Carbon Accounting in Harvested Wood Products

Assessment Using Material Flow Analysis Resulting in Larger Pools Compared to the IPCC Default Method

Gediminas Jasinevičius, Marcus Lindner, Emil Cienciala, and Markku Tykkyläinen

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Summary

Increasing the amount of carbon stored in harvested wood products (HWPs) is an internationally recognized measure to mitigate climate change. Several approaches and tiers of methods may be used to analyze the contribution of HWP in terms of greenhouse gas emissions and removals at a regional and national level. The Intergovernmental Panel on Climate Change (IPCC) provides guidelines on three tiers of methods for estimating annual carbon stock changes in the carbon pool of HWPs. These tiers mostly differ by the availability of input data and the level of HWP aggregation. In this case study for the Czech Republic, we have applied the production approach and alternative tiers of accounting methods, which are described in the IPCC guidelines, including the default method (tier 2) and the most advanced method (tier 3). We used country-specific data and material flow analysis to trace the carbon flow over the entire forest-based sector, including only the domestic harvest and the primary and secondary wood products manufactured within the country. The results of this study show that the carbon stored in the HWP pool could be underestimated if simpler methods and default values nonspecific to the country are applied. At the national level, applying the tier 3 method resulted in a 15.8% higher annual carbon inflow in the pool of HWPs compared to the tier 2 IPCC default method. This means that the advanced method reveals an apparently higher carbon sink in HWPs. A documented increase of carbon storage might bring additional credits to reporting countries, and, more important, it could promote the use of long-life HWPs to mitigate climate change.

Introduction

Background

Through photosynthesis, forests capture carbon dioxide (CO_2) from the atmosphere and store carbon in biomass. After forest harvest, a significant amount of carbon is removed and could be held for decades in harvested wood products (HWPs) (Anderson et al. 2013). In the last decades, European forests have removed more carbon from the atmosphere than the amount that was released through burning or decomposition of biomass (Nabuurs et al. 2013; Goodale et al. 2002). It is estimated that European Union (EU) forests and the forest sector currently produce an overall climate-mitigation impact that amounts to around 13% of the total EU emissions (Nabuurs et al. 2015). Approximately 10% of this carbon might be stored in HWPs (Pilli et al. 2015). The use of wood is also associated with lower emissions of CO_2 and other pollutants when compared to alternative material (Gustavsson et al. 2006; Sathre

Address correspondence to: Gediminas Jasinevičius, European Forest Institute, Sustainability and Climate Change Unit, Yliopistokatu 6, Joensuu 80101, Finland. *Email:* gediminas.jasinevicius@efi.int; *Web:* www.efi.int

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and Gustavsson 2009; Eriksson et al. 2012). Therefore, the use of wood products can lead to a reduction in atmospheric carbon by displacing the more fossil fuel (FF)-intensive products that are used, for example, in housing construction (Perez-Garcia et al. 2005). Thus, the use of HWP can contribute to climate-change mitigation in two different ways: by increasing the total carbon storage in HWPs and by substituting emissions from FFs.

In 2011, at the UNFCCC Conference in Durban, the parties of the conference recognized carbon storage in HWPs as a measure to mitigate climate change by agreeing on the primary carbon accounting and reporting rules (United Nations 2012). The parties decided that the Annex I countries (i.e., developed nations and nations with economies in transition; in total, 43 countries) that agreed to take on commitments to reduce greenhouse gas (GHG) emissions shall report carbon stock changes in HWPs for the second commitment period of the Kyoto protocol (2013–2020) (United Nations 2012). However, it should be noted that the carbon pool in HWPs at the country level may act as a sink or as a source of CO_2, depending on the balance between the carbon inflow and outflow. The main factors influencing carbon stock change in the national pool of HWPs are: domestic wood supply (harvest level); the shares of saw logs; pulpwood and energy wood; the service life of products; and the end use of wood products, such as for disposal/recycling or for use as fuel (Pingoud et al. 2010). It has also been shown that these factors vary between countries (Kim and Song 2014). The estimates of the HWP carbon balance are strongly dependent on the applied accounting approach and data availability (Skog 2008). There are few examples published so far that analyze carbon flow over the entire forest-based sector (Mantau 2015) and periodical reporting of wood flows in Austria (AEA 2016). However, at present, comparative investigations of different accounting methods are largely lacking.

Carbon Accounting Methods and Reporting Practice

The Intergovernmental Panel on Climate Change (IPCC) provides reporting guidelines for countries to estimate the carbon stock changes in HWPs (IPCC 2006, 2014). They propose to use one of three accounting methodological tiers (levels), named tier 1, 2, or 3, respectively, depending on the availability of country-specific activity data and methodology. In the tier 1 method, carbon in HWPs is assumed to be oxidized at the year of forest harvest. Thus, this method makes the simplistic assumption of no carbon stock in HWPs. The tier 2 method requires estimating the HWP carbon pool and its changes for the three default HWP categories, namely: sawnwood; wood-based panels; and paper and paperboard. Country-specific information, factors, and/or methodologies are not required given that the method and data source are proposed by the IPCC guidelines. The tier 3 method foresees estimating the HWP carbon pool and its changes by using country-specific half-life values and/or methodologies covering, at least, the three semifinished HWPs mentioned above. The specific differences between tier 2 and 3 as they were applied in this study are more explicitly described below (table 1).

The guidelines (United Nations, decition 2/CMP.7, 2012) propose the following principles: (1) Carbon shall be accounted only from domestic harvest; (2) carbon stock change shall be estimated using the first-order decay function with default half-life values, where carbon stock change in a particular year is estimated based on annual carbon inflow into the stock and the default lifetimes of products. The default half-life values of products could be replaced by those that are country-specific; and (3) accounting shall be on the basis of instantaneous oxidation for HWPs resulting from deforestation and from wood harvested for energy purposes if verifiable and transparent activity data are not available (United Nations 2012).

