Matsumoto and Kayo
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ORIGINAL ARTICLE

Estimation of carbon stocks in harvested wood products of buildings in Japan: flux-data method and direct inventory method

Ryoto Matsumoto[1*] and Chihiro Kayo[2]

Abstract
In this study, carbon stocks in harvested wood products (HWPs) of buildings in Japan were estimated using the direct inventory method, which is highly accurate, and the flux-data method, which was proposed by the Intergovernmental Panel on Climate Change (IPCC) and is commonly used worldwide. We analyzed the differences between the estimated results and the respective reasons. The results indicate that the flux-data method greatly underestimated the carbon stocks in HWPs of buildings in Japan. In 2019, the values estimated by the flux-data method were only approximately 64% of those estimated by the direct inventory method. The half-lives of HWPs and the estimated continuous rate of change in industrial roundwood consumption proposed by the IPCC were likely the main causes of this difference. As for the decay function, the first-order decay, which is a default function proposed by the IPCC, was considered reliable for the estimations, because the decay function was not the main cause of the obtained difference.

Keywords: Harvested wood products, Carbon stocks, Buildings, Japan, Flux-data method, Direct inventory method, Half-life

Introduction

Wood can store carbon even after being removed from forests, and this characteristic can be used in climate change countermeasures [1]. Under the Paris Agreement, countries are required to report the annual change in their carbon stocks in harvested wood products (HWPs) to the United Nations Framework Convention on Climate Change [2]. Therefore, HWPs are internationally recognized as scientifically relevant in the climate change context. For Japan to achieve its goals of the Paris Agreement, the country should consider a more effective use of the carbon stock function of HWPs, and for this purpose, it is essential to accurately quantify them.

Carbon stocks in HWPs (t-C) can be estimated by converting the volume of existing HWPs (m^3) into the respective amount of stored carbon. However, it is generally difficult to directly ascertain this HWP volume, and in most countries and regions, there are no statistical data on the volume of existing HWPs. Accordingly, the Intergovernmental Panel on Climate Change (IPCC) has suggested three methods (Tiers 1–3) to estimate carbon stocks in HWPs in the 2006 and 2019 guidelines [3, 4]. Among them, Tier 1 and Tier 2 present the flux-data method, which indirectly estimates the existing HWP volume by multiplying annual HWP inflow (m^3/year) by a decay function whose parameter is the half-lives of HWPs (average life span). This method is commonly used in many countries worldwide, because it is simple and does not require a direct determination of the existing HWP volumes. It is also used in the National Inventory Report (NIR) of Japan, which contains estimates of greenhouse gas emissions and removals [5], to estimate

*Correspondence: r.matsumoto.ar@gmail.com
[1] Graduate School of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan
Full list of author information is available at the end of the article

the annual change in carbon stocks of HWPs not used in buildings but in products, such as furniture and paper. The IPCC guidelines [3, 4] provide default half-life values and a decay function called first-order decay (FOD) for these calculations. However, as the half-lives of HWPs and the trend of their decay over time differ among countries and regions, the results based on default values are not necessarily accurate. In fact, the estimated global carbon stocks in HWPs vary greatly depending on the decay function and half-life values [6]. In addition, the default decay function (FOD) used in the flux-data method is considered unsuitable for long-life HWPs because of its larger decay in the early years [7]. Accordingly, previous studies on HWPs have investigated various decay functions other than FOD, including normal distribution [8–10], gamma distribution [11], and logistic distribution [12–15]. Therefore, although the flux-data method is highly versatile, because it can estimate carbon stocks using HWP inflow data that are available in many countries, its accuracy might not be high. Thus, it is important to verify the accuracy of this method and improve its precision.

To verify the accuracy of the flux-data method, the carbon stocks estimated by this method can be compared to the value obtained by the direct inventory method provided in Tier 3, which directly determines the volume of existing HWPs from statistical data [4]. Although statistical data on the existing HWP volume are not available in most countries, in Japan, statistical data on the floor area (m^2) of existing buildings are readily available in the Summary Reports on the Prices of Fixed Assets (hereafter called Summary Report on Fixed Assets) [16]. Moreover, as these data are used for property taxation, they are expected to be highly reliable [12, 17]. Therefore, the direct inventory method can determine the existing HWP volume of buildings without the need for assumptions. This method is used to estimate the annual change in carbon stocks in HWPs of buildings in the NIR of Japan [5]. However, the NIR [5] does not directly estimate the carbon stocks and only calculates their annual changes based on floor areas of constructed buildings (inflow) and demolished buildings (outflow). Therefore, this method is slightly different from the direct inventory method targeted in this study.

Pingoud et al. [15] and Hashimoto and Moriguchi [18] estimated the carbon stocks of HWPs using both methods and compared the estimated results. They attempted to calculate the half-lives of HWPs so that the estimated results of the flux-data method would match those of the direct inventory method for Finnish [15] and Japanese [18] buildings. However, these studies considered the half-lives of HWPs as the only cause for differences between the estimations of the two methods and did not provide a comprehensive validation of the accuracy of the flux-data method. In addition, Hashimoto and Moriguchi [18] applied the results estimated by the direct inventory method to the initial estimation stage of the flux-data method. Therefore, the results do not represent an independent comparison between the flux-data and direct inventory methods.

In this study, we estimated the HWP carbon stocks of buildings in Japan using the flux-data and direct inventory methods and verified the accuracy of the former by comparing the estimated results. We also discussed the causes of the differences in the estimated results and investigated possible improvements for the flux-data method.

Methods

Direct inventory method

To calculate the carbon stocks of buildings, we used the same direct inventory method as the one presented in our previous study [17]. The target regions and methods used in the estimations are described in detail in the following subsections.

