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Carbon storage in harvested wood products for Ireland 1961–2009

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ABSTRACT

Forests are significant stores of carbon (C). This has been recognised by the United Nations Framework Convention on Climate Change and forests are one of the sectors which are included in national greenhouse gas (GHG) inventories. Some of this C pool remains in wood after harvest and can remain in use for long periods of time. Accounting for the C stored in harvested wood products (HWP) can potentially contribute to GHG mitigation. A model was developed for this research to estimate C stocks and flows in HWP in Ireland for the years 1961–2009. The change in carbon stocks in HWP were estimated on an annual basis and shown to increase between 1961 and 2009. This increase in annual net additions to C stocks is the result of an increase in domestic harvest (and the resulting inflow into HWP pool) and an increase in HWP going to end uses with longer half-lives. This model (using a Tier II method) is an improvement to previous national estimates (using the Tier I method). Uncertainty was reduced by utilizing national data. This work shows that HWP has considerable potential to support GHG mitigation in Ireland. Inclusion of HWP in Ireland's National Inventory Report (NIR) would give a more comprehensive picture of how the Irish forest sector is mitigating GHG emissions. This model will be incorporated into CARBWARE (Black 2008), the model used to estimate C stored in each of the 5 forest pools, of current and future Irish forests.

1. Introduction

Forests are significant stores of carbon (C). This has been recognised by the United Nations Framework Convention on Climate Change and forests are one of the sectors which are included in national greenhouse gas inventories. Forest C is accounted for in five pools: soil, deadwood, litter, below-ground biomass, and above-ground biomass [1]. Some of this C pool remains in wood after harvest [2]. The Kyoto Protocol allows C sequestration in forests to contribute to the achievement of emissions reduction targets. Forests may be managed to maximize climate change mitigation. There are, however, trade-offs. Forests managed to maximize C sequestration, may not maximize the production of Harvested Wood Products (HWP) suitable for long-term uses, such as in building construction [3]. Studies have suggested that, worldwide, the amount of C held in HWP is likely to be increasing [4]. One study estimated that the average global rate of increase between 2000 and 2005 was 55 million tons yr^{-1} with an uncertainty of +/−50% [5]. There is, therefore, the potential for C sequestration and the contribution to long term carbon dioxide (CO_2) reduction targets.

Carbon stocks in HWP are important for two reasons 1) C in HWP must be accounted for in order to accurately track

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carbon stocks and flows [6] and 2) C in HWP can play a role in mitigating Greenhouse Gas (GHG) emissions [7]. Under the Kyoto Protocol, carbon stored in wood is regarded as oxidised at the time of harvest [8]. The future contribution of harvested wood products (HWP) to greenhouse gas accounting is being discussed and HWP may be included in ‘post Kyoto’ climate change negotiations.

Several factors contribute to the rate of carbon accumulation in HWP in end uses, these include: amount of annual harvests, type of products made, end use of those products, service life of products, and disposal/recycling or use as fuel at the end of service life [3]. There are additional factors that affect the rate of annual change in carbon stocks in HWP. These include A) The accounting approach used (what carbon flows are used to compute a country’s stock changes), and B) the methods used to estimate carbon flows or stock changes (detail and accuracy).

