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The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy—A case study on available forest resources in Canada

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SUMMARY

Some Parties (Countries) to the UNFCCC decided to include the carbon uptake by harvested wood products (HWP) in a new general accounting framework after 2012 (post Kyoto). The analysis aims to make a comparison between the cascaded use of HWP and the use of wood for energy. We combine the new HWP framework with an assumed increased 50 million m^3 harvest level in Canada and evaluate the impact of the GHG emissions over a 100-year period. Our reference case assumes all harvested wood is an immediate CO_2 emission (IPCC default) and no substitution effects, i.e. annual GHG emissions of 41 million tonnes CO_{2eq}. In our wood utilization scenario's, harvested trees are allocated (in varying shares) to three end-products: construction wood, paper products and pellets for power production. In comparison with our base case, a combination of fossil fuel substitution, material substitution and temporary carbon uptake by HWP leads to significant decreases in GHG emissions. All scenario's show annual GHG emission between 18 and 21 million tonnes CO_{2eq} except for triple use without recycling (at least 24 million tonnes CO_{2eq}). We conclude that GHG emissions of our scenarios are substantially lower than IPCC default. However, it is difficult to incorporate one single method to account for GHG uptake and emissions by HWP, due to end use efficiency and recycling options. Further GHG allocation over individual countries is not straightforward and needs further research.

1. Introduction

Since 1992, 195 countries (Parties) have joined an international treaty, the United Nations Framework Convention on Climate Change (UNFCCC), to cooperatively consider which measures are needed to limit average global temperature increases and the resulting climate change. At the very heart of the response to climate change lies the need to reduce greenhouse gas (GHG) emissions. In December 2011 (COP-17), Governments from 37 industrialized countries and the European Community agreed a second commitment period of the Kyoto Protocol (KP) from 1 January 2013. The major distinction between the Protocol and the Convention is that while the Convention encouraged industrialized countries to stabilize GHG emissions, the Protocol commits them to do so (UNFCCC, 2012).

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There are three main routes by which the forest sectors could contribute: (1) using biomass for energy, (2) substituting energy intensive materials and (3) increasing forest and wood as carbon sink (UNECE, 2010c):

(1) The EU-27 is aiming at a 20% contribution of renewable sources in 2020 of the gross final energy consumption (European Parliament and EU Council 2009) and to decrease its emissions in 2008–2012 by 8% compared to the 1990 level. Examples of renewable energy are the use of wood chips in district heating and of wood pellets for power production in the EU-27. The latter are increasingly imported from North America (Sikkema et al., 2011).
(2) GHG emissions can be reduced when wood is used for construction and replaces energy-intensive materials like concrete and steel (Burschel et al., 1993; Perez-Garcia et al., 2005; Sikkema and Nabuurs, 1995; Sathre and Gustavsson, 2006). A Canadian review for 21 substitution studies around the world found an average GHG emission reduction factor of about 49% (Sathre and O'Connor, 2010). When the waste fibres are "cascaded" through reutilization, further GHG reduction is possible (Dornburg and Faaij, 2005; WBCSD, 2011).
(3) In comparison with the base year 1990, Canada emitted an additional 30% of GHG in all its sectors in 2009, by including the contribution from the land use change and forestry (LUCF) sector (UNFCCC, 2011a). However, the harvest of Canadian trees is regarded as an immediate emission, according to a general default (IPCC, 2006b). Any consecutive carbon storage in HWP is not included in this accounting. When we apply a (former) HWP accounting method as a first indication, HWP may contribute the equivalent of about 40 million tonnes CO_{2eq} emission reduction in 2008 (Fig. 2; dotted line), based on historic production and consumption data since 1960 (FAO, 2012). That would compensate about 7% of the base year emissions.

At COP-17, the Parties to the KP decided to implement a new method for HWP, to better account for the carbon stored in HWP (UNFCCC, 2011b). The 'Kyoto Parties' must account for the temporary carbon uptake by HWP, either consumed domestically or exported, in a second commitment period after 2012. The new method resembles the former 'production method' (UNFCCC, 2003), except for an extra division of solid wood into sawn wood and wood based panels. The production method is of most interest to countries with a large forest area and considerable harvesting volumes (Lim et al., 1999; Nabuurs and Sikkema, 2001). Canada, as a 'non Kyoto country', is not bound to this decision, since it withdrew from the KP in 2011.

Canada representing 10% of the world's forest cover, is a major supplier of wood resources. About 8% of Canada's forests is protected, while less than 0.5% of the managed forests is annually harvested (NRCan, 2011; Stinson et al., 2011). Although Canadian harvest increased from 160 million m^3 in 1990 to about 200 million m^3 in 2004 and 2005, it rapidly decreased after this period to 120 million m^3 in 2009 (Canadian Forest Service, 2012) due to lower demand for timber and paper products in the United States and other countries (UNECE, 2011) (see Fig. 1). Two provinces with the largest harvests are British Columbia (BC) and Quebec. The harvests in BC and Quebec decreased by about 40 million m^3 and 20 million m^3 respectively (Fig. 1; dotted lines). The annual allowable cut (AAC) in Canada is around 250 million m^3 (solid lines). The declining raw material supply in Quebec is due to a re-assessment in 2005 of the AAC, which should ensure the sustainability of wood resources in public forests. The AAC figure of British Columbia includes a significant temporary uplift to salvage trees killed by the mountain pine beetle (MPB) (Canadian Forest Service, 2012; MNRF, 2012). Given the fact that Canada harvest levels are currently far below the AAC, it provides the setting for a case study to evaluate the effect of additional harvests for the production of HWP's.