Target regions, period, buildings, and HWPs

This study covered all 47 prefectures in Japan from 1990, the base year for the first commitment period of the Kyoto Protocol, to 2019, the latest year with available statistical data [16]. The target buildings were classified as wooden, steel-reinforced concrete, reinforced concrete, steel, and concrete blocks/others. We used statistical data of the floor area of existing buildings from the Summary Report of Fixed Assets [16] for both taxable and non-taxable buildings (subject and exempt from property taxation under the local tax law, respectively). The targeted HWPs included log, sawnwood (including glued laminated lumber), plywood (thickness lower or higher than 6 mm), and wood board (particle board, hard board, medium-density fiberboard, and insulation board). We included both domestic and imported HWPs of buildings to emphasize the quantification of total HWPs used in buildings. Under the Paris Agreement, countries not using the production approach (which considers the HWPs derived from logs harvested from the country's own forests) are requested to report the annual changes in HWP carbon stocks using the production approach as supplementary information in their NIR. Moreover, countries are also free to choose any approach that covers both domestic and imported HWPs, including the stock change approach, which covers HWPs consumed in the country [2]. Furthermore, countries can also choose any approach for nationally determined contributions (NDCs) [19].

Estimation of carbon stocks in HWPs of buildings

For the direct inventory method, we used the same formula and parameters as those presented in our previous study [17]. Since that study was written in Japanese, the method is described in English here. The carbon stocks of buildings were estimated using the direct inventory method, as shown in the following equation:

$$\mathrm{CBD}(i,s,j,p) = S(i,s,p) \times V(i,s,j) \times D(j) \times \mathrm{CF}(j), \quad (1)$$

where i represents the year, s is the structural category of buildings (wooden, steel-reinforced-concrete, reinforced concrete, steel, concrete blocks/others), j is the HWP category (log, sawnwood, plywood, wood board), p is the prefectural category, CBD(i) is the carbon stock of buildings (t-C) at the beginning of year i, $S(i)$ is the total floor area of existing buildings (m^2) at the beginning of year i [16], V is the HWP input per unit floor area (m^3/m^2) [14, 20], D is the wood density (oven-dry mass over air-dry volume; t-d.m./m^3) [4, 5], and CF indicates the carbon fraction of oven-dried wood (t-C/t-d.m.) [4, 5].

The total floor area of the taxable buildings from 1990 to 2019 [16] was obtained from the Summary Report of Fixed Assets by submitting a request for the disclosure of relevant administrative documentation to the Ministry of Internal Affairs and Communications, by prefecture, year of construction, and structure. The total floor area of non-taxable buildings was obtained from the website of the Summary Report of Fixed Assets [16].

Because the HWP input per unit floor area indicates the volume of HWPs used in constructed buildings in a year, we separated the total floor area of existing buildings by year of construction and applied the HWP input per unit floor area corresponding to each construction year. For taxable buildings, as the total floor area can be determined based on construction year (i.e., buildings constructed before January 1, 1963, and every 3 years thereafter, such as buildings constructed between January 2, 1963 and January 1, 1966), the HWP input per unit floor area corresponding to each construction year was used for the estimation. However, the data on the total floor area of existing buildings by year of construction referred to only two categories: wooden and non-wooden buildings, and a further breakdown of non-wooden structures was unattainable. Therefore, based on the percentage of the floor area of non-wooden buildings by structure applied to the floor area of newly constructed buildings [21, 22], we estimated the floor area of existing non-wooden buildings by year of construction by classifying them into steel-reinforced concrete, reinforced concrete, steel, and concrete blocks/others. For non-taxable buildings, because it was not possible to determine the total floor area of existing buildings by year of construction and structure, the minimum and maximum values of carbon stocks were estimated by assuming that all buildings were either steel-reinforced concrete or wooden structures, which have the lowest and highest HWP inputs per unit floor area, respectively. The HWP input per unit floor area for these two structures was the annual average of the recorded values. In 2019, taxable and non-taxable buildings accounted for 95.5% and 4.5% of the total floor area of existing buildings.

For the HWP input per unit floor area, the log, sawnwood (including glued laminated lumber), and plywood values were obtained from the Survey on Labor Demand and Construction Materials [20]. This survey was conducted approximately once every 3 years, and only the aggregate data for each fiscal year (from April to March) were published, so we considered these data as the annual value (from January to December). In addition, materials subject to loss (temporary materials that are discarded after construction) were not included in this study, because they are not expected to remain in the buildings. For the HWP input per unit floor area of wood board, we used values from 1976 to 2012, when data on the volume of wood input to buildings were available [14], and to be consistent with the Survey on Labor Demand and Construction Materials and the total floor area of existing buildings by year of construction, the values for every 3 years were used. The HWP input per unit floor area of wood board was calculated by multiplying the annual shipment of wood board according to type (including domestic and imported) [14] by the percentage of shipment for each use in the corresponding year [14] to obtain the input of wood board by type and use, and then dividing the input for building use by the floor area of newly constructed buildings in the corresponding year [21, 22]. For some years, the HWP input per unit floor area for log, sawnwood, and plywood were missing, and they were supplemented by the average of the previous and following years. For wood boards, the HWP inputs per unit floor area for insulation boards were missing for 1976–1985, so the values for 1988, the year closest to the survey year, were used to supplement the missing years. As a reference, Table 1 shows the HWP input per unit floor area for log, sawnwood, and plywood, and Table 2 shows the HWP input per unit floor area for wood boards.

We used density and carbon fraction values reported in the 2019 IPCC guidelines [4] and used in the NIR of Japan [5]. Because conifers account for most of the domestic supply of sawnwood materials [23], the log and sawnwood used in the buildings were judged to be mostly

Table 1 HWPs (log, sawnwood, and plywood) input per unit floor area by structure (m^3/m^2)

Structure	2017					Average (1979–2017)				
	W	SRC	RC	S	CB/O	W	SRC	RC	S	CB/O
Log	0.009702	0.000000	0.000098	0.000004	0.000000	0.017984	0.001149	0.001295	0.001518	0.001550
Sawnwood	0.155427	0.000000	0.001429	0.002128	0.000795	0.166754	0.007406	0.009409	0.010472	0.036377
Plywood (thickness < 6 mm)	0.000388	0.000025	0.000226	0.000124	0.000076	0.001852	0.000351	0.000595	0.000461	0.001314
Plywood (thickness ≥ 6 mm)	0.022178	0.000818	0.006405	0.003369	0.000898	0.016340	0.002334	0.003963	0.003246	0.004385

"2017" is the latest survey results. "Average" is average of survey results from 1979 to 2017

HWPs, harvested wood products; W, wooden buildings; SRC, steel-reinforced concrete buildings; RC, reinforced concrete buildings; S, steel buildings; CB/O, concrete blocks and other buildings

Table 2 HWPs (particle and fiber board) input per unit floor area (m^3/m^2)

	2012	Average (1976–2012)
Particle board	0.005488	0.002323
Hard board	0.000241	0.000167
Medium-density fiberboard	0.004955	0.001688
Insulation board	0.001615	0.001956

"2012" is the latest survey results. "Average" is average of survey results from 1976 to 2012

HWPs, harvested wood products

from conifers, so their densities were estimated based on the values for conifers.