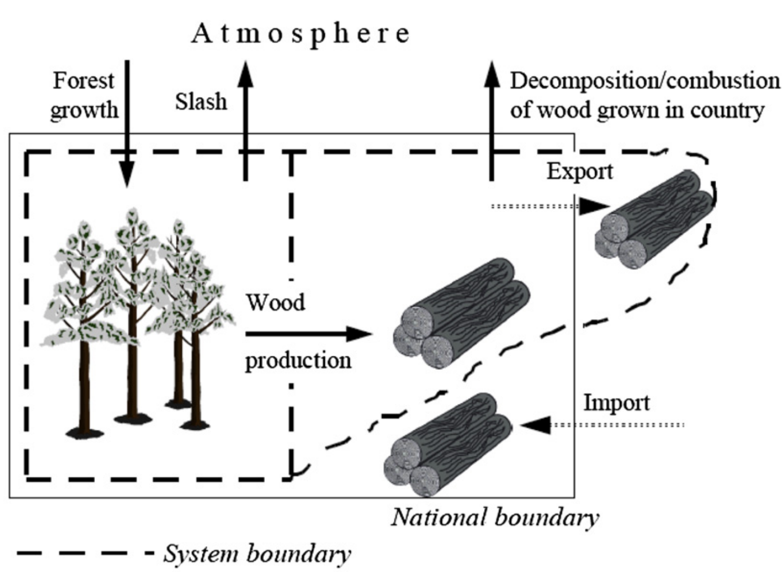
How imports and exports flows are counted is the main difference between approaches [9]. While various accounting approaches have been proposed, the most frequently referred to are the three described in detail by the Intergovernmental Panel on Climate Change (IPCC) in the 2006 guidelines [10]: the Production Approach (Fig. 1), the Stock-Change Approach, and the Atmospheric-flow approach. Each of these approaches yields the same estimate of annual change in carbon in HWP at the global level. They differ, however, in what percentage each country would claim of the global annual change in HWP storage or net emissions to the atmosphere. To avoid double counting, a single approach must be agreed on by all parties. The IPCC (2006) defined a set of variables for C HWP reporting that can be used to estimate annual change in C in HWP using each of the 3 accounting approaches.

In addition to the approaches described, IPCC (2006) also outlines a number of methods to estimate annual HWP C change. These methods were presented as Tiers I–III. Tier *I* method uses default (global) data sources (available online through the FAO) and worksheet (model) available for download from the Internet [4]. The Tier *II* method is more detailed, using (more accurate) national data and more detailed analysis of product lifetimes in end uses [10]. The most detailed Tier *III* method is described as using more detailed national data including end use data, lifetime analysis, and a mixture of methods if necessary for best fit with available data and first order decay or other decay function [10]. Countries are advised to include as much detail as possible, according to data availability, because as detail increases, so should accuracy [10].

Some debate continues about which approach should be agreed on and used by all countries. The European Union (EU) decided (July 2009) to support the Production Approach from domestic harvest with two options;

1. include exports when emissions occur
2. count exports as immediately oxidised.

Carbon stocks in Irish HWP were estimated by Greene *et al.* in an analysis that focused on the effects of accounting approach on national estimates using a Tier *I* method [11]. Data on the proportions of various wood products that are in various end uses has since become available for Ireland [12–14], and O’Driscoll pers. comm. June 2010. Given these new data sources and the changes in C accounting policy, it is timely to revisit HWP estimates for Ireland. This project has the following objectives; 1) Develop a model for estimating the annual change in C stored in HWP for Ireland, using the Production Approach (including carbon in exports) and 2) Use the model to estimate annual changes in carbon stock in HWP from 1960 to 2010. The resulting model is described and the results are presented in this paper.



Stock change = (stock change forest) + (stock change domestic-grown products)
= (forest growth - slash -wood production) + (wood production - decomposition/combustion of wood grown in country)

Fig. 1 – Illustration of production HWP accounting approach. Sources: [9, 25, 26].

2. Methods

The methods used follow those suggested for Tier II and Tier III in the IPCC guidelines [10]. National data on harvest, trade, and wood product end uses were obtained from the Irish Central Statistics Office, the Food and Agriculture Organisation of the United Nations (FAO) Forestry database, and from consultation with industry experts. A decay rate for end uses – for use in first order decay curves – was based on estimates of the half-lives of end uses (Table 1). Estimates of half-lives and uncertainty in half-lives for HWP in end uses were based on published estimates and default values (Table 1 and Table 2). Product volumes were converted to CO_2 equivalent using conversion factors specific to Ireland (Table 3a) and default values (Table 3b). In order to account for emissions from stocks of wood products placed in use prior to 1961, estimates begin from the year 1900 following default methods outlined in IPCC [10].