The aim of our analysis is to combine the new HWP method with an increased future harvest level in Canada and to make a comparison between the cascaded use of HWP and the use of energy wood instead of fossil fuels. We have selected three markets for harvested wood: the export of (1) sawn wood and OSB for construction to Japan, (2) market pulp and newsprint to the US and (3) wood pellets for power production to the EU-27 (see Appendix A for a more detailed account for these markets). We will evaluate the global impact of the GHG emissions in the period 2012–2112. The time frame is selected because HWP will have released most of the carbon stored after 100 years, even when wood is used for construction purposes. We also evaluate different end-of-life options, and we evaluate the uncertainty in our results by taking both worst

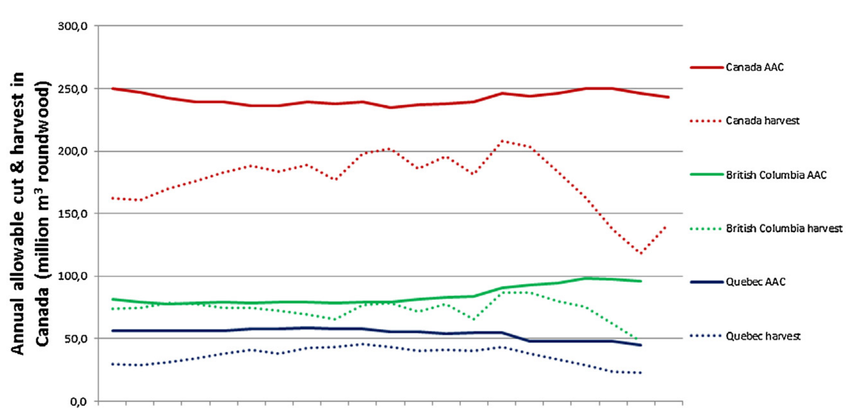

Fig. 1 – Trend lines of roundwood removals and AAC in Canada's managed forests, and its two major wood production provinces British Columbia and Quebec – 1990 until 2010 (Canadian Forest Service, 2012; NRCan, 2012a).

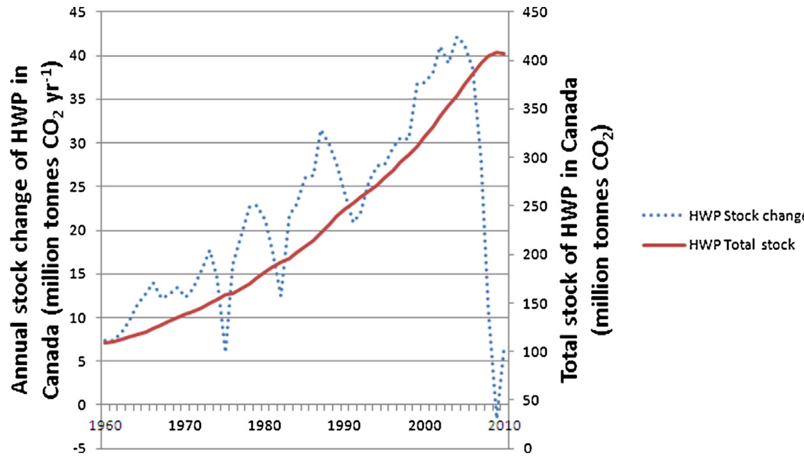

Fig. 2 – Total stock and annual stock change of HWP* in Canada between 1960 and 2010 (FAO, 2012; IPCC, 2006a) according to the (former) production method (Pingoud and Wagner, 2006).
***The HWP contribution until 2010 is based on former modelling, which had 2 HWP categories: solid wood products and pulp and paper products (IPCC, 2006a).**

and best use of existing technologies for production, conversion and end-use of HWP's into account. Our evaluation focuses on an aggregated GHG inventory on a global scale and we neglect any countervailing trading effects between the UNFCCC Parties. A first step towards a possible GHG allocation per country is given in the Discussion section. Furthermore, we limit the inventory to GHG contributions starting from the harvesting stage and compare them with our hypothetical base case: all harvested wood as an immediate emission according to the IPCC's default.

2. Methodology

The IPCC guidelines for the inventories of GHG (IPCC, 2006b) are divided into six sectors, of which three are direct relevant for our aggregated GHG inventory: industrial processes, energy and waste management. Emissions related to the industrial processing of wood products are inventoried by means of life cycle inventories (LCI) per commodity. These are aggregated with the GHG emissions arising from harvesting activities, and several transport stages into a total GHG figure per commodity (Table 1). We started our inventory with fossil fuel consumption data, followed by the electricity needs for these processes. Next, the energy and waste management is combined into one overview for end-of-life, based on a progressive LCA approach, i.e. cradle-to-cradle use of waste materials (Table 2). The LUCF sector (forest carbon) is excluded from our inventory, except for the direct emissions from all harvested wood in IPCC's default, or for those from energy wood and from HWP (after end-of-life) in our selected markets.

2.1. *HWP and product lifetimes*

According to the Kyoto Parties (UNFCCC, 2011b) ''emissions from HWP removed from forests which are accounted by a Party under article 3 [of the KP], shall be accounted for by that Party only. Provided that transparent and verifiable activity data for the HWP categories are available, accounting shall be done on the basis of the change in the HWP pool during the second and subsequent commitment periods, estimated using the first-order decay function, derived from (IPCC, 2006b), with default half-lives of 2 years for paper products, 25 years for wood panels and 35 years for sawn wood. Wood harvested for energy purposes should be accounted on the basis of instantaneous oxidation''. Thus, instead of immediate emissions for all harvest, only wood harvested for energy is regarded as an immediate emission, while all other wood products will release CO_2 over time. This accounting method for HWP is part of our aggregated GHG inventory. We do not account for any emissions from HWP in the years before 2012, i.e. a zero HWP stock in 2011. The stock of HWP (in m^3 harvested wood as allocated for selected wood commodities) is calculated using formulas A and B (see Appendix B for a compilation of carbon flows from the use of HWP), after which it can be converted to CO_2 equivalents (CO_{2eq}). The annual build-up of HWP (in m^3) in a given year is retrieved from the difference in stock in that year and that in the previous year (formula C).

Depending on the average lifetime, the HWP stock will slowly degrade when the products reach the end-of-life cycle (Section 3.2). The respective volumes are derived from the outflow of HWP (formula D). This formula D is also applied for the available volumes in case the wood waste fibres are re-utilized in another product or when the paper waste fibres replace fresh pulp wood. We implemented the following recycling options: the reutilization of discarded sawn wood (waste wood) for OSB and that of collected waste paper for newsprint production again. Although the use of waste wood is merely practiced for particleboard, we have assumed it applicable for OSB as well (see Appendix C for the optional recycling of wood and paper waste flows).

Table 1 – Overview of assumptions for the GHG emission calculation of selected wood and paper products during lifetime in scenario 1.