Flux-data method

Target regions, period, buildings, and HWPs

The target regions, period, and HWPs were the same as those used in the direct inventory method. In addition, because the flux-data method estimates the carbon stocks at the beginning of year $i+1$ using the HWP inflow to carbon stocks during year i (see Eq. (2) below), the HWP inflow must include data that go the farthest possible into the past, preferably prior to 1990, to provide more accurate estimates. Therefore, in accordance with the 2006 IPCC guidelines [3], 1900 was adopted as the starting year of the estimation. The target buildings were almost the same as those used in the direct inventory method. However, the statistical data [21, 22] on newly constructed buildings used in the flux-data method excluded buildings with a floor area of 10 m^2 or less, because the Building Standards Law stipulates that submission of a Notification of Building Construction is not required for such small-sized buildings. Consequently, there was an error in this respect compared to the buildings targeted by the direct inventory method. Moreover, because there was no classification of taxable and non-taxable buildings in the statistical data used in the flux-data method [21, 22] and data by structure could be obtained for all buildings, we used the same estimation method for all buildings.

Estimation of carbon stocks in HWPs of buildings

The flux-data method estimates the carbon stocks base on FOD, which is the default decay function suggested by the IPCC guidelines [3, 4] and is widely used internationally. Carbon stocks in buildings under the flux-data method applying FOD were estimated using Eqs. (2)–(4):

$$\mathrm{CBF}(i+1,s,j,p) = e^{-k(j)} \times \mathrm{CBF}(i,s,j,p) + \frac{1-e^{-k(j)}}{k(j)} \times \mathrm{Inflow}(i,s,j,p), \quad (2)$$

$$\mathrm{Inflow}(i,s,j,p) = W(i,s,p) \times V(i,s,j) \times D(j) \times \mathrm{CF}(j), \quad (3)$$

$$k(j) = \frac{\ln(2)}{\mathrm{HL}(j)}, \quad (4)$$

where CBF(i) is the carbon stocks of buildings (t-C) at the beginning of year i, Inflow(i) is the carbon inflow of HWPs to buildings in year i (t-C/year), $W(i)$ is the floor area of newly constructed buildings in year i (m^2/year) [21, 22], and HL is the half-lives of HWPs. We adopted 1900 as the initial year, for which the carbon stocks (CBF(1900)) were set to 0.

For the estimation of carbon inflow (Inflow) after 1961, the floor area data of newly constructed buildings from 1961 to 1988 were obtained from the Building Statistical Annual Report [22], and data for after 1989 were obtained from the Newly Constructed Building Statistics [21]. The same values as those in the direct inventory method [see Eq. (1)] were used for density, carbon fraction, and HWP input per unit floor area.

The Inflow for 1900–1960 was estimated using Eq. (5), according to the 2006 IPCC guidelines (Eq. 12.6) [3]:

$$\text{Inflow}(i) = \text{Inflow}(1961) \times e^{(U \times (i-1961))}, \quad (5)$$

where Inflow(i) is the carbon inflow of HWPs to buildings in year i (1900–1960) (t-C/year), and U is the estimated continuous rate of change in industrial roundwood consumption between 1900 and 1961 (hereinafter called EI), for which the default value for Asia (0.0217) given in the 2006 IPCC guidelines [3] was used.

The half-life values of HWPs were set to 35 years for log and sawnwood, and 25 years for plywood and wood board, referring to the default values given in the 2019 IPCC guidelines [4].

Results

Figure 1 shows the nationwide HWP carbon stocks of buildings and the respective annual changes estimated using the direct inventory and flux-data methods and population [24] from 1990 to 2019. The nationwide carbon stock in 2019 was approximately 231 million t-C with the direct inventory method, and approximately 148 million t-C (~64% of 231 million t-C) with the flux-data method. The carbon stocks of non-taxable buildings were not included in the results of the direct inventory method, because abnormal values were observed for data of building floor areas for several prefectures and years, so data reliability could not be guaranteed. However, these values represented approximately 1.61 million t-C at minimum (assuming 100% steel-reinforced concrete buildings) and approximately 19.32 million t-C at maximum (assuming 100% wooden buildings) for 2019. Therefore, the results of the direct inventory method might underestimate the actual nationwide carbon stocks in buildings. The nationwide carbon stocks of buildings estimated using the direct inventory method presented an increasing trend from 1990, and they increased in all years except in 2011, when the Great East Japan Earthquake occurred. In contrast, the nationwide carbon stocks estimated using the flux-data method showed an increasing trend after 1990, peaked in 2008, and decreased thereafter. The nationwide population also peaked in 2008 and decreased thereafter, which is consistent with the results of the flux-data method. The largest difference between the results estimated by the two methods was observed in 2019, at approximately 83 million t-C. There were no significant differences between the percentage of nationwide carbon stocks in buildings by structure in 2019 obtained by the two methods. Regarding the percentage by structure, wooden buildings accounted for nearly 90% in both methods, which confirmed that wooden buildings have a dominant carbon stock function compared to buildings with other structures. Regarding HWP categories, sawnwood accounted for the largest share (approximately 80%) in both methods.