In line with the 2009 EU decision regarding HWP, this research used the Production Approach. In this approach, carbon in HWP produced from domestic harvest only was accounted for. Carbon in HWP was assumed to remain in the respective pool as long as they were in use and included exported HWP from domestic harvest. Wood products in solid waste disposal sites (SWDS) were not included in our estimates. When products went out of use it was assumed that the carbon was emitted to the atmosphere.

2.1. *The model*

Harvest and trade data from FAO, product categories and carbon content, end-use data, half-lives, and first order decay rates were used to estimate annual change in C stored in HWP by tracking annual inputs to and outputs from the HWP C pool. These estimates were calculated using a model (WoodCarb-Ireland) developed for Irish input data and end-use categories. The model was a hybrid of the spreadsheet models HWP [4] and WOODCARB II [7] in Microsoft Excel. The HWP model provided the basic framework using production, import and export data of aggregated HWP categories, associated default half-lives and first order decay rates. Modifications to the HWP model were made following methods developed for WOODCARB II [7], but, tailored to suit the data available for Ireland including:

Table 1 – Half-life estimates of end uses included in the model.

End use	Half life (years)
Construction[a,b]	67
Furniture[b]	30
Pallets/packaging[b]	6
Fencing and other (saw wood)[c]	35

a Average half-life of construction end use categories.
b Source: [19].
c Source: [18].

Table 2 – Sources and estimates of uncertainty in the model.

Sources of uncertainty	Uncertainty (%)
Data on solid wood production and trade	±15
Data on paper production and trade	±15
Factors converting wood and paper to carbon	±20
Half-lives for solid wood products in use	±30
Half-lives for paper products in use	±50
Bark as a fraction of roundwood (wo bark)	±10
Production change rate prior to 1961	±50

Sources [[18], Appendix 3a.1] and [7] were reviewed in making these estimates.

- HWP product categories of sawn wood (coniferous and non-coniferous), structural panels (plywood and OSB), non-structural panels (MDF, particle board, fibreboard, hardboard, insulating board, veneer sheets), stakewood, and conversion factors for each product
- End-use categories of construction, furniture, fencing, packaging, other, and associated half-life estimates

Equations (1) through (3) were used to estimate the annual change in Carbon for the current year [7]. Equation (1) estimates, for current year (t), the stock of carbon of primary product (i) in end use (j), where the primary product was originally placed in use in year (T).

$$CT_{ij}(t) = \exp(-kT_j \times (t-1900)) \times \text{Inflow}T_i \times F_{T_{ij}} \quad (1)$$

Equation (2) estimates, for current year t, the total stock of carbon held in all primary products held in all end uses that were placed in all end uses from year $T = 1900$ to the current year t.

Table 3a – Conversion Factors for carbon in HWP used in the model.

Product category	Density[a] tonnes/m^3		Tonnes C per oven-dry tonne of wood material[b]		Carbon factor tonne C per m^3 of air dry wood material
Medium Density Fibreboard (MDF)	0.74	×	0.47	=	0.35
Particleboard	0.63				0.29
Oriented Strand Board (OSB)	0.63				0.29
Insulating board (average)	0.29				0.14

a Source: [27].
b Source: [10].

$$C(t) = \sum_{T=1900}^{t} \sum_{i-1}^{n} \sum_{j=1}^{m} CT_{ij}\left(t\right) \tag{2}$$

Equation (3) estimates, for the current year (t), the change in total carbon stock in products in use.

$$\Delta C(t) = C(t) - C(t{-}1) \tag{3}$$

where: exp(x) is e^x. t is the current year (year for which annual change in HWP carbon stock is being estimated)

Inflow Ti is the annual amount of carbon in primary product i that goes into products in use in year T.