Type of product (basic unit)	Lumber (unit = 1 m^3)	Wood based panels (m^3)	Paper products (tonne)	Energy products (tonne)
Canadian situation: 1 m^3 logs = 6.19 GJ = 0.392 dry tonnes (CIPEC 2009)	***Lumber kiln dried & planed (coniferous sawn wood)*** **==Export to Japan==**	***OSB and plywood interior*** **==Export to Japan==**	***Market pulp (ECF bleached) and newsprint (without recycled paper)*** **==Export to the US==**	**Industrial wood pellets with drying by renewable energy sources (RES) or natural gas** **==Export to EU-27==**
Canadian allocation of 1 m^3 harvested logs (Government of Canada 2011)	32.6%	9.7%	36.2%	21.5%
Drying needs in m^3 log per unit product (in % of product feedstock)	0.13 m^3 rwe (12%); (CIPEC 2009)	0.25 m^3 for OSB (22%) and 0.18 m^3 for plywood (17%) (CIPEC 2009)	Assumption: re-use of steam production is sufficient to dry feedstock	24 to 25% of feedstock input (Katers and Snippen 2011; Sikkema et al 2010); 59 – 61 m^3
Drying need (in % harvest), to be subtracted from pellet allocation	**3.9%**	**2.2% OSB; 1.7% plywood**	**No wood needed for drying**	**Only 5.2% in case of RES drying;**
Remaining allocation *(all drying needs energy wood)*	***32.6%***	***9.7%***	***36.2%***	***10.7% to 15.5% (scenario 1)***
Canadian input of feedstock: logs per unit product in m^3 roundwood equivalent (rwe) excl. drying (Li et al 2010)	*1,04 m^3 rwe (Note that lumber becomes 'less voluminous' due to shrinkage)*	*1,10 m^3 rwe (OSB) and 1.08 m^3 rwe (plywood)*	*2.32 m^3 rwe*	*2.47 m^3 rwe*
Default figures for carbon contents (IPCC 2006a)	0.225 tonne C per m^3	0.295 tonne C per m^3	0.45 tonne C per tonne pulp or per tonne paper	Not applicable due to accounting for immediate CO_2 emissions after harvest (IPCC 2006b) 0.196 kg C /m^3 log (CIPEC 2009)
For comparison: biogenic fixed carbon (Werner et al 2007; Hischier 2007)	0.223 tonne C per m^3 (coniferous); 0.323 tonne C per m^3 (hardwood)	0.241 kg C per m^3 OSB; 0.315 kg C per m^3 plywood	0.589 tonne C per tonne pulp; 0.520 tonne C per tonne newsprint	
Production of commodities in Canada, incl. upstream processes (harvest & transport)	***Softwood lumber in sawmill***	***Structural OSB and plywood interior purposes***	***Market pulp and newsprint***	***Industrial wood pellets***
*- Canadian LCI data for GHG production & harvesting processes *), which exclude any additional materials (glue, fillers)*	*71.4 kg CO_{2eq} per m^3 product for coniferous logs (CIPEC 2009), for marginal mix BC (Farhat and Ugursal 2010)*	*38-74.5 kg CO_{2eq} per m^3 OSB and plywood (CIPEC 2009), for marginal mix BC (Farhat and Ugursal 2010)*	*251.5-353.3 kg CO_2 per tonne pulp (NRCan 2012) resp. per tonne newsprint (CIPEC 2008); marginal mix Quebec (Farhat and Ugursal 2010)*	*Between 19.3 kg CO_2 (6 units RES drying) and 69.8 kg CO_2 (4 units gas drying) per tonne (Control Union Certifications 2012)*
Applied emissions for power (Farhat and Ugursal 2010)	*Marginal mix BC: 0.018 kg CO_2 per kWh*	*Marginal mix BC: 0.018 kg CO_2 per kWh*	*Marginal mix Quebec: 0.007 kg CO_2 per kWh*	*Marginal mix BC: 0.018 kg CO_2 per kWh*
Outcome Canadian LCI if average power mix is used for Canada: 0.283 kg CO_2 per kWh	No fillers or glue used	66-100 kg CO_2 per m^3 (CIPEC 2009)	1,194 kg CO_2 per tonne newprint (CIPEC 2008)	No fillers or glue used
For comparison: European LCI data for production emissions, **incl.** materials like glue & fillers. Note: power use is based on an average electricity mix	No fillers or glue used	313 – 501 kg CO_{2eq} per produced m^3 panel in West Europe (Werner et al 2007)	1,300 kg CO_{2eq} per tonne newsprint production in Scandinavia (Hischier 2007)	No fillers or glues used
Average density N. America for further logistics (UNECE 2010a)	0.517 tonne (coniferous) per m^3 sawn wood	0.613 tonne (OSB) or 0.584 tonne (plywood) per m^3	-	-
International logistics after Canadian factories	***British Columbia, Canada –Tokyo region, Japan***	***British Columbia, Canada –Tokyo region, Japan***	***Quebec, Canada – Chicago region, USA***	***Vancouver, Canada –Rotterdam, the Netherlands***
- Road transport in Canada: 0.114 kg CO2 per tonne km (CN 2011)	-	-	(50 km Quebec region) 5.7 kg CO_2 per tonne product	-
- Train transport: 0.01785 kg CO_2 per tonne km (CN 2011)	(780 km) 12.9 kg CO_2 per tonne product	(780 km) 13.9 kg CO_2 per tonne product	(1000 km Ottawa – Chicago) 17.9 kg CO_2 per tonne	14.9 kg CO_2 per tonne pellet (Control Union Certifications 2012)
- Ocean transport 0.010732 kg CO_2 per tonne km (Spielman et al 2007)	(7,925 km Pacific Ocean) 85.1 kg CO_2 per tonne product	(7,925 km Pacific Ocean) 85.1 kg CO_2 per tonne product	-	94.8 kg CO_2 per tonne pellet (Control Union Certifications 2012)
- Road transport in country of export: 0.114 kg CO_2 per tonne km (CN 2011)	(100 km in Japan) 11.4 kg CO_2 per tonne product	(100 km in Japan) 11.4 kg CO_2 per tonne product	(50 km Chicago region) 5.7 kg CO_2 per tonne product	-
- River transport in country of export and handling E-plant	-	-	-	24.9 kg CO_2 per tonne pellet (range 21.3-28.5 kg CO_2) (Control Union Certifications 2012)

Table 2 – Overview of assumptions for the GHG emission calculation for the end of life for waste wood, waste paper and wood pellets.