Figure 2 shows the carbon stocks in buildings estimated using the direct inventory and flux-data methods by prefecture in 2019. According to the direct inventory results, the largest carbon stocks, in descending order, were obtained for Tokyo (~12.3 million t-C),

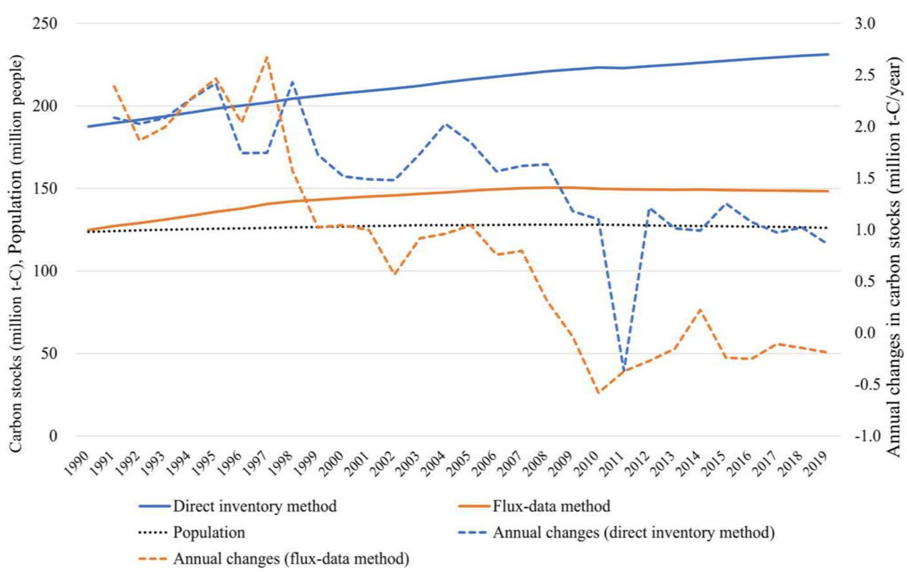

Fig. 1 Carbon stocks in HWPs of buildings, annual changes, and population in Japan. HWPs, harvested wood products. Annual changes are defined as the carbon stocks in the current year minus those in the previous year

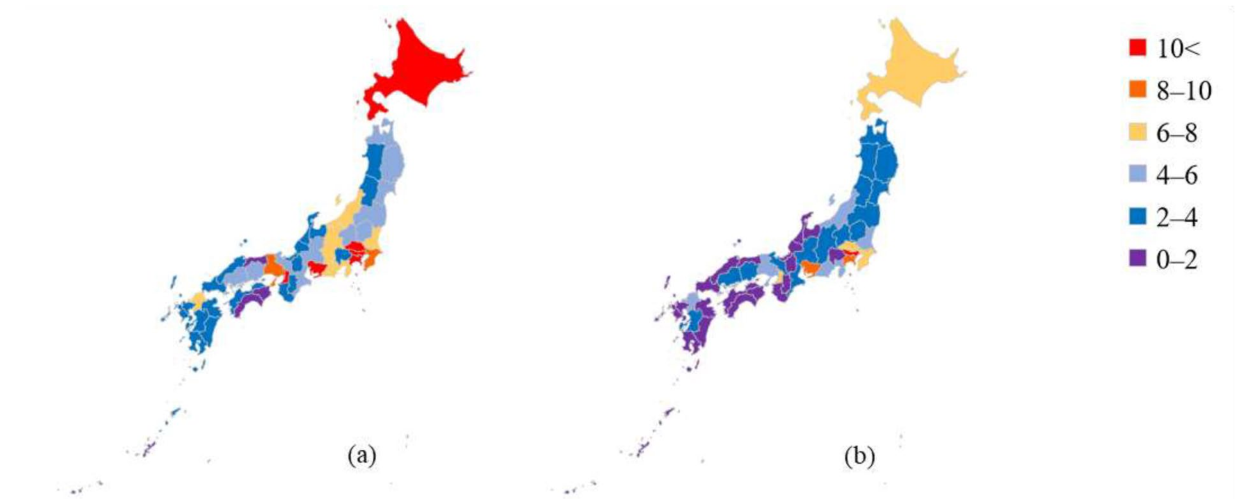

Fig. 2 Carbon stocks in HWPs of buildings in Japan by prefecture in 2019 (million t-C). **a** Direct inventory method and **b** flux-data method. HWPs, harvested wood products

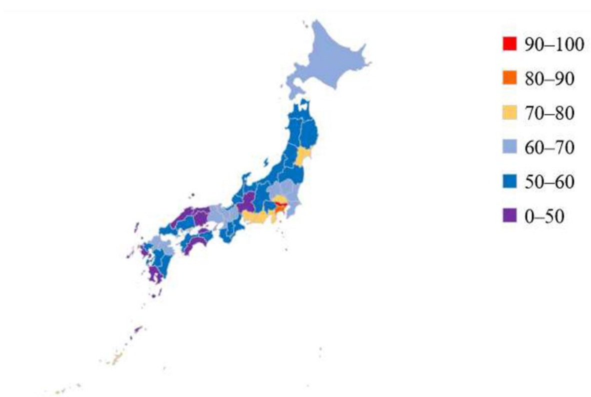

Fig. 3 Percentage of flux-data to direct inventory estimations of carbon stocks of buildings by prefecture (2019)

Aichi (~11.4 million t-C), Hokkaido (~11.3 million t-C), Saitama (~10.7 million t-C), Kanagawa (~10.5 million t-C), and Osaka (~10.0 million t-C). The largest carbon stocks according to the flux-data results were observed, in descending order, for Tokyo (~11.4 million t-C), Kanagawa (~9.2 million t-C), Aichi (~8.3 million t-C), Saitama (~7.9 million t-C), Hokkaido (~7.9 million t-C), and Osaka (~7.0 million t-C). The results of the direct inventory method exceeded those of the flux-data method in all prefectures. Figure 3 shows the ratio of carbon stocks from the flux-data method to those from the direct inventory method by prefecture in 2019. The percentage tended to be higher in urban prefectures with large populations and active economies, including Tokyo (~92%), Kanagawa (~88%), Miyagi (~75%), Saitama (~74%), and Aichi (~72%).