Inflows are for years $T = 1900$ to current year t.

Inflow is subdivided into several primary products ($i = 1$ to n), Mg yr^{-1}.

T is the year when products initially go into the "products in use" pool.

i is the primary wood or paper product, $I = 1$ to n (defined below).

j is the end use for products, $j = 1$ to m (defined below).

F_{Tij} is the fraction of primary product i inflow in year T that goes into end use j

k_{Tj} is the annual rate at which the products placed in end use j in year T go out of use. This is the annual rate at which the product is discarded from use. The rate is constant for the life of products placed in use in a particular year. Discarded material may be recycled (including, for example, paper or chipping for mulch), burned, composted, or sent to SWDS.

C(t) is the total carbon held in products in use, Mg.

ΔC(t)is the annual change in carbon in products in use between the end of year t−1 and the end of year t, Mg yr^{-1}

Note that,

$$k_{T_j} = \ln(2)/HL_{T_j}$$

Where HL_{T_j} is the half-life in years for products placed in end use j in year T. The half-life is the number of years it takes for half of the initial inflow amount to be discarded.

Equation (4) was used to disaggregate imported timber used for HWP production and HWP from domestic harvest. This method follows the IPCC Guidelines (2006), and was applied to the FAO data for each year (1961–2009):

$$\text{Inflow}_{DH} = p \times \left(\frac{IRW_P}{(IRW_P + IRW_{IM} - IRW_{EX} + WCH_{IM} - WCH_{EX} + WR_{IM} - WR_{EX})}\right) \tag{4}$$

Where: Inflow_{DH} is carbon in annual production of solid wood and paper products that came from wood harvested in Ireland

P is Production (solid wood and paper products).

IM is Imports.

EX is Exports.

IRW is Industrial roundwood.

WCH is Wood chips.

WR is Wood residues.

Several adjustments were made to the FAO data in order to calculate equation (4); 1) Linear interpolation was applied to the relevant data sets to replace 0 values in the years where data were unavailable, and 2) linear interpolation was used to estimate Industrial roundwood production for 1980 and 1981. According to FAO estimates for the years 1980 and 1981, Industrial roundwood exports rose sharply, while Industrial roundwood production (harvest) was stated as being the same as in 1979. This inconsistency between the reported harvest and export estimates produced an unexpected ratio (Equation (4)) and a sharp spike in C stock change estimates. This was considered unrepresentative and therefore Industrial Roundwood production value for 1981 was adjusted, by linear interpolation between the 1980 and 1982 values. Several other FAO data points were based on previous years, but Industrial roundwood estimates for 1981 alone proved to be problematic in the calculation of equation (4) for the years 1961–2010. The changes to the FAO data were made to calculate equation (4) only. The FAO data as referred to elsewhere in the calculation of carbon stocks were used without these adjustments.

The calculations were based on the assumption that solid wood (or paper) products are alike in the amount of roundwood used to make them in both Ireland and in other countries where saw logs or pulpwood may be exported and used to make products [7]. Exported products (or logs and chips) were assumed to have end uses in the same proportions as in Ireland. The half-life of end uses from exported products was also assumed to be the same as in Ireland.

An uncertainty assessment was conducted on the estimated C stock in HWP for the years 1990–2009 using Monte Carlo method and @RISK software. Sources of uncertainty were identified (Table 2). Normal probability distributions were used, and estimates of uncertainty from each source were assigned by specifying the 90% confidence intervals using guidance provided in IPCC (2006) [10] with adjustments where appropriate, considering national data sources for end

Table 3b – Conversion Factors for carbon in HWP used in the model.

Product Category	Gg oven dry product per m^3 of product		Tonnes C per oven-dry tonne of wood material		Carbon factor tonne C per m^3 of air dry wood material
Fibreboard	1.02	×	0.5	=	0.51
Hardboard	1.02				0.51
Veneer sheets	0.59				0.30
Plywood	0.48				0.24
Sawn wood C	0.45				0.23
Sawn wood NC	0.56				0.28
Pulp Paper and Paperboard	0.90				0.45

Source: [18].