Given that carbon reporting of HWP was voluntary in the first commitment period of the Kyoto Protocol (2008–2012), only limited experience exists among the parties. Only 8 of 43 Annex I countries reported HWP carbon for the first commitment period of the Kyoto Protocol. The reporting countries used different approaches and methodologies for estimating the carbon in HWPs. Some of the countries identified improvements that would be needed for better carbon estimates in their National Inventory Reports (NIR). For example, Latvia reported that statistical data on roundwood use by the industry sector are needed for better estimates. Wood density of different tree species should be considered when estimating the national carbon pool, because wood density varies among tree species (NIR Latvia 2014). Canada reported that temporal coverage is limited by the available Food and Agriculture Organization of the United Nations (FAO) trade flow data (NIR Canada 2014). Although the national carbon stock estimates bring valuable information, the national reports under UNFCCC are not detailed enough to provide guidance on methodological development; thus, additional research is needed.

Denmark could not report the HWP emissions because of a lack of data (NIR Denmark 2014). Meanwhile, new research on HWPs for Denmark revealed several inconsistencies between the Food and Agriculture Organization of the United Nations, Statistics Division (FAOSTAT) and the statistics of Denmark caused by: (1) faulty FAOSTAT data; (2) products reported in the wrong categories (e.g., roundwood reported for lumber production may, in fact, be used for industrial purposes); and (3) uncertainties in value-to-volume conversion (Schou et al. 2015).

A material flow analysis (MFA) on the primary use of roundwood in Slovakia indicated that the consumption of wood was 16% higher than the domestic wood consumption reported in statistics, attributed to the use of industrial wood residues (Parobek et al. 2014). The EU-level study by Mantau (2012) applied wood flow analysis, integrating all wood products to calculate the wood resource balance in the production of semifinished products and energy use. These cases illustrate that better activity data on domestic wood use for HWPs might improve estimates of the national carbon pool. Reporting practices vary between the countries, and, more important, an understanding of how methodological choices affect the national estimates of carbon pool change is needed.

The objective of this national case study was thus to explore how the tier 3 method using MFA and country-specific data

Table 1 General characteristics of the tier 2 and 3 methods applied

Characteristics	*Tier 2*	*Tier 3*
Approach	Default method (IPCC 2014)	Material flow analysis
System boundaries	Primary HWPs (sawnwood, wood-based panels, and paper and paperboard)	Primary and secondary HWPs (sawnwood, wood-based panels, paper and paperboard, pulp for viscose, sawnwood [for EURO pallets], carpentry products, packaging, flooring, and wooden construction and flooring)
Data source	FAOSTAT (production, imports and exports for primary HWPs)	Country specific (wood flow through the production processes of primary and secondary HWPs, derived from survey results; see *Country-Specific Data on Harvested Wood Products*); data on forest harvest and exports derived from national statistics (CZMA 1993–2013; preceding 1993 from FAOSTAT and country-specific factors)
Proportion of domestic wood harvest in HWPs	Estimated from apparent consumption (FAOSTAT data)	Imports of HWPs excluded from the material flow analysis
Carbon conversion factors (dry wood density)	Default factors (IPCC 2014)	Country-specific factors derived from local studies (Vavrčík and Gryc 2012; Zeidler 2012; Gryc et al. 2011) (see table S1-6 in supporting information S1 on the Web)
Half-life values	Default values (IPCC 2014)	Country-specific values derived from survey results for log houses, viscose pulp, and EURO pallets; default values for sawnwood, paper, and wood-based panels (IPCC 2014)

Note: HWPs = harvested wood products; FAOSTAT = Food and Agriculture Organization of the United Nations, Statistics Division.

affect the estimate of the carbon pool in HWPs compared with tier 2 method (IPCC 2014).

Data and Methods

Forest-Based Sector in the Czech Republic

In the Czech Republic, there are approximately 2.6 million hectares of forests, consisting predominantly of conifers. Almost 60% of the total forest area is owned by the state. The annual harvest in the year 2013 was 15.3 million cubic meters (m^3) of roundwood (under bark), of which 13.2 million m^3 was industrial roundwood that could be used for manufacturing wood products. The trade balance of roundwood and primary wood products is negative because of the exports to neighboring countries, mainly to Austria and Germany (see table S1-1 in supporting information S1 available on the Journal's website). The wood industry has traditionally consisted mainly of small- and medium-sized enterprises, but foreign investments have led to the appearance of a few large producers (Inno 2008). The sawmill industry consumes over 60% of domestically available industrial roundwood. The rest is mainly consumed by the pulp and paper– and wood-based panel industries. Roundwood for fuel and removed felling residues constitute 25% of the total harvest, but these two commodities are not accountable for carbon storage in HWPs attributed to the short life span of those commodities.

After the dissolution of Czechoslovakia in 1993, the production of primary wood products in the Czech Republic has increased, on average, across all categories by 27%, mainly attributed to increased fellings (CZMA 2014). The proportion among primary wood products remained roughly stable, with some deviations caused by economic factors or natural hazards (figure S1-1 in supporting information S1 on the Web).

Material Flow Analysis

By applying MFA, it is possible to trace the wood (carbon) in the forest-based sector (Binder et al. 2004; Korhonen et al. 2001). In this case study, we traced the carbon flow from forest harvest through the production processes of primary and secondary wood products (figure 1) in the literature also named as semifinished and finished HWPs, respectively. Primary wood products include roundwood, sawnwood, wood-based panels, and pulp. Primary products include also recovered materials, such as recovered paper for production of pulp. Secondary wood products are those that have been further processed, including furniture, carpentry products, packaging, flooring, wooden constructions, etc.