Discussion

Causes of differences between the results of the direct inventory and flux-data methods

As mentioned in the Results section, the carbon stock of buildings in 2019 estimated using the flux-data method was only approximately 64% that estimated using the direct inventory method, and the estimation results of the latter were considered more accurate [17]. Therefore, the flux-data method underestimated the carbon stock of buildings in Japan. This section discusses the causes for these estimation differences. These differences were analyzed regarding three influencing factors: half-life values, decay functions, and EI. Therefore, to investigate their effects, we arbitrarily changed these three assumptions and compared the estimation results of both methods to examine the cause of the differences. The sum of squares of differences between the estimated results from 1990 to 2019 were used as indicators, and the solver function of Excel was used to identify the parameters that minimize this sum of squares.

Ranges of HWP half-lives, decay function, and EI

When attempting to minimize the sum of squares of the difference between the two methods, we set the following ranges for the parameters (i.e., half-life and EI) to avoid obtaining unrealistic values.

The half-lives of HWPs were set to 35 years for log and sawnwood and to 25 years for plywood and wood board. These values were determined with reference to the 2019 IPCC guidelines [4], and they are also applied to other HWP applications, such as furniture. However, the half-lives of long-lived buildings in HWP applications are expected to be longer than this value. According to previous studies [25–27], the life span of buildings in Japan has been increasing since the 1980s. As of 2005, the average life span of buildings with different structures and uses varied from 40 to 60 years, and that of wooden houses, which store more carbon than other structures, was estimated at approximately 50 years. In another study [14], the half-lives of wood boards used in buildings were set to 35 years after consultation with experts. Thus, the HWP half-lives proposed by the IPCC (35 years for sawnwood and 25 years for plywood and wood board) might be low for estimating carbon stocks of buildings in Japan. Therefore, the half-lives of HWPs were likely longer than the IPCC value. We set the lower limit to 25 years, and the upper limit to 70 years considering the trend toward a longer service life of buildings in Japan. The HWP half-lives were set to integer values. In addition, conditions were also set for the relationship between the half-lives of log and sawnwood and those of plywood and wood board. Log and sawnwood are mainly used as structural materials for buildings, so their half-lives are almost the same as the average life of buildings. In contrast, plywood and wood boards are often used as interior materials, such as wall and floor materials, so their half-lives are likely shorter than those of structural materials because of remodeling. Therefore, the conditions were set so that the half-lives of log and sawnwood would always be longer than the respective half-lives of plywood and wood board, and the former would not be more than 1.5 times the latter.

The first-order decay function was applied as the default decay function of the flux-data method but, as mentioned in the Introduction, FOD is not suitable for long-lived HWPs [7]. Previous studies on HWPs in Japan [12–14] often used a logistic distribution, and studies estimating the average life of buildings [25, 26] show that the decay of buildings in Japan is close to a log-normal or normal distribution. In this study, in addition to FOD, logistic, log-normal, and normal distributions were investigated as decay functions, and verification using a solver was performed for each of them. These decay functions have a decay coefficient, which determines their shape. In this study, the decay coefficient of each decay function was also treated as a variable for verification by the solver, because the carbon stocks changed significantly with the decay coefficient. However, to avoid an unnatural function owing to arbitrary changes in the decay coefficient, some conditions were set. Based on the shape of each decay function, the decay coefficients were set from 0.05 to 0.3 for the logistic distribution, from 0.1 to 2.0 for the log-normal distribution, and from 1 to 5 for the normal distribution. The coefficient used to determine the shape of the normal distribution was the standard deviation. In this study, the standard deviation was set as the half-lives of HWPs/α, referring to previous studies [6–8], and α was set as the decay coefficient of the normal distribution. The decay coefficient was set to two decimal places.

The Asian EI value of 0.0217 proposed by the IPCC was adopted in this study. However, it is unlikely that one single value is adequate for the entire Asian region, especially considering that Japan experienced many wars and subsequent periods of high economic growth during 1900–1960, and thus, achieved the highest economic growth among Asian countries. In addition, the EI presented in the 2006 IPCC guidelines [3] is positive for all world regions and assumes that the HWP carbon inflow increased at a constant rate between 1900 and 1961. Although the number of constructed buildings in Japan increased yearly after 1900, the number of non-wooden buildings also increased. Therefore, considering that most HWPs used in buildings are located in wooden buildings, it is not clear whether the volume of HWPs used in buildings necessarily increased in Japan since 1900. For these reasons, the EI was set from − 0.03 to 0.03. The EI was set with four decimal places.

Identifying the causes of difference

Table 3 shows the optimal parameter values to minimize the sum of squares of difference for each decay function, and Fig. 4 shows the shape of each decay function when

Table 3 Optimal parameters to minimize the sum of squares of the difference according to decay function

	FOD	Logistic distribution	Log-normal distribution	Normal distribution
Half-lives of log and sawnwood (y)	65	54	64	70
Half-lives of plywood and particle and fiber board (y)	65	53	64	66
Decay coefficient	–	0.30	2.00	1.00
EI	0.0017	0.0015	− 0.0041	− 0.0027
Sum of squares of differences	122.913	138.328	70.895	81.573

Sum of squares of differences refers to the values estimated by the flux-data and direct inventory methods

FOD, first-order decay; EI, estimated continuous rate of change in industrial roundwood consumption between 1900 and 1961