	Solid wood products (lumber& wood based panels)		Paper products (newsprint)	*Wood pellets (energy)*
Default values	A. Best case: energy recovery of mixed waste	B. Worst case: energy recovery of mixed waste	Energy recovery of waste paper sludge (Norske Skog Parenco 1991-2010; EPA 2010)	*Power production in EU-27*
Type of burning (replacement)	Waste incineration: electricity production 30% efficiency (Odegard et al 2012)	Waste incineration: electricity production 20% efficiency (Bogner et al 2008)	Bio CHP for heat & steam production: 89% *(Pers. communication with Wattenberg, Norske Skog)*	*Cofiring of wood pellets in power plant*
Replacement of fossil fuel alternative	Marginal fossil fuel mix in Japan (coal replacement	Marginal fossil fuel mix in Japan	Natural gas fired CHP: 90% (Laurijssen et al 2010)	*Marginal electricity mix of EU-27*
Emissions of fossil fuel alternative	0.690 kg CO_2 per kWh (Osaka Gas 2012)	0.690 kg CO_2 per kWh in Japan (Osaka Gas 2012)	Nat. gas: 56.8 kg CO_2 per GJ_p (Norske Skog Parenco 1991-2010)	*0.713 kg CO_2 per kWh (European Commission 2010)*
Related energy content & emissions of biomass feed in	Mixed waste: 9 GJ_p per tonne (Dornburg and Faaij 2005)	Mixed waste: 9 GJ_p per tonne (Dornburg and Faaij 2005)	Waste paper sludge: 4.8 GJ_p per tonne) (Norske Skog Parenco 1991-2010)	*2.01 MWh per tonne pellet; Efficiency cofiring pellets:41.2%; energy content of pellets: 17.6 GJ_{LHV} $tonne^{-1}$*
Waste wood & waste paper production	Immediate emission after decay of HWP first order reaction (formula D)	Immediate emission after decay of HWP first order reaction (formula D)	Immediate emission after decay of HWP first order reaction (formula D)	*Not applicable*
Resulting emission factors per m^3 harvested wood Derived from BAU allocation	Avoided GHG emission reduction: 0.027 – 0.084 tonne CO_{2eq} "Mixed waste" (wood based panel – lumber)	Avoided GHG emission reduction: 0.018 – 0.056 tonne CO_{2eq} "Mixed waste" (wood based panel – lumber)	Avoided GHG emission reduction: 0.042 tonne CO_{2eq} "Paper sludge" (both newsprint and pulp)	*Avoided GHG emission reduction: 0.107-0.112 tonne CO_{2eq} per m^3 harvest, without any correction (allocation) for drying needs (see Figure 4)*

2.2. *Chain emissions*

For the consumption of fossil fuels we calculated with emission values, including upstream losses of fossil fuels, for the production of solid wood products (CIPEC, 2009), market pulp (NRCan, 2012b), newsprint (CIPEC, 2008) and pellets in Canada. Data from the traditional industries are based on annual surveys by CIEEDAC (Nyboer and Lutes, 2011; Nyboer, 2011), whereas pellet data are derived from 10 production units (with an aggregated annual production of 1.25 million tonnes) that are certified by the GGL framework (Control Union Certifications, 2012). In case of the use of wood (residues) for drying matters, we included the upstream emissions (e.g. transport from bark from sawmill to pellet plant), where possible. A full overview of emissions per type of fuel use is given in Appendix D.

Further, we used marginal electricity mixes, as we assume that the production of additional HWPs will also require additional electricity production, i.e. we apply the consequential approach (Evans et al., 2009). The consumption and GHG emission pattern of electricity use by the forest industries is recorded via historical data series (attributional approach), i.e. assuming an average electricity generation mix and corresponding GHG emissions for Canada, Japan, US and EU-27. As we assume that additional electricity will be required, the emissions per kWh were changed from the average mix in each country into the respective marginal mix. See Table 1 for details.

Finally, two types of substitution occur in our selected wood markets:

- *Material substitution*. According to Tsunetsugu and Tonosaki (2010), the use of 1 m^3 of wood products leads to an emission reduction of about 38% in Japan when replacing steel-reinforced concrete in newly constructed buildings up to three stories high. The life cycle GHG emission occurring during transport of all building materials from production plant to building site and upstream processing of construction elements on the building sites are included in this calculation. The construction wood substitution in Japan comprises sawn wood (85%) and panels (15%), the latter consisting of plywood and OSB. In case of pulpwood, we do not assume any displacement of energy intensive materials, thus the use of market pulp and newsprint leads to GHG emissions.
- *Fuel substitution*. In 2011, more than 1 million tonne of Canadian pellets are exported to the EU-27 for electricity production thereby substituting fossil fuels. We assume that marginal fossil electricity is replaced (see also Table 2) and an average co-firing efficiency of 42% for wood pellets. The ultimate GHG emission reduction for pellets is based on the total carbon footprint for co-firing (Control Union Certifications, 2012) and a fossil fuel comparator for power production in the EU-27, as stated in draft legislation (European Commission, 2010; Department of Energy and Climate Change, 2012).

3. Scenario definition and input data

In our HWP evaluation, we consider an increased annual harvest of 50 million m^3 starting in 2012 and ending in 2112. This additional harvest figure is based on the harvest level in between that of 2009 with 120 million m^3 (Government of Canada, 2011) and of 2010 with 140 million m^3 (NRCan, 2012a) versus a possible future harvest level of about 180 million m^3 per annum. The latter level is in line with the projection for 2020 (Government of Canada, 2011) and an outlook study for 2030 (UNECE, 2012). The new level of 180 million m^3 will stay below the sustainable AAC levels of 2000–2010 (Fig. 1). Regarding the expected demand for wood, we use the projected industrial wood consumption in Canada for the domestic production of lumber, panels and paper products (Government of Canada, 2011). Our future demand assumes a fixed additional demand for paper products and flexible demand for both construction wood and pellets (see also Appendix A). We completed the projected demand for HWP's, by allocating the remaining part of the harvested wood to energy purposes. First, the need for wood residues (hog fuel) for drying purposes is allocated, the remaining fraction is allocated to the production of pellets.