A wood flow analysis is useful for estimating the current carbon stock (Päivinen et al. 2012; Jasinevičius et al. 2015). For this study, we built a national wood value chain for the Czech Republic, using country-specific data on wood-based material flows and their parameters, such as the allocation coefficients of wood materials to industrial production and carbon conversion factors (table 1). The wood value chain was built in accord with carbon accounting principles, which have been agreed upon internationally as described above in the *Introduction*. Imported HWPs

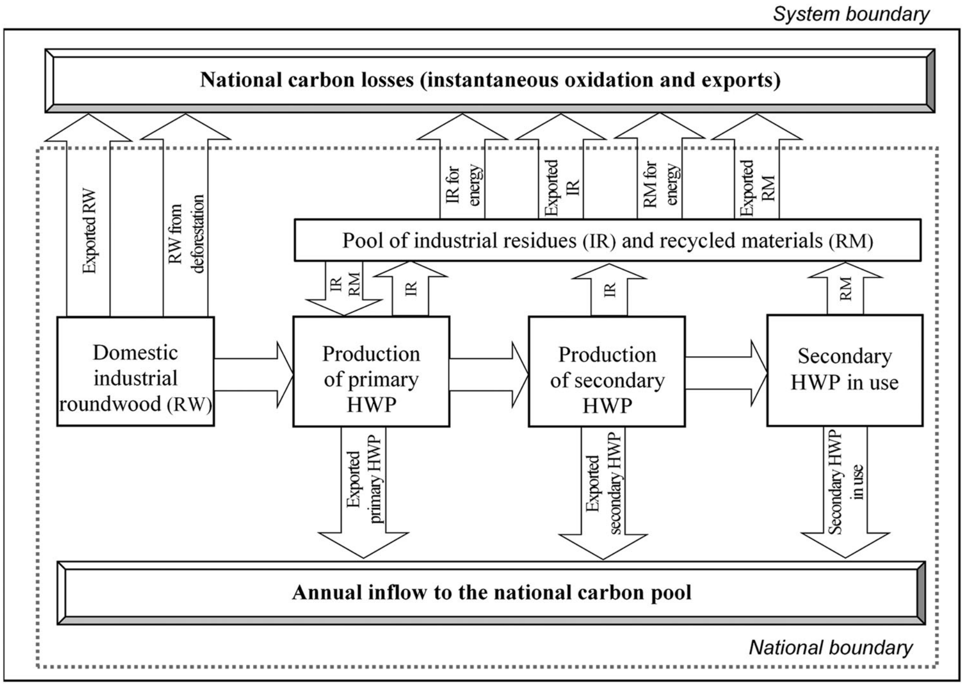

Figure 1 Scheme of wood-based carbon flows in the forest-based sector in the Czech Republic (year 2013). The boxes represent wood processing processes or temporary carbon pools (e.g., recovered paper, industrial residues). The horizontal and vertical arrows represent domestic carbon flows entering and leaving processes. HWP = harvested wood product.

and industrial roundwood from deforestation activities are excluded from the wood chain. The export of domestic industrial roundwood is considered as a national carbon loss and is not included in the national carbon budget (figure 1). According to the IPCC guidelines, the tier 3 method should at least cover the three primary HWP categories (sawnwood, wood-based panels, and paper and paperboard). In this study, we covered six categories of primary HWP. In summary, the method described above is in line with the accepted carbon accounting principles and meets the tier 3 method requirements.

In order to compare the results of the different methods, we also estimated the emissions and removals from HWPs by applying the IPCC tier 2 method. We applied the methodology proposed in the IPCC good practice guidelines (IPCC 2014). In this case, we used historical FAOSTAT data for primary wood products (i.e., sawnwood, wood panels, and paper) for the period from 1961 to 2013 (FAOSTAT 2016). Historical data from 1961 to 1992 were estimated by applying country correction factors attributing the country-specific proportion for the Czech Republic, because previous 1993 FAOSTAT data are available only for the former Czechoslovakia. These factors were derived from the country-specific data reported for the period from 1993 to 1997, the first 5 years of the two separate independent states after separation.

MFA includes also carbon pool in secondary HWPs. Domestic feedstock for the secondary HWPs was estimated by using the shares of apparent consumption (production minus export) of primary HWPs (UNECE 2014). For the purpose of this study, we grouped the secondary HWPs based on similar production patterns and material used (table S1-3 in supporting information S1 on the Web). However, the comparison of methods includes only primary wood products, because the tier 2 method does not propose accounting guidelines for secondary wood products.

Country-Specific Data on Harvested Wood Products

Country-specific data on felling removals and partly on primary wood products are available from national statistics. However, data on wood material flow over the entire sector are not provided and had to be collected.

We developed a survey for wood processing companies (see supporting information S2 on the Web) to collect data on the commodities entering and leaving the production processes in these companies. Data on the use of industrial residues were also gathered. For example, we asked whether residues were used for production of wood products or for energy generation. In addition, we asked producers to estimate the average lifetime of the main products manufactured.

