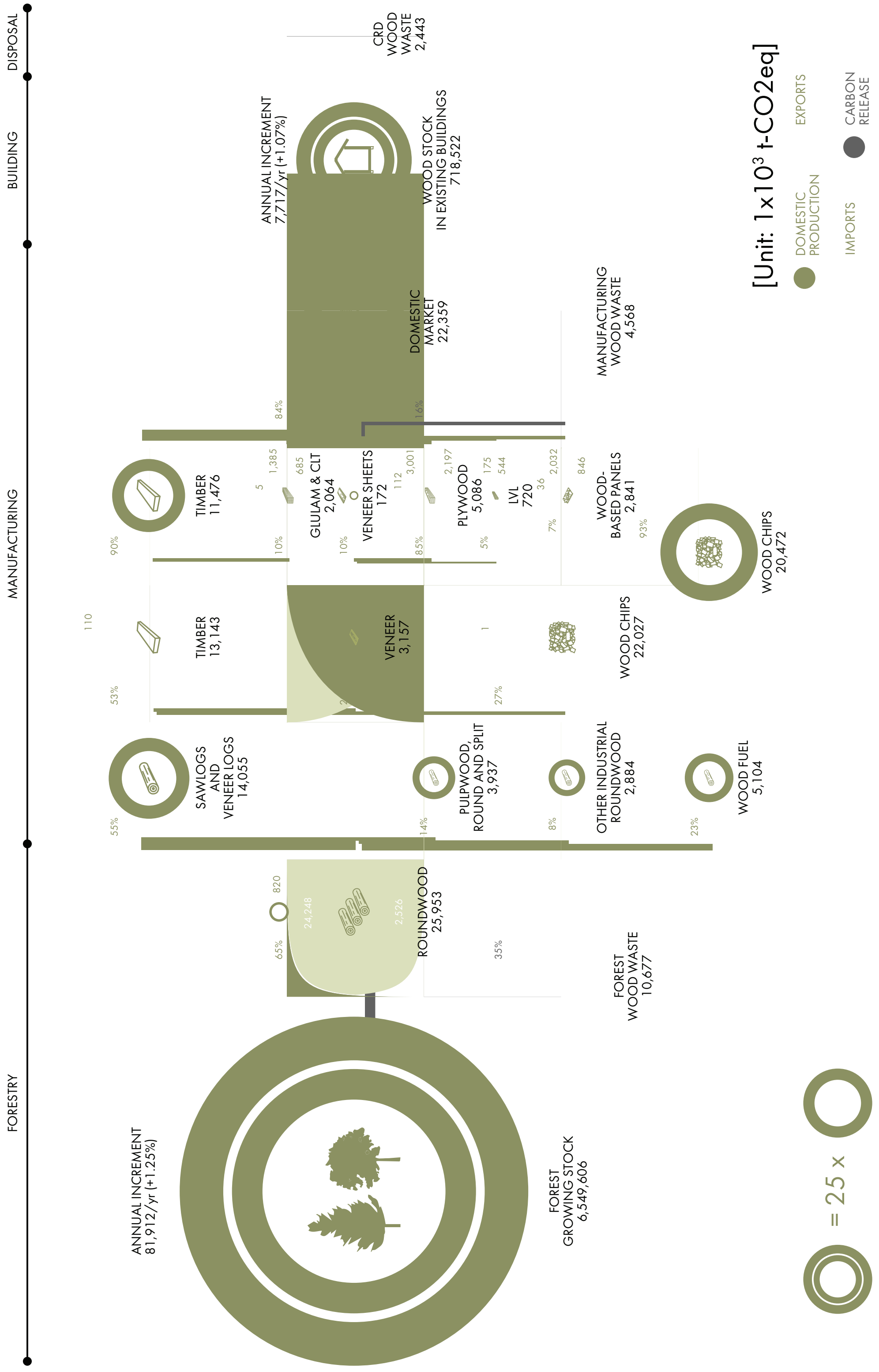

Figure 4: *Carbon content flow of forest resources in Japan (Reference year 2017)*

In 2025, the roundwood removals and imports are predicted to change by +36.29% and -25.27%, respectively. A reduction of forest area by 92,721 ha is predicted to be caused due to the low planting ratio and the difficulties of natural regeneration [18]. In terms of processing GHG emissions, 5.83% more of total GHG emissions is predicted to be generated, which is 14.27% more from forestry, 6.15% more from manufacturing, 6.77% more from disposal, but 3.12% less from building due to the decline in demand. In the carbon content flow, the carbon uptake in forests and forest products is predicted to decline by 25.54% and 3.12%, respectively. This is predicted to lead to a 20.73% decline in total carbon uptake. As a result, there is predicted to be a lower dependency on imports, worse sustainability of forests, a greater amount of GHG emissions, and a lower amount of annual carbon uptake. To solve these potential threats, both the improvement of forest resources sustainability and the reduction of GHG emissions resulting from domestic manufacturing should be taken into consideration. With a higher replanting ratio of harvested forest lands, there are predicted to be more sufficient domestic forest resource and more carbon uptake in forests. This may compensate for the material volume loss by domestic harvesting and the GHG emissions released by domestic manufacturing. The promotion of biomass energy utilization should be also encouraged since the substitution of biomass for fossil fuel is predicted to be efficient in terms of emission reduction (discussed in section 4.3).