3.1. *Feedstock allocation scenarios over different end uses*

Next to our base case (Section 1), we defined three major scenarios for the increased harvested volumes:

1. *Triple use: business as usual* (Fig. 3). The allocation to the most common wood consumer markets after 2012 is based on the historic market division of harvested logs (and adjacent wood residues) in Canada until 2009 (Government of Canada, 2011). That division resulted into 32.6% lumber, 9.7% wood based panels for construction, 36.2% paper products, and 21.5% of the harvested wood for energy purposes. The allocation of energy purpose is mainly existing of drying feedstock for solid wood and pellet production: about 4% for sawn wood, about 2% for wood based panels and about 5% for pellets (CIPEC, 2009; Katers and Snippen, 2011; Sikkema et al., 2010). In case of pulp and paper, we assume re-use is sufficient for drying purposes of pulp wood (see Appendix C). We assumed that the remaining volume of energy wood, between 11% and 16% of the annual harvest, is used to produce wood pellets. The actual conversion of 50 million m^3 logs into final products (Li et al., 2010) is equivalent to an annual production of about 15.6 million m^3 lumber, 4.4 million m^3 OSB or 4.5 million m^3 plywood, 7.8 million tonnes of pulp or paper and between 2.2 and 3.1 million tonnes of pellets.
2. *Dual use: combination of construction wood and energy*. In this scenario, the full share of pulpwood, which was used for paper products in the triple use scenario is now allocated to energy use, whereas the use of solid wood remain the same. The final pellet share, after subtraction of drying needs, is now between 38% and 52%. We choose this division by assuming US' future market for newsprint will remain structurally low, while EU's energy sector has to meet additional renewable energy targets (see Appendix A for an account of this scenario).
3. *Single use: energy wood only*. In a rather theoretical scenario, all additional harvested wood is allocated to energy after subtraction of drying needs: between 76% and 100% of the logs are utilized for pellet production. This division is made in order to allow for a comparison of the GHG mitigation potential from energy wood with construction wood (sawn wood and wood based panel).

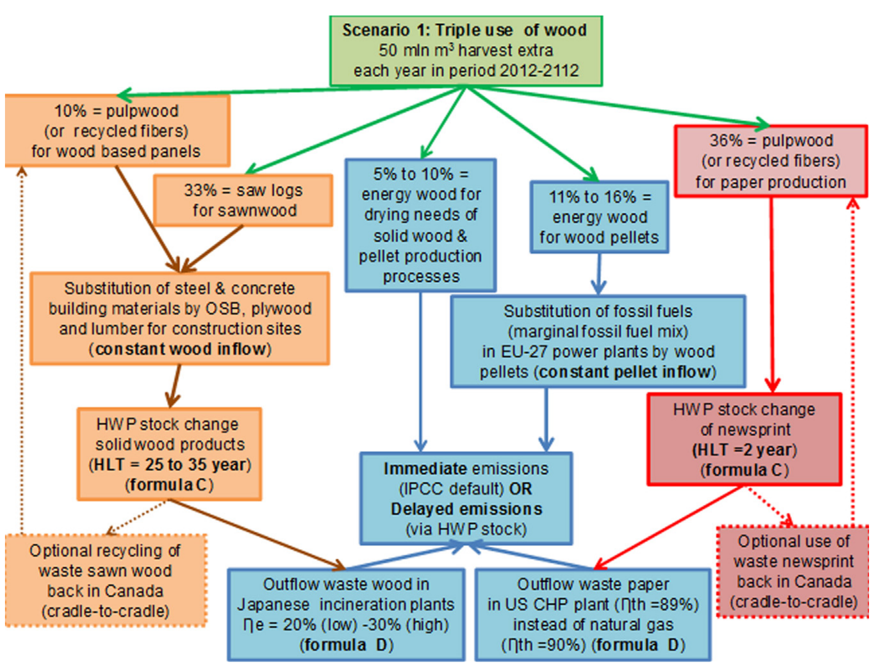

Fig. 3 – The allocation of additional Canadian harvest in scenario 1, the triple use for the building sector, energy sector and newsprint factories, including the possible recycling of waste paper and sawn wood.

3.2. End of life options for wood and paper waste

We consider two different end-of-life options: solid waste incineration in Japan and paper waste incineration via CHP's in USA (Fig. 3). Both the wood and paper waste are assumed to be combusted without accounting any GHG emissions: the release of CO_2 is already inventoried during the outflow from HWP (see Appendix B) and CH_4 and N_2O emissions from biomass burning are considered negligible (Norske Skog Parenco, 1991–2010; Risholm-Sundman and Vestin, 2005). Table 2 shows the GHG emission ranges per m^3 harvested wood for waste wood incineration and waste paper sludge combustion. Landfilling as end-of life option is not shown in our scenario's due to the expected cradle-to-cradle practice and consecutive recycling options. Note that landfilling is evaluated in Appendix C.

With regards to solid waste incineration in Japan, we have the applied a current (lower) efficiency rate of 20% to produce power from mixed waste (Bogner et al., 2008). A relatively new plant in the Netherlands achieves an efficiency of about 30% for mixed waste incineration (Odegard et al., 2012), which we use as upper rate, assuming that such efficiencies will also be reached by more plants in the case study regions in the coming decades. In the US, natural gas fired turbines constitute one-third of the installed CHP capacity, within the pulp and paper sector. The sector largely self generates electricity on site and is keen to use non-recyclable waste fibres (paper sludge) as well, while the sludge needs to be disposed (EPA, 2010). Due to the lack of US data, we again use Dutch efficiency rates. Similar to the US, the Dutch sector uses natural gas and paper sludge, although it exists of only one single dedicated bio-CHP. This CHP, on site of a Dutch newsprint plant, has an efficiency of 89% for paper waste (Norske Skog, 2011), and replaces natural gas with an efficiency of 90% (Laurijssen et al., 2010).

4. Results

The constant inflow of HWP (formula A) is used for compiling the substitution effects for sawn wood, wood based panels, paper products and wood pellets, after subtraction of drying needs. Fig. 4 shows the annual GHG emission reduction effects of various HWP and pellets.

4.1. GHG emissions of HWP without recycling

For each scenario, Fig. 5 shows the contribution to the global GHG balance. In our base case, all harvested wood is regarded like an immediate emission according to IPCC's default: the maximum emission would be 41.3 million tonnes CO_{2eq} per year. Each of three scenarios consists of an upper and a lower line, respectively indicating low and high GHG avoidance of our selected products. For example, the production of OSB has relative low CO_2 emissions in comparison with plywood (Werner et al., 2007).