According to the Czech statistics, there were 29,362 companies and 33,147 employed persons in the sector of wood processing and wooden products as of 2013 (table S1-1 in the supporting information S1 on the Web). However, some of those companies are inactive or very small (on average, 1.1 employees per company). Therefore, we targeted the large operating companies involved in the Czech wood production and wood processing industry in order to cover the majority of the wood flow in the country; however, we also interviewed small- and medium-sized enterprises to get a sample representing the more dispersed minor wood flows. Additionally, the principle wood industry associations were also approached. In total, 42 companies responded (of 150 approached) to the survey and most of them were interviewed using on-site visits. As a result, we received the responses corresponding to 60% of domestic material inflow to primary and 10% to secondary wood products (table S1-2 in the supporting information S1 on the Web).

The country-specific parameters considered in this study included the composition of wood species and wood density. Fellings by tree species were taken from national statistics (CZMA 2014) and wood density from country-specific studies. Carbon conversion factors for primary products were calculated from the oven-dry mass of coniferous and nonconiferous roundwood (table S1-6 in supporting information S1 on the Web).

In the Czech Republic, logs are classified according to their quality grade (three grades [I to II]I and four subgrades [A to D]). This grading also defines the purpose of wood use (Hüner and Trůbl 2007). We applied this country-specific methodology for allocating the domestic harvest to the production lines of HWPs (tables S1-4 and S1-5 in supporting information S1 on the Web).

For estimating the carbon stock changes, we used the flux data method and a first-order decay function as described in the IPCC guidelines, chapter 2.8.3 (IPCC 2014). The initial stock is based on the average of inflow during the first 5 years for which data are available (average of 1961–1965).

In addition to the three IPCC categories, we defined three new nationally relevant categories of primary HWPs (wood for log houses, pulpwood for viscose, and wood for EURO pallets). The half-life values for the new three categories were estimated from the survey responses (table 2).

The carbon stock changes are projected until 2030 for both methods tier 2 and 3. The annual carbon inflow is based on future removals of roundwood, given that removals and carbon inflow in the Czech Republic were closely related in the past (figure 2). Forest harvest projections were published in the European Forest Sector Outlook Study II (UNECE and FAO 2011). The harvest projections for the outlook study were estimated by using the European Forest Information Scenario Model—EFISCEN (Sallnäs et al. 1990; Schelhaas et al. 2007). However, the outlook study results are based on data preceding 2010, and projections are out of date; thus, we ran EFISCEN (version 3.1.3) in 2015 by using up-to-date country-specific information on forest resources and management in the Czech Republic.

Results

In order to compare the results of different carbon accounting methods, we estimated the carbon inflow and stock change by applying both tier 2 and 3 IPCC methods.

The results of the tier 2 method show covariation between roundwood removals and carbon inflow from the main product groups in to the pool of HWPs (figure 2). This indicates that, in the Czech Republic, the main driver for carbon inflow into the pool of HWPs is domestic roundwood removals.

The tier 3 method based on MFA and country-specific data revealed the structure of the wood processing industry in the Czech Republic and their associated carbon flows from domestic harvest as shown in figure 3.

MFA shows that carbon inflow into the primary HWP was higher than the domestic industrial roundwood supply. The higher inflow is attributed to the use of industrial residues and recovered paper for the production of pulp and wood–based panels. According to the survey results, up to 50% of feedstock for pulp and wood–based panels consists of industrial residues, mainly chips and sawdust, derived from the production of primary and secondary wood products. The inflow into the primary wood products associated with residue use contains 336 kilotonnes (kt) of carbon (figure 3). The rest of industrial residues is consumed for energy or exported. The comparison of methods shows that the annual carbon inflow into the carbon pool of primary HWPs is 15.8% higher with the tier 3 method when compared to the tier 2 method (figure 4).

By applying the tier 3 method, the estimated carbon stock, on average, is 16% higher when compared with the tier 2 method, specifically, 45.7 and 53.2 million tonnes (Mt), respectively (figure 5).

Discussion

We collected country-specific data on HWPs in the Czech Republic and quantified carbon stock and stock changes in HWPs using two different accounting methods: the tier 2 IPCC default method and the more-advanced tier 3 method. When applying tier 3 method, the carbon stock, on average, was estimated to be 16% higher when compared to the default

Table 2 Country-specific and default half-life values for primary wood products used in this study

HWP category	*Source*	*Half-life (years)*	*Proportion of carbon inflow (%)*
Wood for log houses	Estimates, this study	45	1
Sawnwood	IPCC default	35	47
Wood-based panels	IPCC default	25	31
Pulp for viscose	Estimates, this study	5	8
Sawnwood (for EURO pallets)	Estimates, this study	3	4
Paper	IPCC default	2	9

Note: IPCC = Intergovernmental Panel on Climaate Change.