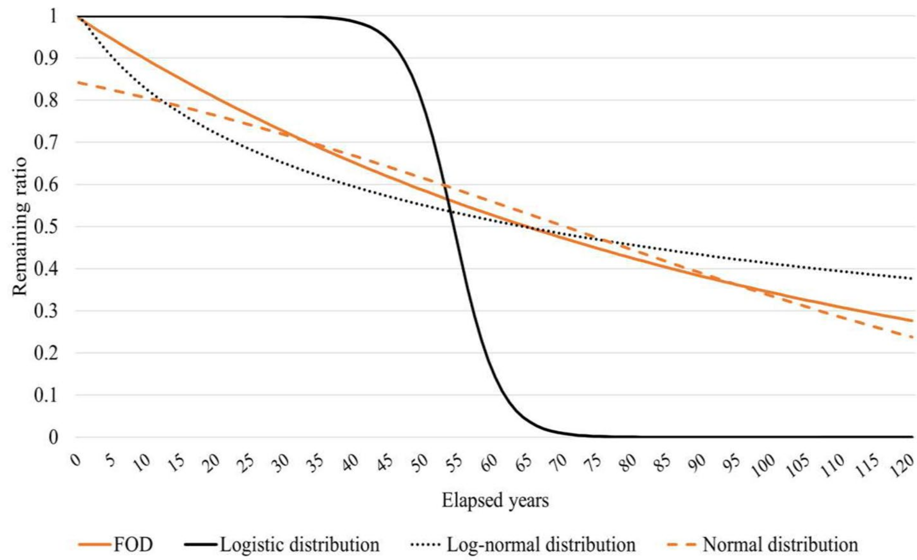

Fig. 4 Decay functions. FOD, first-order decay. Each decay function was calculated by applying half-lives and decay coefficients to minimize the sum of squares of the differences between the results estimated by direct inventory and flux-data methods (values in Table 3)

using the values in Table 3. As shown in Table 3, the closest result to the value estimated by the direct inventory method (minimum sum of squares of difference) was obtained for the log-normal distribution, followed by the normal distribution, FOD, and logistic distribution. However, Fig. 4 shows that the remaining ratio of the normal distribution already decreased to approximately 0.84 in the first year of construction (0 year of elapsed time), and the shape of the function was almost linear, which was not a reasonable shape for a normal distribution. Previous studies [25, 26] have shown that the decay of buildings in Japan present a distribution close to a log-normal or normal distribution, and the verification results of the log-normal distribution in this study were consistent with the trend of previous studies, whereas the normal distribution showed different results.

Table 3 shows that for the logistic distribution, even the shortest HWP half-life, which was more than 50 years, was substantially longer than the half-lives of HWPs proposed by the IPCC (35 and 25 years). This suggests that the values proposed by the IPCC are likely underestimated for buildings in Japan, and this is likely one of the main reasons for the underestimation of carbon stocks in buildings using the flux-data method.

Figure 5 shows the trend in nationwide carbon stocks in buildings from 1990 to 2019 estimated using the direct inventory and flux-data methods applying the values shown in Table 3. Regardless of the decay function, the results were in good agreement with the values estimated by the direct inventory method. Therefore, we can conclude that it is possible to estimate carbon stocks with high accuracy regardless of the decay function. The log-normal distribution minimized the sum of squares of difference, and it was considered the most suitable decay function based on the half-life values and validity of the distribution shape. The second smallest sum of squares of differences was obtained for the normal distribution. However, as mentioned above, the validity of its distribution shape was questionable. In contrast, FOD is a widely recognized decay function provided by the IPCC. It is also a simple function that does not require any parameters other than the HWP half-lives, unlike the other three decay functions targeted in this study. Therefore, as the results indicate that FOD is a suitable decay function to estimate carbon stocks, we concluded that FOD is a versatile decay function for estimating HWP carbon stocks. In addition, Table 3 and Fig. 4 indicate that the shape and half-lives of the log-normal distribution (which presented the smallest sum of squares of difference) were close to the shape and half-lives of FOD. These results also suggest that FOD is a reasonable function for the flux-data method.

As shown in Table 3, the EI values were below the default value for Asia (0.0217) provided by the IPCC guidelines for all decay functions, and they were negative for the log-normal and normal distributions. These facts suggest that the EI values proposed by the IPCC were large compared to the reality of buildings in Japan, and that the HWP volume in buildings before 1960 may not be as small as assumed by the IPCC.

These factors can explain the differences in the results obtained by the direct inventory and flux-data methods.

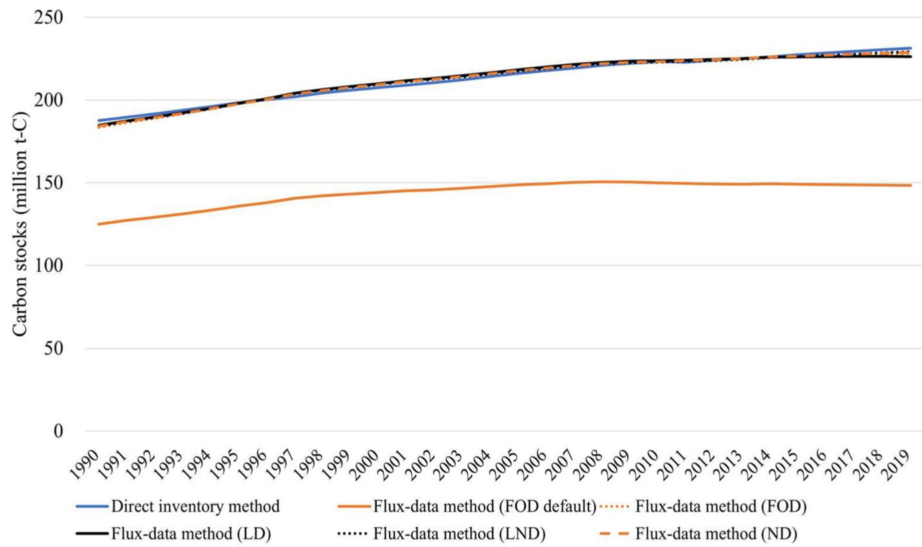

Fig. 5 Nationwide carbon stocks in HWPs of buildings estimated using different methods and parameters. HWPs, harvested wood products; FOD, first-order decay; LD, LND, and ND represent logistic, log-normal, and normal distributions, respectively. The flux-data method (FOD default) uses the default parameters (half-lives and decay coefficients) suggested in the IPCC guidelines, whereas the other flux-data methods consider parameter values that minimize the sum of squares of differences between the values obtained by the direct inventory and flux-data methods (values in Table 3)

As for the decay function, although the log-normal distribution was the most suitable function, FOD was considered a reasonable function as it did not cause substantial estimation changes. As for the half-lives of HWPs, the 35 or 25 years suggested by the IPCC guidelines were underestimated for HWPs of buildings in Japan, because the actual values are likely at approximately 65 years. Therefore, the disparity in HWP half-lives was considered the main cause of the differences between the results. In addition, as the default EI value for Asia proposed by the IPCC was likely not suitable for buildings in Japan, EI was also considered a cause of estimation differences.