The single use scenario displays a constant annual emission, because all harvest (energy wood) is regarded like an immediate emission each year. But this emission is far lower than in the base case, as now we take the

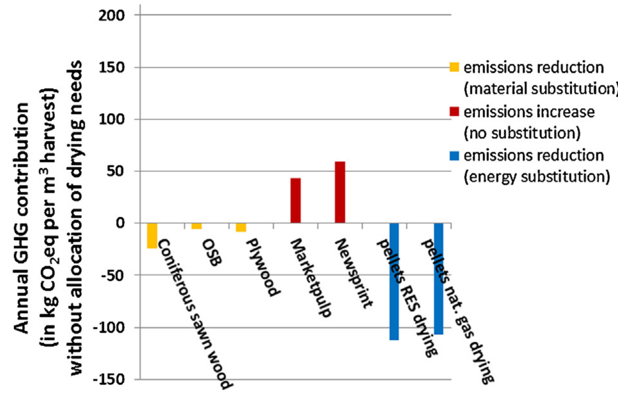

Fig. 4 – GHG emissions of selected wood commodities starting from the harvest of trees in Canadian forests until end of life (based on the allocations of scenario 1).

substitution of fossil fuel into account. The other scenarios show continuously increasing GHG emissions, as the carbon is slowly released via a first order reaction (non-linear curve). For the dual and triple use we have compiled two sub scenarios: a lower efficiency of waste incineration with large GHG emissions and an upper efficiency with low GHG emissions. Both triple and dual use have a considerable increase of GHG emissions in the first year, due to the immediate GHG release from energy wood (pellet production and feedstock drying). In case of dual use, the constant annual GHG effects of material and energy substitution will only partly compensate for the initial emissions peak (Fig. 5).

The dual and the triple use curves are approaching an equilibrium stage at the end of our modelling period, when the outflow of waste wood from the HWP pool becomes almost equal to the inflow of new wood products. Our results show that the dual use for construction and energy (best case) is the best option on short term until 2052, to achieve the most optimal GHG savings. After 2052, the GHG savings from single use score better, in comparison with dual use, due to the increasing release of carbon from solid timber products in the dual use scenario. When comparing single use (worst case) with triple use (worst case), this critical stage will even be reached in 2027, i.e. after 15 years the use of 100% pellets scores better. Note that these equilibrium stages are based on a situation without taking into account any C stock changes in the forest other than the annual harvests.

4.2. Global GHG contribution of harvested wood including recycling

In the previous section, we have not considered any form of recycling of waste wood or paper. Fig. 6 shows the new situation, after recycling is included. Our results show that when recycling is included, the dual use of trees for construction and for energy (best case) is the best option on short term (until 2047) to achieve optimal GHG savings. After 2047, the single use scores better again, similar to the situation

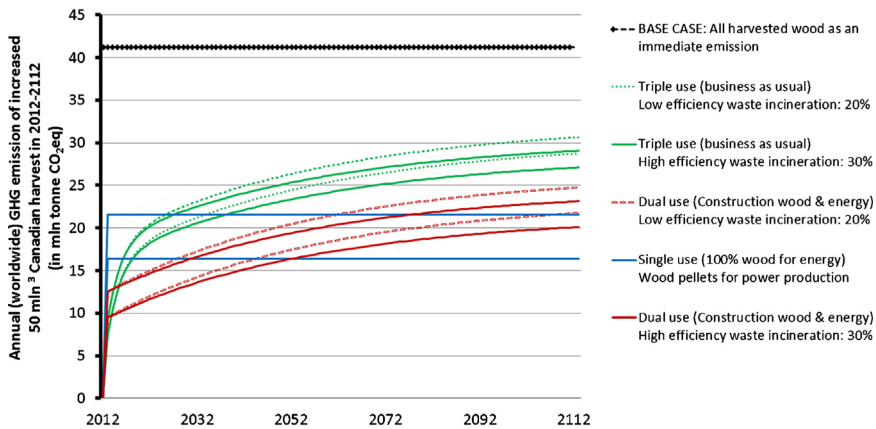

Fig. 5 – The annual GHG contribution for different scenarios, for an increased harvest of 50 million m^3 per annum. Per scenario: an upper line and a lower line, illustrating best and worst cases.

without recycling, and again without any changes in forest carbon stocks. For a more detailed comparison with the base case, we compiled *an annual average over* a period of 100 years in Table 3, next to the IPCC default emissions for the harvest (41.3 million tonne CO_{2eq}). All scenario's come quite close to each other, except for triple use without recycling.

- The left hand columns in Table 3 exclude recycling and show that single and double use of wood lead to the largest increase of GHG emissions in the long term (between 18 and 19 million tonnes CO_{2eq}). When we divide the additional harvest over three end-products by including pulp and paper (triple use), the GHG emissions increase and reach at least 24 million tonnes CO_2. Note that we assume the demand for newsprint to be constant for the next 100 years, whereas those for construction wood and pellets are flexible (Section 3).
- The right hand columns show the outcome including recycling, i.e. cradle-to-cradle reutilization of waste fibres. Three main effects of the addition of the recycling step can be observed. First, the emissions for the triple use scenario are considerably reduced through the recycling of waste paper. An additional production and export of pellets is possible, as fresh pulp fibres become available when newsprint is partially made from recycled paper. Second, the re-utilization of fibres for the production of OSB and newsprint achieves significant energy savings and consequent GHG emissions reductions (see Appendix C for a justification of the recycling options). Third, the total GHG emissions for the dual use scenario becomes a little lower after one recycling step for sawn wood. Next to the previous effect of lower energy input, there is a longer carbon uptake in products (sawn wood followed by OSB) and a slightly increased OSB production plus related material substitution in time. Nevertheless, the delay of waste wood causes a much lower substitution effect at the end-of-life, as relative less waste wood for incineration plants is available in a 100 year time frame. Thus, although somewhat counter-intuitive, more recycling leads in the dual-use scenario ultimately to higher GHG emissions.

5. Discussion

5.1. Uncertainty analysis

According to Dymond (2012) GHG estimates from HWP are most sensitive to uncertainties around manufacturing efficiency and mill waste handling. In our case study, some of the available Canadian manufacturing data of Section 3 are

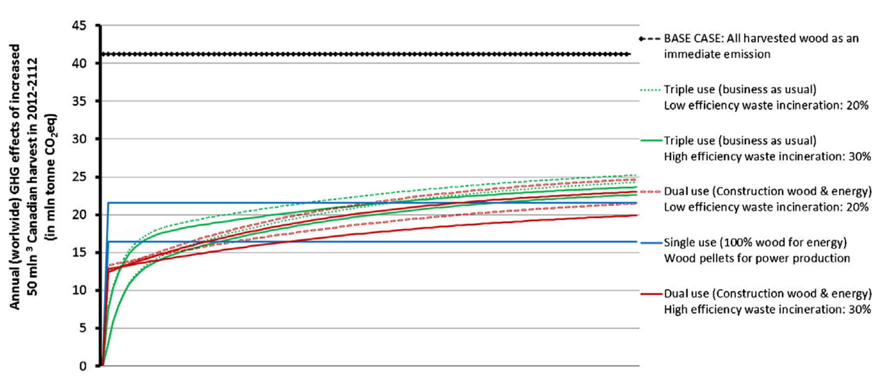

Fig. 6 – The annual GHG contribution for different scenarios with an increased harvest, but now including recycling of waste fibres. Per scenario: an upper line and a lower line, illustrating best and worst cases.