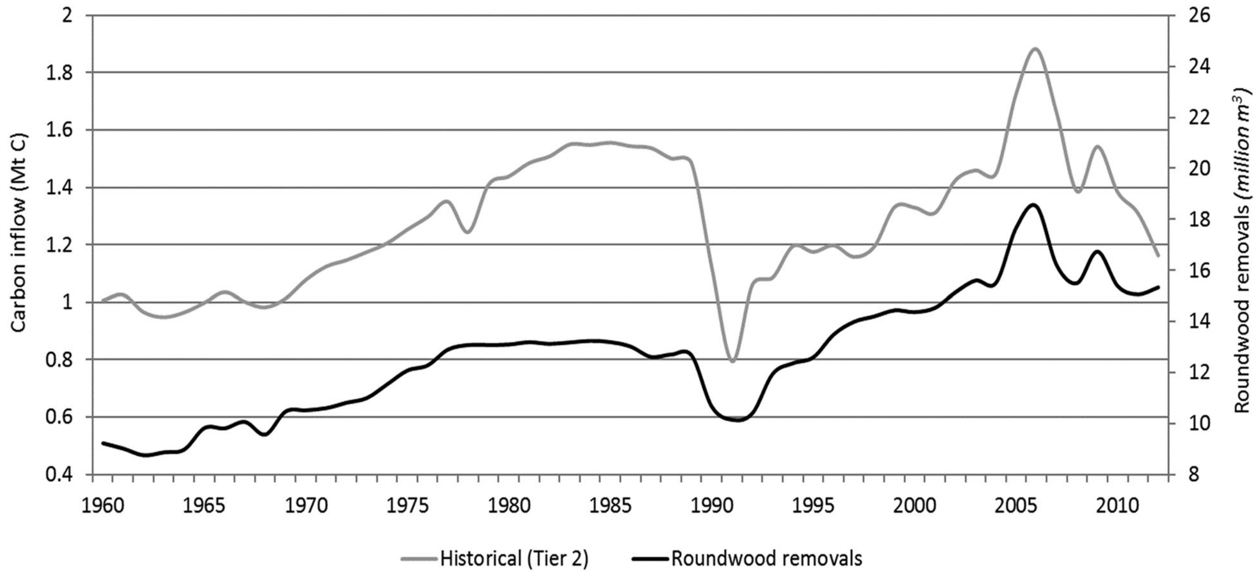

Figure 2 Domestic roundwood removals and carbon inflow into the pool of HWP. High wood removals in the year 2007 reflect salvage felling following the windstorm "Kyrill." Low wood removals in the years 1991–1994 are related to the collapse of the Soviet Union, followed by economic downturn. HWP = harvested wood product. m^3 = cubic meters; Mt C = million tonnes of carbon.

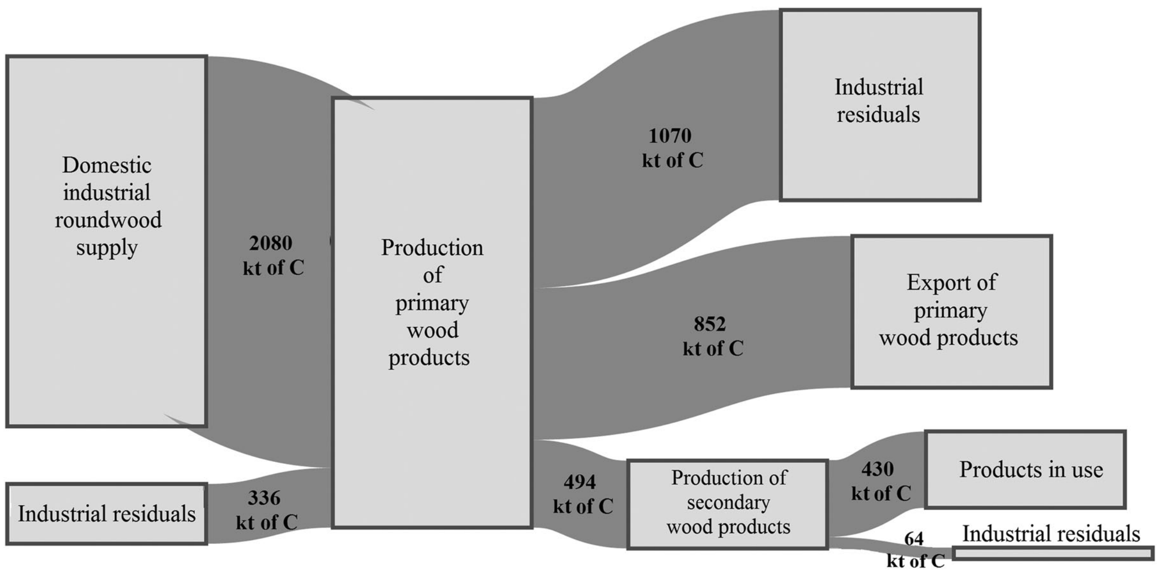

Figure 3 Carbon (material) flow in the Czech Republic using a simplified structure of the wood processing industry. In this figure, carbon is reflected only from domestic harvest and domestic industrial residues. The output includes domestic product use, exported products, and industrial residues from production of primary (including nonwooden residues from pulp industry) and secondary wood products. For more details on carbon flow, see figure S1-4 in supporting information S1 on the Web. kt of C = kilotonnes of carbon.

method of tier 2. The annual carbon inflow into the HWP pool was 15.8% higher in 2013 with the tier 3 method, and this appears to be mainly caused by the industrial residue usage for the production of primary HWPs, which is not considered in the tier 2 method. To our knowledge, this is the first national comparison study carried out to compare the tier 2 and 3 methods for the reporting of HWP carbon stock changes. HWP reporting is mandatory for Annex II countries of the Kyoto Protocol for the second commitment period, and countries will have to establish their HWP accounting practices. When choosing between alternative methods, these results might be seen as an incentive for the use of the tier 3 method because the observed HWP carbon storage is substantially larger when compared to calculation with the tier 2 method. An Irish case study also found increasing carbon pools in HWPs and identified them as a considerable potential to support GHG mitigation (Donlan et al. 2012). On the other hand, a scenario projection for the EU-28 found that the HWP sink will slowly tend to saturate and