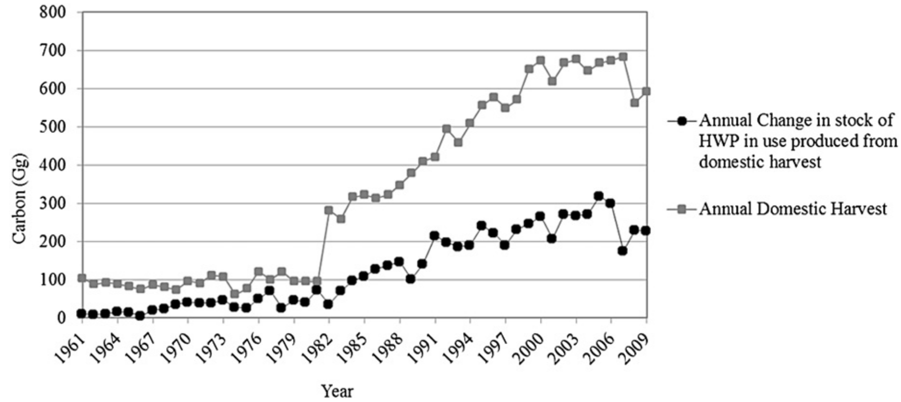


Fig. 2 – Carbon content of domestic harvest (Gg) and Carbon stocks in HWP from domestic harvest (Gg) in Ireland 1960–2009.

uses and some conversion factors used (C content in secondary products). There can be model uncertainty to the degree that the model we used to estimate the discard rate from products in use is inaccurate. Modelling uncertainty is accounted for to some degree in our estimation of uncertainty in discard rates (+/−30%, +/−50%). If our use of first order decay curves overestimates discard in early years then we may be underestimating recent additions to C in HWP and our uncertainty should be greater on the high side than we estimate.

A sensitivity analysis was conducted using a Multivariate Stepwise Regression technique in the @RISK software to identify the input data with the largest impact on the C stock estimates for 2009.

3. Results

Additions to carbon stocks in HWP were estimated on an annual basis and shown to increase between 1961 and 2009 (Fig. 2). This increase in annual additions to carbon stocks was the result of an increase in domestic harvest (as potential inflow into HWP pool) and an increase in HWP going to end uses with longer half lives. The general trend in domestic harvest showed little change from 1961 to 1981, with a sharp increase between 1981 and 1982, then a steady increase from 1983 to 2000 (Fig. 2). At least 55% of the increase between 1981 and 1982 can be attributed to the reported increase in pulpwood harvest (FAO). There was also a sharp increase in exported wood products between 1980 and 1982, of which 87% consisted of pulpwood. This increase in harvest and export was likely the result of the closure (in the late 1970's) and subsequent reopening (in 1983) of one wood based panel factory and the anticipation and start-up of another wood based panel factory (also in 1983) (O'Driscoll pers. comm. June 2010).

The difference between domestic harvest and change in carbon stocks for any given year is the amount of C released from A) wood used for fuel and B) wood placed in use in current or prior years [10]. Estimates of C inflow to the HWP pool by end use category (Fig. 3) show an increasing inflow of C into all end use categories (except other). The most