4.2 BIOMASS SUBSTITUTION DURING TIMBE R MANUFACTURING

As mentioned before, a large amount of GHG emissions is generated from timber processing. For the details of this process, Komata et al. [19] suggested that most of GHG emissions due to domestic timber processing are from the drying process. They pointed out that the substitution ratio of biomass for fossil fuel in Japan is relatively low (41%), compared to countries in Europe (90%), Oceania (85%) and North America (80%). Thus, this scenario analysis was conducted to discuss the reduction of GHG emissions using different levels of biomass substitution. On the basis of the case study on biomass substitution in different countries [9], and the emission factors for the kiln-drying process [20], three scenarios with different levels of biomass substitution were estimated. S1 was assumed as timber processing without biomass energy use (fossil fuel: 100%, biomass energy: 0%). S2 was assumed as the lowest level of biomass substitution (fossil fuel: 60%, biomass energy: 40%). And S3 was assumed as the highest level of biomass substitution (fossil fuel: 10%, biomass energy: 90%). In S2, the GHG emissions from domestic timber processing is predicted to decrease by 19.26% and the total GHG emissions from forest resource processing is predicted to decrease by 1.89%. In S3, GHG emissions from domestic timber processing is predicted to decrease by 42.28% and the total GHG emissions from forest resource processing is predicted to decrease by 4.15%. Theoretically, the substitution of biomass energy during the wood-drying process of domestic timber manufacturing alone will reduce the GHG emissions by a relatively large amount. Considering the GHG emissions from long-distance overseas transportation of imported timber, the promotion of biomass energy utilization during manufacturing may allow domestic timber to be more competitive in the future.

4.3 OUFLOWS OF WOOD WASTE

When discarded forest products are material-recycled, carbon is not released and it can be stored for a longer period of time [21], material-recycling should be encouraged. However, very little wood waste is material-recycled and flows back to the carbon pool at the moment. Thus, this scenario analysis was conducted to discuss the reduction of GHG emissions and carbon release by two scenarios to the achievable improvement of wood waste management. S1 was assumed as the improvement reducing 10% more volume of total wood waste. S2 was assumed as the improvement with 10% more shares of material-recycling in all disposal methods of wood waste. In S1, there is predicted to be a decline in total GHG emissions by 2.69%. There is predicted to be a decline in carbon outflows by 9.42%. In S2, the GHG emissions are predicted to decrease by 13.36%, specifically manufacturing wood waste management by 5.25% and CRD wood waste management by 23.62%. This leads to a decline in total GHG emissions of 3.59%. The carbon release is predicted to decrease by 11.24%, specifically forest wood waste by 10.06%, manufacturing wood waste by 14.06% and CRD wood waste management by 11.11%. By reducing the volume of wood waste, there would be lower GHG emissions and less carbon release. By disposing more wood waste through material-recycling, the GHG emissions and carbon release would decrease even more. A better choice of recycling methods guarantees less GHG emissions and less carbon release, than the pure reduction of wood waste. To improve wood waste management, efforts should be put into both the reduction of volume and the choice of recycling methods.

5 CONCLUSIONS

The sustainable use of forest resources is one of the main challenges in the society, while the state of forest resources in Japan can be enhanced in terms of material flow and environmental perspectives. To understand the overall image of forest resources in Japan, this research has attempted to perform analyses of material flow and carbon footprint. The results show that the large amount of unmanaged forest wood waste, the low replanting ratio, and the lack of monitoring on supply-demand relationships are some of the main problems of forest resources in Japan at present. By 2025, we have predicted a decrease in the sustainability of forests due to greater domestic production. To solve these problems, policies encouraging waste management and replanting, as well as standards of evaluation on the sustainability level of harvesting are needed. For the carbon footprint of forest resources, major GHG emissions originate in imported products, waste management, and timber processing. To improve the disposal of wood waste, efforts should be put into both the reduction of volume and the choice of recycling methods simultaneously. Since there is a relatively low biomass substitution ratio in Japan, the promotion of biomass energy may contribute to the decline of emissions from timber processing. This research resulted in inventory and holistic flowcharts of forest resource flow focusing on the quantities, processing GHG emissions, and carbon content flow. The inventory and flowcharts could be used to perform other analysis of forest resources, or as a platform for discussion on the current problems and points of improvement. The results may be useful for environmental policy development.