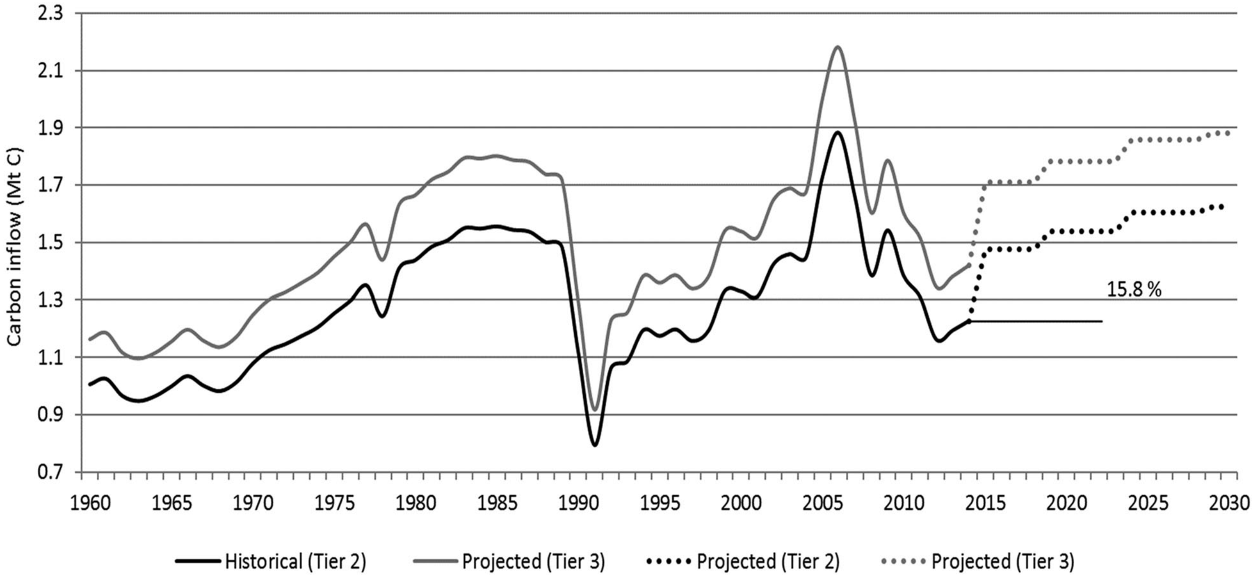

Figure 4 Historical and projected carbon inflow into the national HWP pool under tier 2 and 3 methods. Carbon inflow in 2013 was estimated to be 15.8% higher when applying the tier 3 method. This comparison includes only primary wood products, because the tier 2 method does not propose accounting guidelines for estimating carbon inflow for secondary wood products. HWP = harvested wood product; Mt C = million tonnes of carbon.

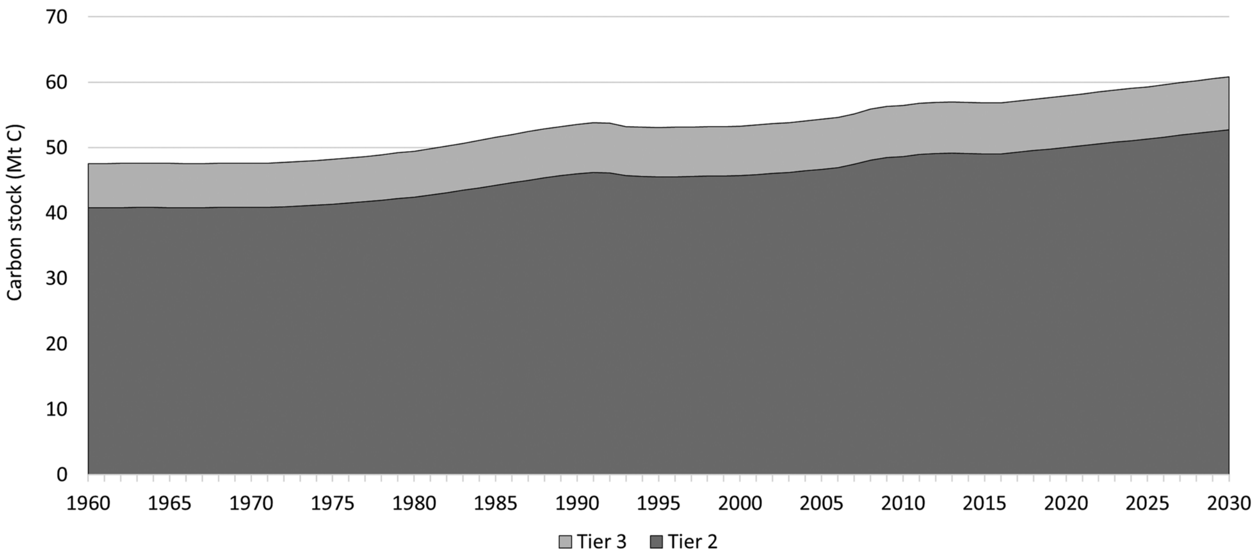

Figure 5 Total carbon stock in HWP under tier 2 and 3 methods. On average (years 1961–2030), carbon stock is higher by 16.2% when the tier 3 method is applied compared with the tier 2 method. The initial carbon stock is based on the average of inflow during the first 5 years for which data are available as proposed by IPCC guidelines (IPCC 2014). For carbon stock change, see figures S1-2 and S1-3 in supporting information S1 on the Web. HWP = harvested wood product; Mt C = million tonnes of carbon.

approach zero in the long term (Pilli et al. 2015). Both studies applied a tier 2 method. Similar to the Irish case study, we found, for the Czech Republic, a considerable potential for enhanced carbon storage in HWPs. Following a stabilization of the sector after the economic crises of the 1990s, the sink is also projected to increase in the future, mainly because of increased harvests and the introduction of wood products with longer lifetime.

The tier 3 method could be applied in more countries, if reliable data on HWPs are available. In most countries, the data on domestic primary and, especially, secondary wood products do not exist because of the large number of commodities and their trade. Further, the HWP sector is influenced by the global market and is also affected by natural hazards. For example, in the case of the Czech Republic, salvage fellings increased dramatically attributed to the wind storm in 2007 (CZMA 2008), which influenced the production of HWPs and carbon inflow into the pool (figure 2). Therefore, several simplifying assumptions and uncertainties should be discussed.