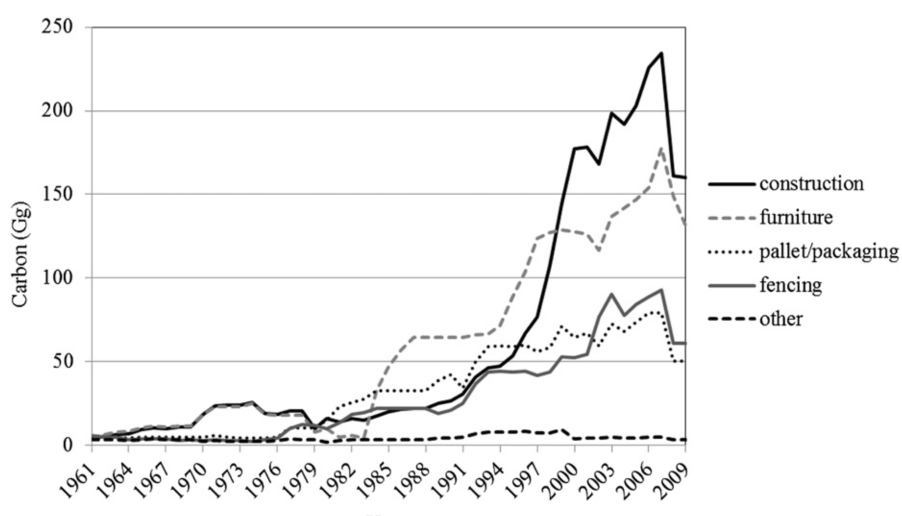


Fig. 3 – Carbon inflow to HWP in end uses in Ireland (Gg) from 1961 to 2009.

remarkable increase, however, was in the construction category between 1990 and 2007. This end use category has the longest estimated half-life (67 years, Table 1).

The results of the uncertainty assessment showed the affect of uncertainty in parameter and input data on the estimated change in HWP C stock. The 90% confidence interval range as percent of the change in HWP C stock for 2009 was between −20% and +19%. The 90% confidence interval range for the years 1990–2009 was between −29% and +31%.

Sensitivity analysis indicated that the uncertainty estimate was most sensitive to 1) uncertainty in the factors converting wood to C, 2) uncertainty in the data on production and trade, and 3) half-lives of solid wood products in use. The regression of output (stock change) variation from the mean on input variation from the mean indicated coefficients were 0.704 (variation in factors converting wood to C), 0.524 (variation in production and trade data) and 0.442 (variation in half-lives of solid wood products in use). The coefficients indicate the amount of change in the output (as proportion of one standard deviation) caused by a change of one standard deviation in the input.

4. Discussion

The model developed for this research (WoodCarb-Ireland) supported a Tier II estimate of C stocks in HWP during 1961–2009. This improvement reduced uncertainty associated with Tier I methods [11] as it utilized end-use data, more detailed product categories and conversion factors specific to Ireland. The 90% confidence interval for the 2003 estimate by Green *et al.* using a Tier I method was 251 Gg C ± 48% (131 Gg C–372 Gg C) [11]. Their estimate and our estimate for HWP C change uses the production approach and excludes change in C in solid waste disposal sites. The range for their estimate overlaps the 90% confidence interval for our 2003 estimate of using a Tier II method: 268 Gg C −20% to +19% (213 Gg C–318 Gg C).

The development of Tier II methods for HWP accounting for Ireland is in line with the IPCC recommendations that HWP be reported at Tier II or III levels in countries where there are annual changes in HWP C stocks that are significantly different from zero [10]. This model will be incorporated into CARBWARE [15], the model used to estimate C stored in each of the 5 forest pools, of current and future Irish forests.

Inclusion of HWP in Ireland's National Inventory Report (NIR) would give a more comprehensive picture of the potential of Irish forest sector to mitigate GHG emissions. In 2008 Ireland's net total GHG emissions were 65,969.17 (Gg CO_2 equivalent) including land use, land used change and forestry (LULUCF) which contributed (−) 1470.10 (Gg CO_2) [16]. In 2008, CO_2 stocks in HWP (in use) were estimated at −842 (Gg).