Table 3 – Average annual GHG emissions (in million tonnes of CO_{2eq}) over a period of 100 years for three scenario's, assuming an increased annual harvest of 50 million m^3 in Canada, in comparison with default (41.3 million tonnes of CO_{2eq} per annum) immediate GHG emissions. Any GHG effects from carbon flows in the forest are excluded.

	Scenarios without recycling (Figure 5)				Waste utilization with 1 (average) recycling step (table C1) (Figure 6)			
	A. Best case (solid waste combustion with 30%		B. Worst case (solid waste combustion with 20% efficiency)		A. Best case (solid waste combustion with 30% efficiency)		B. Worst case (solid waste combustion with 20% efficiency)	
IPCC default (all harvest is an emission for the country of harvest)	**41.3**				**41.3**			
Scenario 1 Triple use of wood harvests for construction, paper and pellets (business-as-usual)	**24.3**		**25.4**		**19.7**		**20.9**	
Possible allocation per country for the average of best & worst case *)	Canada 36.1	USA -2.0	Japan -6.7	EU-27 -3.7	Canada 34.7	USA -1.9	Japan -5.3	EU-27 -8.8
Scenario 2 Dual use for construction wood and pellets (no paper products)	**18.1**		**19.2**		**18.4**		**19.5**	
Possible allocation per country for the average of best & worst case *)	Canada 36.4	USA 0	Japan -6.7	EU-27 -12.8	Canada 35.2	USA 0	Japan -5.3	EU-27 -12.8
Scenario 3 Single use for pellets (energy wood only)	**19.0**				**19.0**			
Possible allocation per country *)	Canada 42.4	USA 0	Japan 0	EU-27 -25.1	Canada 42.4	USA 0	Japan 0	EU-27 -25.1

*) Assumptions for the allocation per country: (i) emissions of ocean shipping are not accounted for; (ii) emissions of the fossil fuel mix are allocated to the EU-27; (iii) emissions for steel & concrete production to Japan; (iv) recycling of waste fibers takes place in Canada, after which the recycled product is re-exported.

incomplete for the purpose of our LCI approach. CIEEDAC for example is collecting energy use and emissions data (Nyboer and Lutes, 2011; Nyboer, 2011), but these databases lack GHG emission data for glue (panels), fillers (paper) or a specification for external electricity (Upton et al., 2007). Also, waste re-utilization (recycling) and its GHG impact on production process, may have a larger bias. For Canadian circumstances (Gaudreault et al., 2009; Laurijssen et al., 2010) we compiled a GHG emission reduction between 0.1 and 3.3 kg CO_2 per 1% waste paper increase (Table C1). We found two other effects, 9.7 kg CO_2 per 1% fibre in the Netherlands (Norske Skog Parenco, 1991–2010) and 23 kg CO_2 less per 1% waste fibre in Switzerland (Hischier, 2007). However, in both countries, external effects do play a major role, such as the set-up of new bio CHP and different transport distances for fresh and waste fibres.

Further, with regard to material substitution effects (Section 2), we assumed a specific GHG emission reduction of 38% for Japanese building sites (Tsunetsugu and Tonosaki, 2010). For comparison, the alternative use of the global average of 49% (Section 1) would lead to an extra reduction of 0.9 million tonnes CO_{2eq} per annum in scenarios 1 and 2. Finally, we neglected ''non-CO_2'' GHG emissions (Section 3). By aggregating the neglected N_2O and CH_4 contribution (Petersen-Raymer, 2006; Sjølie and Solberg, 2011; Upton et al., 2007), annual emissions increase by about 0.5 million tonnes of CO_{2eq} in our scenarios.

5.2. *Impact of carbon flows in the forest*

Our analysis focuses on GHG emission starting from harvest and show that different end uses result in varying GHG savings over time. The underlying assumption is that trees are a renewable resource, and that the CO_2 released after harvest is compensated by renewed uptake of carbon through the regrowth of the forest. How may a higher level of forest harvest in Canada (from 130 million m^3 to 180 million m^3, as assumed in Section 3) affect the carbon balance in the forest? The exact impact and time required to compensate for forest carbon changes depend on many different factors, such as climate zone (geographical area), forest age, tree species harvested, harvesting practices, natural succession or replanting, frequency of wildfires and degree of insect infestation, such as the MPB (Section 1). Recent research has shown that regrowth of a harvested forest stand can take several decades, especially in case of older, secondary management forests (BERC, 2012). Therefore, forest biomass harvest merely for energy has been heavily debated by both NGO's (Birdlife International, 2012; Greenpeace, 2011) and scientists (Walker et al., 2010; Zanchi et al., 2012; Euractiv, 2012).

First, less frequent harvesting and more selective harvesting are expected to achieve more carbon storage, as inventoried for temperate forests in the US (Nunery and Keeton, 2010). The HWP pool of intensively managed temperate forests is stated to be insufficient to compensate for forest carbon storage in extensively managed forests (Schwenk et al., 2012). Extracting biomass for bioenergy from boreal forests on a permanent basis, assuming a current net increment, is stated to increase atmospheric carbon concentration, in comparison with a non-harvest scenario (Holtsmark, 2013). When biomass is sourced from harvest residues (e.g. slash) instead of tree standing biomass, the atmospheric carbon increase is assumed to be lower (McKechnie et al., 2011). Second, Lamers et al. (2013) showed for BC that the use of non-merchantable insect-damaged trees, primarily for timber and pulp, can yield immediate or short-term GHG benefits. In another study (De Aquino Ximenes et al., 2012), the GHG contribution for sustainably managed forest in Australia was inventoried, providing all forest carbon dynamics, carbon storage in HWP and both material and energy substitution effects. These Australian forests could contribute significantly to GHG emissions reduction, after a 200 year timeframe and several harvest cycles, more than if the forest had not been harvested.