The Czech wood industry is composed of a few large, and many medium and small, companies. Given that response rates to data surveys from the industry tend to be low, especially from small- and medium-sized enterprises, we decided to target the large companies with our survey and made additional efforts to collect some information from the diverse smaller companies. When we designed the survey, it was decided to cover as much of the total material flow as possible. We succeeded in getting responses representing 60% of the domestic Czech wood material flows in 2013. The survey results have shown that production efficiency (material inflow and outflow) is very similar in the enterprises, irrespective of their size. The highest divergence in the same group of producers was 6%.

By applying MFA, we were able to separate domestic and imported carbon over the entire wood chain, including secondary production. In the forest wood chain, we included only domestically harvested industrial roundwood. However, the production of primary wood products also includes industrial residues as they were reported by the producers. It remains to be determined whether the incorporated residues are domestic. We assume that most industrial residues are domestic because of the fact that the Czech Republic is a net exporter of roundwood and industrial residues (in 2013, the export and import of residues was 1.4 and 0.7 million m^3, respectively) (UNECE 2014). Further, during our investigation we observed that large pulp mills are located next to saw mills in order to reduce the transportation costs of residuals. It could be that a small fraction of residues associated with imported industrial roundwood is mixed with domestic residues, but given that the volume of roundwood imports into the Czech Republic is small, we assume that this fraction is negligible.

In order to quantify the carbon in HWPs, we applied country-specific conversion factors. For primary wood products, we calculated factors from the oven-dry mass of coniferous and nonconiferous roundwood. Those factors differ slightly from default conversion factors proposed by IPCC guidelines (IPCC 2014). For instance, in the case of sawnwood, we estimated conversion factors of 0.226 and 0.310 megagrams of carbon per m^3 (Mg C/m^3) for coniferous and nonconiferous roundwood, respectively, instead of the 0.225 and 0.280 Mg C/m^3 proposed by the IPCC. Even this slight difference, particularly for nonconiferous roundwood, has an impact on national carbon estimates. Sensitivity analysis showed that country-specific conversion factors increased annual carbon inflow for primary wood products by 1.5%.

In this study, the country-specific data, especially regarding secondary wood products, are rather unique given that such data are largely missing in other countries. Comparable data have been reported at a much more aggregated level for Europe (Mantau 2012). However, the collected data for the Czech Republic refer to one year only, 2013. Therefore, a major weakness of this study is that we had to assume that there were stable material flow characteristics for the past given that most of the wood processing companies were not able to report the material flow for past years. Because the proportions between the main HWPs is roughly the same (figure S1-1 in supporting information S1 on the Web) and given that the production of HWPs is related to the domestic harvest (figure 2), we have assumed that the relative difference of carbon inflow estimates between tier 2 and 3 applies also to historical data and future projections. This assumption is necessary in order to be able to estimate carbon stock changes and compare them across the two accounting methods. If the survey were to be repeated in the future, the values for the intermediate years could be interpolated. For the historic situation, it is unlikely that such data could be reconstructed without major uncertainties.

We maintain that it is useful to apply country-specific wood flows and carbon conversion factors because they are most strongly affected by the structure of the forest-based sector and, most likely, are less affected by annual fluctuations. However, in the long term, wood flows could fluctuate, influenced by the demand and supply of HWPs or by the efficiency of the wood industry. The country-specific half-life values may be considered relatively stable and realistic for the near- to mid-term future. It should be noted, however, that the use of wood for certain products has only a limited history because, for example, viscose production was only recently expanded to a larger scale. Similarly, the projections into the longer-term future cannot account for new product developments, which might be associated with very different half-life values compared to the current products made from similar wood assortments.

The lifetime of products depends on many factors, including not only their functional life span, but also economic cycles or fashion trends, which very likely vary from one country to another (Chang et al 2014). HWP half-life values in the United States were found up to 100 years for wooden single-family houses, including disposal in dumps and landfills (Skog and Nicholson 1998). Realistic half-life of paper products in Austria was found to be 4.6 years, more than twice the default half-life of 2 years as proposed by the IPCC guidelines (Bird 2013). In this study, we investigated the lifetime for six categories of HWPs: log houses; sawnwood; wood-based panels; EURO pallets; pulp for paper; and pulp for viscose (table 2). Whereas default lifetime values of HWPs result from averaging diverse products, we found that the specific product mix of the Czech forest-based sector could deviate significantly from the default values proposed by the IPCC guidelines. In recent years, a large share of sawnwood is used for EURO pallets, with considerably lower half-life values, whereas pulp wood is increasingly used for production of viscose, with much longer half-life values compared to the default values for paper. To avoid a bias in the remaining sawnwood category, we investigated also the country-specific half-life values of a long-lived wood product (i.e., log houses). However, it should be noted that this product has a relatively small wood flow and could have perhaps been kept under the remaining product pool. Our country-specific half-life values for three categories of wood products (45 years for log houses, 5 years for viscose, and 3 years for EURO pallets) lie within the overall range of reported half-life values from the literature, with an overall impact of higher calculated carbon stock at the end of the study period. The largest impact came from pulp for viscose, because this category corresponds to 8%

of the total carbon flow in the country. It should be noted that this category appeared first in 2011 when a massive production of viscose pulp started in the Czech Republic.