Causes of difference by prefecture

Figure 3 shows the carbon stocks of buildings estimated by the direct inventory and flux-data methods for each prefecture, and the results of the flux-data method tended to be closer to those of the direct inventory method in prefectures with large populations and active economies, such as Tokyo and Kanagawa. The results suggest that this phenomenon might be attributed to the average life span of buildings, which differs according to prefecture. The results of the flux-data method were greatly underestimated compared to those of the direct inventory method for Japan, and one of the main reasons was the underestimated half-lives of HWPs. It can be assumed that the prefectures, where the estimated results were similar present an average life span of buildings close to the suggested IPCC values, that is, they might have a shorter average life span of buildings than other regions. This might occur, because a high population and economic activity increase the demand for buildings, which induces the rebuilding of existing structures in a shorter period, thereby decreasing the average life span of buildings. Accordingly, a previous study [27] reported that the average life span of buildings tends to be shorter in cities with larger populations. Therefore, the HWP half-lives proposed by the IPCC are likely shorter than the overall values for Japan, but this is not true for all prefectures. In particular, as the average life span of buildings is expected to be shorter in prefectures with large populations and high economic activity, we consider that the flux-data method using the IPCC half-life values is a relatively reasonable estimation method for these prefectures.

Conclusions

In this study, we estimated the HWP carbon stocks of buildings in Japan by prefecture using the direct inventory method, which has high accuracy, and the flux-data method, which is widely used worldwide. The results verified the accuracy of the commonly used flux-data method. In addition, by deriving parameters and decay functions, the causes of the differences between the results estimated by these two methods were discussed. The main conclusions obtained in this study are as follows:

1. The 2019 nationwide carbon stocks in buildings estimated using the direct inventory method were approximately 231 million t-C, and approximately 148 million t-C (~64% of the former) using the flux-data method based on the default IPCC values. Therefore, the flux-data method significantly underestimated the carbon stocks of buildings in Japan. In addition, the results of the direct inventory method showed an increasing trend in almost all years from 1990 to 2019, whereas the results of the flux-data method showed a decreasing trend after peaking in 2008.
2. The half-lives of HWPs were the main cause of underestimation by the flux-data method, and the actual values are likely higher than the default values proposed by the IPCC. For the decay function, the sum of squares of differences was minimized when the log-normal distribution was used, but when FOD was used, the results were also close to those estimated by the direct inventory method. Therefore, it can be assumed that the decay function was not the main cause of the differences in the estimated results. In addition, because of its versatility, FOD was considered appropriate for such estimations. The results also suggest that the EI of most buildings in Japan are likely smaller than the default value for Asia proposed by the IPCC. Therefore, EI was also considered one of the main causes of the different estimates.
3. The results of the direct inventory and flux-data methods tended to be similar in prefectures with large populations and active economies, such as Tokyo and Kanagawa. This was attributed to the shorter life span of buildings in places with high economic activity owing to the higher need and frequency of rebuilding projects. Therefore, for cities with a more active economy, the estimation results can be relatively reasonable, even if the IPCC default values of HWP half-lives are used.

In this study, the half-lives of HWPs, decay function, decay coefficient, and EI were treated uniformly for all investigated years. However, the half-lives of HWPs and decay tendency of buildings can differ according to the period. To improve the accuracy of the flux-data method, this issue should be addressed. However, it would be difficult to determine the half-lives and decay trends of HWPs by age. It is nearly impossible to obtain these data even for buildings, which have relatively more data available for HWP applications in Japan. Moreover, the greatest advantage of the flux-data method is that it can estimate carbon stocks from data that are relatively easy to obtain. Therefore, this advantage would be greatly diminished if data by age of HWPs were required.

As large errors were obtained for the nationwide estimations of HWP carbon stocks of buildings in Japan, substantial errors are expected to occur for other HWP applications, such as furniture and civil engineering structures and for other countries and regions upon use of the flux-data method using the IPCC default values. Therefore, the findings of this study are useful for other applications and countries as they help elucidate the accuracy and associated factors for estimations of carbon stocks in HWPs using the flux-data method. Especially in Japan, it is necessary to consider that the HWPs used for other applications, including furniture and paper, for which the flux data method is used to estimate the annual change in carbon stocks, are likely to have large errors in the estimated results. In addition, since the findings of this study can contribute to improving the accuracy of the flux data method, it will be possible to use this method to make simpler and more accurate estimates of the carbon stocks in HWPs of buildings, where the direct inventory method is currently used in the NIR.

Abbreviations

HWPs: Harvested wood products; IPCC: Intergovernmental Panel on Climate Change; NIR: National Inventory Report; FOD: First-order decay; EI: Estimated continuous rate of change in industrial roundwood consumption between 1900 and 1961; UNFCCC: United Nations Framework Convention on Climate Change; W: Wooden buildings; SRC: Steel-reinforced concrete buildings; RC: Reinforced concrete buildings; S: Steel buildings; CB/O: Concrete blocks/other buildings.

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Author contributions

RM and CK provided the conceptualization of this research and were responsible for the methodological part of the study. Data curation was performed by RM. The first draft of the manuscript was written by RM, whereas CK performed review and editing steps. CK was also responsible for the funding acquisitions of this research. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Graduate School of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan. [2]Institute of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan.