Nevertheless, more empirical analysis for Canada's managed and unmanaged forests is needed to evaluate any forest carbon change for our modelling period until 2112 to complement our analysis. Note that only limited historical carbon data are available. In this respect, we checked some macro level data since 1990. The harvest level in Canada's managed forests in 1990–2009 had an average of about 179 million m^3 per annum (Government of Canada, 2011), more or less equal to our future level. The largest carbon fluxes in 1990–2009 consisted of carbon uptake by growing trees (around 2950 million tonnes CO_{2eq} per annum) and a release due to the decay of dead organic matter (DOM) and soil (around 2700 million tonnes CO_{2eq} per annum). The decay reflected the long-term effect of past disturbances, especially insect epidemics that have left substantial quantities of DOM (Environment Canada, 2011). A last contributor, GHG emissions from wildfires, determined whether the Canadian forests are accumulating or loosing carbon. The wildfire emissions varied between 11 and 260 million tonnes of CO_{2eq}, the upper range occurring in 2007. Since 1990, the forest carbon pool accumulated carbon, except for 2007, when about 45 million tonnes of CO_{2eq} was released in the Canadian forests (Government of Canada, 2010).

5.3. *GHG accounting on a country level*

The accounting rules for HWP and energy, i.e. the allocation of GHG effects over individual countries, are politically sensitive (Pingoud, 2006). A new international accounting method may determine the compliance with any national obligations in future commitment periods after 2012 (post Kyoto period). The current UNFCCC proposal for HWP accounting is in favour of harvesting countries (Macintosh, 2012). In Table 3 we have subdivided the aggregated emissions (as an average for the best and worst cases) to the individual countries Canada, the US, Japan and the EU-27. Different to the aggregated figures, we do not allocate any emissions from international shipping of wood pellets and of construction wood to the individual countries, as these are currently excluded from KP obligations. These shipping emissions are between 1.2 and 1.7 million tonnes CO_{2eq} in scenario's 1 through 3.

Canada can lower its GHG emissions via a slow release of CO_2 from its HWP, from 42.4 million tonnes CO_{2eq} in scenario 3 to 36.1 million tonnes CO_{2eq} in scenario 1 due to relative long life times and a net inflow in the HWP storage pool. Note that the GHG allocation for Canada in scenario 3 is larger than IPCC's default, as the emissions from Canadian pellet production are included on top of the immediate emissions from 100% energy wood. In case of fibre reutilization, the GHG emissions of OSB and newsprint are lower than without recycling. These emissions are allocated to Canada, as we assume a cradle-to-cradle approach, in which all wood and paper waste is returned to Canada. Overall, the GHG emissions of Canada decrease after recycling, due to a longer uptake in HWP.

Next, Japan also benefits from such an accounting method, assuming the replaced concrete and steel are produced in Japan. In scenario's 1 and 2, the GHG emission reduction is between 5.3 and 6.7 million tonnes CO_{2eq}. However, recycling now results into a lower reduction: the effect of more material substitution (extra volume of OSB with recycled fibres) is actually offset by lower fossil fuel substitution (less post-consumer wood available for incineration after end-of-life). Actually, in all our cases, the GHG reduction effects for fossil fuel substitution are based on future marginal electricity mixes per country (see Section 2). This fuel substitution effect is considerable for the EU-27: between 3.7 and 25.1 million tonnes of CO_{2eq}. The GHG emission reduction in the EU-27 more than doubles, from 3.7 to 8.1 million tonnes CO_{2eq}, after paper waste recycling. When newsprint is partially made from recycled paper, fresh pulp fibres become available for extra wood pellet production (Section 4.1). Finally, when newsprint is used for CHP's in the US, the GHG emissions reduction is about 2 million tonnes, with a more or less similar effect with and without waste paper recycling.

5.4. *Conclusions and recommendations*

All scenario's come quite close to each other, except for triple use without recycling. The latter scores worst as the global GHG emissions reach at least 24 million tonnes CO_{2eq}, whereas all other scenario remain between 18 and 21 million tonnes CO_{2eq}. In case of a lacking infrastructure, single and dual use become serious alternatives to support GHG emission reduction, the former only when it complies with the sustainability issues raised by NGOs and the scientific community. Nevertheless, the triple use scenario shows significant GHG reductions on the country levels; but note that any GHG allocation is also highly depending on recycling energies, energy conversion efficiencies and other applicable GHG modelling data (Section 5.1).

Following our experiences with this HWP analysis, we conclude and recommend the following:

1. *Carbon footprint*. The new accounting rule for carbon uptake by wood products, is a good incentive to optimize the use of harvested wood in terms of improved GHG savings.

According to UNFCCC (2011b), the existing default for HWP (immediate emissions after harvest) could be replaced by new carbon accounting for wood and paper products, provided that "verifiable and transparent data are available on the fate of these products", which relies on country specific data. Accounting rules will have to start from basic reporting formats, and may include other elements such as sustainable forest management (Pingoud, 2006). We suggest to introduce a carbon footprint for HWP in the building sector, in combination with existing chain-of-custody procedures for certified wood products (e.g. FSC, PEFC). With regards to biomass certification (e.g. Green Gold Label, ISCCplus, Laborelec, NTA 8080), an equivalent carbon footprint of pellets is already incorporated in a track- and trace systems between pellet supplier and end consumer.

2. *Principal use of (round)wood from* boreal and temperate forests needs to be evaluated from a holistic perspective, i.e. it should include forest carbon flows related to forest management. Especially a scenario where roundwood is used for 100% pellet production is both economically unlikely and may create a significant carbon change, whereas multiple end-use is economically feasible and typically achieves far better overall GHG emission reductions.
3. *IPCC guidelines*. We support the initiative to impose one new Post Kyoto accounting method for HWP. Problems may occur for future accounting by non-Kyoto countries, as those may have other alternative reporting for HWP in place (IPCC, 2006b). In order to prevent double counting or omission of carbon flows in any of the country reports, it is necessary to reconsider in a next step all other HWP reporting methods. Also the GHG emissions from international shipping of commodities may be accounted for in a post KP, and further allocated over the trading countries.
4. *Level playing field for all sectors*. Next to production of wood for renewable energy (e.g. wood pellets), also solid wood products, like sawn wood and wood based panels contribute significantly to GHG emission reduction. Future policy incentives focusing on GHG emission reduction should include both the energy sector and the forest product sector, to provide a level playing field.
5. *Optimize waste utilization*. Harvested wood from high quality trees should be first used for sawn wood, after which it could be re-utilized for wood based panels and the waste panels are combusted with energy recovery (cascading). From the perspective of GHG savings, the utilization of wood waste for OSB panel production is attractive for further support, as this cascade step is relatively underdeveloped. Finally, current paper recycling practices are very relevant, as paper re-utilization considerable reduce GHG emissions after one recycling round.

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Appendices A–D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.03.007

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