IPCC guidelines, including the tier 2 method, are based on a political decision (United Nations, decision 2/CMP.7, 2012). Political decisions are usually compromised by the negotiation process and can only be approximated (Pingoud and Wagner 2006). Those approximations are translated into default values for accounting practices. Default values are meant to be applied for all the reporting countries. In reality, the crucial parameters for estimating carbon stock change in HWPs, such as half-lives, carbon conversion factors, and material use for production, differ from country to country. In this study, we obtained activity data and parameters specific for the Czech Republic, but, more important, MFA allowed for the tracing of domestic wood over the entire wood chain. While applying the tier 2 method, the domestic wood fraction was just roughly estimated by using estimated trade statistics. The Czech Republic trade of HWPs is mainly within the EU countries. The statistical office of the European communities (Eurostat) only estimates trade within the EU member states, given that there is no customs control between EU countries. The methods for estimating intra-EU trade include a number of statistical discrepancies (Eurostat Statistics 2016). Therefore, we believe that the application of the tier 3 method as MFA including only domestic wood should give more-realistic results than the tier 2 method.

Our findings might be relevant for reporting countries as an example that could assist in choosing an accounting method and data source suitable for the country report. The results of this study identified higher carbon stock in HWPs when the tier 3 method was applied. This suggests that, in some EU countries, HWPs will have a higher carbon stock when the tier 3 method is applied, when compared with the tier 2 method. In the case of the Czech Republic, the use of industrial residues for producing long-life wood products, such as wood-based panels and pulp for viscose, has great potential. In 2013, 50% of wooden industrial residues (bark excluded) were used for producing HWP (figure S1-4 in supporting information S1 on the Web). The remaining 50% was exported or used for bioenergy and other purposes. The Czech Republic is a net exporting country of industrial roundwood. In 2013, the export of industrial roundwood was almost 4.3 million m^3. This corresponds to 33% of domestic production (CZMA 2014). Within the frame of carbon accounting rules, the export of domestic industrial roundwood is considered to be a national carbon loss. It means that the annual accountable carbon in the Czech Republic could be 33% higher, if domestic wood were to be processed in the country. From the national perspectives, the Czech Republic has the potential to account for a higher carbon stock in HWPs without increasing forest harvest, but just by increasing domestic wood processing in the country. However, from the global perspectives, carbon stock in HWP would remain constant if harvest levels remain steady.

The efforts needed to collect country-specific data are substantial. Are these efforts justifiable? A recent study by Mantau (2015) argued that the main challenges in calculating a comprehensive view on resource flow are data availability and data reliability. Sectors with many small entities are systematically underestimated because of the cut-off thresholds of official statistics or internal use. In order to draw a full picture of the wood sector, a bottom-up approach is needed. In the case of the Czech Republic, when the tier 3 method was applied, the carbon stock change for the second commitment period of the Kyoto Protocol (2013–2020) was 60,000 tonnes higher as compared with tier 2. This corresponds to –220,000 tonnes of CO_2 emissions. Translating this into monetary value, considering an average price (2015) of 7.61 euros per tonne of CO_2 (EEX 2015), this equals more than 1.5 million euros.

In this study, we analyzed carbon accounting methods and carbon storage in HWP. However, in order to determine the overall climate-change mitigation effect of HWPs, more information on the material and energy substitution effects (Gustavsson et al. 2006; Sathre and Gustavsson 2009; Eriksson et al. 2012) and cascade use of wood (Keegan et al. 2013; Sikkema et al. 2013) would be desirable. Data on wood disposal in landfills are also uncertain following the recent changes in European regulations. More research is needed to find optimal management solutions that minimize short-term biogenic carbon losses with increased carbon sinks and enhanced substitution effects of HWPs.

Conclusions

This case study identifies that carbon storage in the pool of HWPs could be underestimated, depending on the accounting method chosen. In the case of the Czech Republic, the results have shown that the annual carbon inflow into the pool is substantially higher when estimated by the tier 3 method as compared with the tier 2 method. It also means that the Czech Republic has a potential to account a higher carbon stock in HWP, and this may promote the production and use of long-life wood products. The higher carbon inflow into the pool calculated with the tier 3 method was mainly associated with industrial residue use for the production of primary wood products and country-specific carbon conversion factors. In the case of the Czech Republic, the estimated carbon stock is also higher when country-specific half-life values are applied. Nevertheless, the results indicated that, in the Czech Republic, there is a significant potential to increase the amount of accountable carbon in HWPs without increasing forest harvest levels. The main obstacle for a wider application of the tier 3 method is the scarcity of country-specific data on HWPs and the entire wood processing chain, specifically secondary production. In most of the countries, detailed data on HWPs required for adopting the tier 3 method do not exist. This gap could be filled by periodically conducted MFA in the forest-based sector as demonstrated in this study.

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About the Authors

Gediminas Jasinevičius is a Ph.D. candidate at the University of Eastern Finland, Faculty of Social Sciences and Business Studies and researcher at the European Forest Institute in Joensuu, Finland. **Marcus Lindner** is the Head of the Sustainability and Climate Change program at the European Forest Institute. **Emil Cienciala** is Head of Science at the Institute of Forest Ecosystem Research in Jílové u Prahy, Czech Republic. **Markku Tykkyläinen** is a professor at the University of Eastern Finland, Faculty of Social Sciences and Business Studies.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information S1 presents the general characteristics of the forest-based sector in the Czech Republic as well as various sets of data and research findings related to the main study, by six tables and four figures.

Supporting Information S2: This supporting information S2 provides a summary of the questionnaire used in the main study. In order to obtain data on wood material flow, we developed a questionnaire (see example below) for wood processing companies. The objective of this questionnaire was to collect data on commodities entering and leaving production processes in these companies producing primary and secondary wood products. Data on the use of industrial residues were also gathered. In addition, we asked producers to estimate the average lifetime of the main products manufactured.