ACKNOWLEDGEMENT

The authors acknowledge the assistance of all concerned.

REFERENCES

[1] Japanese Ministry of Agriculture, Forestry and Fisheries. Annual Report on Forest and Forestry in Japan, 2018.

[2] J. Lenglet, J. Y. Courtonne, and S. Caurla. Material flow analysis of the forest-wood supply chain: A consequential approach for log export policies in France. Journal of Cleaner Production, Volume 165, 2017, Pages 1296-1305.

[3] M. Gonçalves, F. Freire, and R. Garcia. Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. Resources, Conservation and Recycling, Volume 169, 2021.

[4] U. Mantau. Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. Biomass and Bioenergy, Volume 79, 2015, Pages 28-38.

[5] X. Zhang, H. Yang, and J. Chen. Life-cycle carbon budget of China's harvested wood products in 1900–2015. Forest Policy and Economics, Volume 92, 2018, Pages 181-192.

[6] M. Head, A. Levasseur, R. Beauregard, and M. Margni. Dynamic greenhouse gas life cycle inventory and impact profiles of wood used in Canadian buildings. Building and Environment, Volume 173, 2020.

[7] K. Kobayashi, S. Nakajima, Y. Tsunetsugu, and T. Ikaga. Analytic study on woody material flows in view of carbon reduction: discussing utilization of building-related woody waste and forest wood residues as biomass. Journal of Environmental Engineering, 2011, Volume 76, Issue 659, Pages 91-96.

[8] K. Kobayashi, K. Wakabayashi, K. Fujitsu, and S. Taniguchi. Woody resource utilization for environmental impact reduction with focus on building industry, Journal of Environmental Engineering, 2019, Volume 84, Issue 765, Pages 1019-1027.

[9] Y. Nambu, T. Ikaga, H. Hondo, K. Kobayshi, and Y. Tsunetsugu. Developing a LCA database of wood materials, AIJ Journal of Technology and Design, 2012, Volume 18, Issue 38, Pages 269-274.

[10] British Standards Institution, BS EN 15978 Sustainability of Construction Works–Assessment of Environmental Performance of Buildings–Calculation Method, British Standards Institution, London, 2011.

[11] Japanese Ministry of Agriculture, Forestry and Fisheries, https://www.maff.go.jp/e/ (accessed 11 September 2021).

[12] Food and Agriculture Organization of the United Nations, http://www.fao.org/home/en/ (accessed 11 September 2021).

[13] Japan industrial Waste Information Center. Aggregate units and weight conversion factors for each type of industrial waste Ver.1.4. https://www.jwnet.or.jp/assets/pdf/jwnet/gyouseihoukoku_jyuuryoukanzankeisuu.pdf (Accessed 20 April 2021).

[14] Japanese Ministry of Land, Infrastructure, Transport and Tourism. Survey on Unit Requirements of Labor Force and Materials in Construction Industry, 2017, https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00600040 (Accessed 9 December 2021).

[15] Japanese Ministry of the Environment. National Greenhouse Gas Inventory Report of JAPAN, 2021, Greenhouse Gas Inventory Office of Japan (GIO), http://www.nies.go.jp/gio/archive/nir/jqjm1000000x4g42-att/NIR-JPN-2021-v3.0_GIOweb.pdf (accessed 11 September 2021).

[16] Inventory Database for Environmental Analysis (IDEA). http://idea-lca.com/?lang=en (accessed 11 September 2021).

[17] 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Volume 4 Agriculture, Forestry and Other Land Use. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed 11 September 2021).

[18] H. Komata, S. Sakai, Y. Ishikawa, and N. Hattori. GHG emissions and energy payback ratio in utilization of forest residue as fuel for the boiler. Abstracts for ILCAJ meeting, 2010, Volume 2010, The 6th meeting of the institute of Life Cycle Assessment, Japan, Session ID A1-03, Pages 5.

[19] Japanese Ministry of Agriculture, Forestry and Fisheries. Annual Report on Forest and Forestry in Japan, 2017.

[20] H. Komata, Y. Kato, M. Takayama, and Y. I shikawa. Evaluation of Greenhouse Gas Emissions and Problems of the Methods for the Production of Lumber, Glued Laminated Timber and Plywood. Journal of the Hokkaido Forest Products Research Institute, 2010, Volume 539, Pages 1-5.

[21] R. Sikkema, M. Junginger, P. McFarlane, and A. Faaij. The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy—A case study on available forest resources in Canada. Environmental Science & Policy, Volume 31, 2013, Pages 96-108.