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References

1. Intergovernmental Panel on Climate Change (IPCC) (2014) Working Group III contribution to the fifth assessment report of the intergovernmental panel on climate change. In: climate change 2014: mitigation of climate change. Cambridge University Press, Cambridge.
2. United Nations Framework Convention on Climate Change (UNFCCC) (2019) Decision 18/CMA.1 modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement (FCCC/PA/CMA/2018/3/Add.2). Poland. https://unfccc.int/sites/default/files/resource/cma2018_3_add2_new_advance.pdf?msclkid=49b521f4b92711ecb805f329e26e1a4b. Accessed 25 Mar 2022
3. IPCC, Pingoud K, Skog KE, Martino DL, Tonosaki M, Xiaoquan Z (2006) Harvested wood products. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) 2006 IPCC guidelines for national greenhouse gas inventories: agriculture, forestry and other land use, vol 4. Institute for Global Environmental Strategies (IGES), Hayama
4. Rüter S, Matthews WR, Lundblad M, Sato A, Hassan RA (2019) Harvested wood products. In: Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S (eds) 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: agriculture, forestry and other land use, vol 4. IPCC, Geneva
5. Greenhouse Gas Inventory Office of Japan and Ministry of the Environment, Japan (2021) National greenhouse gas inventory report of Japan 2021. Chapter 6. Center for global environmental research, earth system division. National Institute for Environmental Studies, Ibaraki, p 6-73–6-84.
6. Suyari A, Shinoda Y, Kayo C (2020) Carbon stocks in harvested wood products in various countries of the world. J Jpn Wood Res Soc 66:76–86. https://doi.org/10.2488/jwrs.66.76
7. Marland ES, Stellar K, Marland GH (2010) A distributed approach to accounting for carbon in wood products. Mitig Adapt Strateg Glob Change 15:71–91. https://doi.org/10.1007/s11027-009-9205-6
8. Fishman T, Schandl H, Tanikawa H, Walker P, Krausmann F (2014) Accounting for the material stock of nations. J Ind Ecol 18:407–420. https://doi.org/10.1111/jiec.12114
9. Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, Miatto A, Schandl H, Haberl H (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. PNAS USA 114:1880–1885. https://doi.org/10.1073/pnas.1613773114
10. Kalt G (2018) Carbon dynamics and GHG implications of increasing wood construction: long-term scenarios for residential buildings in Austria. Carbon Manag 9:265–275. https://doi.org/10.1080/17583004.2018.1469948
11. Zhang X, Chen J, Dias AC, Yang H (2020) Improving carbon stock estimates for in-use harvested wood products by linking production and consumption—a global case study. Environ Sci Technol 54:2565–2574. https://doi.org/10.1021/acs.est.9b05721
12. Tsunetsugu Y, Tonosaki M (2010) Quantitative estimation of carbon removal effects due to wood utilization up to 2050 in Japan: effects from carbon storage and substitution of fossil fuels by harvested wood products. J Wood Sci 56:339–344. https://doi.org/10.1007/s10086-009-1107-4
13. Kayo C, Tsunetsugu Y, Tonosaki M (2015) Climate change mitigation effect of harvested wood products in regions of Japan. Carbon Balance Manag 10:24. https://doi.org/10.1186/s13021-015-0036-3
14. Tonosaki M, Tsunetsugu Y, Takagi M (2015) Estimation of carbon storage by wood-based panels in Japan. Wood Ind 70:424–427
15. Pingoud K, Perälä A-L, Pussinen A (2001) Carbon dynamics in wood products. Mitig Adapt Strateg Glob Change 6:91–111. https://doi.org/10.1023/A:1011353806845
16. Local Taxation Bureau, Ministry of Internal Affairs and Communications (1990–2019) Summary reports on the prices of fixed assets. Ministry of Internal Affairs and Communications, Tokyo.
17. Matsumoto R, Kayo C (2021) Carbon stocks in harvested wood products used in buildings in Japanese prefectures. J Japan Wood Res Soc 67:138–148. https://doi.org/10.2488/jwrs.67.138
18. Hashimoto S, Moriguchi Y (2004) Data book: material and carbon flow of harvested wood in Japan. Center for Global Environmental Research, National Institute for Environmental Studies, Japan, Ibaraki.
19. UNFCCC (2019) Decision 4/CMA.1: further guidance in relation to the mitigation section of decision 1/CP.21 (FCCC/PA/CMA/2018/3/Add.1). Poland. https://unfccc.int/sites/default/files/resource/cma2018_3_add1_advance.pdf?msclkid=b0c30830b92b11eca0e0a2345b203f77. Accessed 25 Mar 2022
20. Land Construction Industry Bureau, Ministry of Land, Infrastructure, Transport and Tourism (1981–2019) Report on the survey on labor demand and construction materials (construction sector). Ministry of Land, Infrastructure, Transport and Tourism, Tokyo
21. Infrastructure Transport Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2021) Newly constructed building statistics report. https://www.mlit.go.jp/sogoseisaku/jouhouka/sosei_jouhouka_tk4_000002.html. Accessed 28 Nov 2021
22. Construction Economics Bureau, Ministry of Construction (1962–1989) Building statistics annual report. Tokyo
23. Statistics Division, Minister's Secretariat, Ministry of Agriculture, Forestry and Fisheries (2021) Timber supply and demand report. https://www.maff.go.jp/j/tokei/kouhyou/mokuzai/. Accessed 28 Nov 2021
24. Statistics Bureau, Ministry of Internal Affairs and Communications (2021) Population projection. https://www.stat.go.jp/data/jinsui/2.html#series/. Accessed 28 Nov 2021
25. Komatsu Y, Kato Y, Yoshida T, Yashiro T (1992) Report of an investigation of the life time distribution of Japanese houses at 1987: estimation based on the ledgers of buildings for fixed property taxes. Trans AIJ J Archit Plan Environ Eng 439:101–110. https://doi.org/10.3130/aijax.439.0_101
26. Tsutsumi H, Komatsu Y (2004) Transition of the lifetime of wooden houses since 1980. Trans AIJ J Archit Plan Environ Eng 69:169–174. https://doi.org/10.3130/aija.69.169_2
27. Komatsu Y (2008) Life time estimations of Japanese buildings and houses at the years of 1997 and 2005. Trans AIJ J Archit Plan Environ Eng 73:2197–2205. https://doi.org/10.3130/aija.73.2197