Harvest rates and the end use and durability of forest products as well as economic factors will affect annual change in HWP C stocks in the future. The rate of increase in C stocks in HWP from 1961 to 2010 is confirmed by the slope and R^2 value of a linear trendline ($y = -23.437 \times +46{,}065$, $R^2 = 0.87$) fitted to the data. As availability of wood for HWP is influenced by forest policy and management, we cannot necessarily expect the trend to continue without adequate policy provision even if there are continuing markets for HWP in Ireland. In Ireland, afforestation rates have fallen from >15,000 in 2003–7500 ha yr^{-1} in 2009 [17]. If this trend continues, Irish forests will become a source (not sink) of CO_2 after 2035 [17]. This reduction in afforestation if continued will also limit the availability of domestic harvest in the future.

The WoodCarb-Ireland model includes a framework for further development. The WOODCARB II [7], a more detailed and complex model, was reduced to accommodate available data for Ireland during this research. There is potential, therefore, for considerable expansion by adapting additional features of WOODCARB II. This could include the incorporation of additional end use and half-life detail, and calibration if additional data for Ireland become available in the future.

4.1. *Evaluation of data sources*

The FAO data used for this research were the best available data for Ireland. These data were considered reliable; however, there were some inconsistencies in reported values. There were some data that produced unexpected jumps in model estimates of annual additions to carbon stocks. For example, there was an inconsistency between the industrial roundwood production (harvest) values and export values for the years 1980, and 1981. Production (harvest) values, seemed to be based on the previous years value and export values appeared to be (roughly) interpolated. The 1981 FAO values for pulpwood export (225,000 m^3) were 259% of pulpwood production (harvest) (87,000 m^3).

The uncertainty of the model results could be improved if additional national data become available. As no data for Ireland were available for half lives of wood products, default [18] and previously published estimates [19] were used. The uncertainty of these estimates (±30% for solid wood products and ±50 for paper) is quite high. Furthermore, opportunities to calibrate the model for Irish HWP were limited due to lack of data. Using model estimates of carbon stock changes in HWP consumed in Ireland (the Stock Change accounting approach) we estimated the solid wood products coming out of use in recent years (HWP originating from both domestic and imported timber). These discard amounts may have been composted, burned or deposited in solid waste disposal sites (SWDS). We compared the discard amounts to available data on solid wood products received and deposited in SWDS. The estimated discard amounts were notably larger than receipts at SWDS. This suggested that either A) The first order decay curve may overestimate discards from use in early years (just after items are placed in use), B) the half life for products is much longer than we estimated, or C) a large portion of HWP are burned or exported (in the form of secondary products) and did not reach waste disposal sites. Ireland is not, however, a net exporter of secondary wood products [20]. If explanation c) is minimal, then model estimates of discards could be large because the first order decay curve overestimated discards in early years or half-lives estimates were too short. If this is the case our estimates of recent annual carbon additions may have been too low. In this case, uncertainty in annual additions to HWP may have been greater on the high side than we estimated. Using model estimates of annual HWP C additions from wood consumed in Ireland, we estimated C held in buildings (construction) for recent years. We used this model estimate and reported estimates of total building floor area to estimate and compare the implied estimates of wood stored per unit floor area in dwellings in Ireland for 2001 and 2005 [21–23] with estimates for Finland for 2007 [24]. The model based estimates, as expected, indicated substantially less wood carbon per unit floor area for Ireland (somewhat less than one-quarter the level for Finland). This is expected since many fewer homes in Ireland are built using wood frame construction. In 1992 5% of housing built in Ireland used timber frame construction. This percentage increased to 30% in 2006 [22]. With our rough comparison to Finland we do not find evidence that we overestimated C stored in buildings. If we did make an overestimate, the amount seems limited. If information becomes available for Ireland on wood use per unit floor area we could refine our estimates of half-lives needed for our model to match external estimates of the amount of C held in buildings.

5. Conclusion

This work shows that HWP has considerable potential to continue supporting GHG mitigation and that utilizing national data and a Tier II method can reduce uncertainty associated with C stocks in HWP for Ireland. The results of this research will contribute to the assessment of the role of forests and HWP in Ireland's GHG reporting commitments.

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