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Meta-analysis of greenhouse gas displacement factors of wood product substitution

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ABSTRACT

A displacement factor can express the efficiency of using biomass to reduce net greenhouse gas (GHG) emission, by quantifying the amount of emission reduction achieved per unit of wood use. Here we integrate data from 21 different international studies in a meta-analysis of the displacement factors of wood products substituted in place of non-wood materials. We calculate the displacement factors in consistent units of tons of carbon (tC) of emission reduction per tC in wood product. The displacement factors range from a low of −2.3 to a high of 15, with most lying in the range of 1.0 to 3.0. The average displacement factor value is 2.1, meaning that for each tC in wood products substituted in place of non-wood products, there occurs an average GHG emission reduction of approximately 2.1 tC. Expressed in other units, this value corresponds to roughly 3.9 t CO_2 eq emission reduction per ton of dry wood used. The few cases of negative displacement factors are the result of worst-case scenarios that are unrealistic in current practice. This meta-analysis quantifies the range of GHG benefits of wood substitution, and provides a clear climate rationale for increasing wood substitution in place of other products, provided that forests are sustainably managed and that wood residues are used responsibly.

1. Introduction

The forest sector can play an important role in climate change mitigation. The portfolio of forest-related mitigation activities includes afforestation, reducing deforestation, maintaining or increasing carbon stocks in forests, and using sustainable forest harvests to substitute for GHG-intensive fuels and materials. The role of sustainably managed forests in the global GHG balance is properly considered over a long time span, recognizing the cyclical carbon flows between the atmosphere, trees, soil and wood products, and including the avoided emissions when wood is used in place of other materials or fuels.

The atmospheric carbon removed by growing trees is stored in several reservoirs or "pools." There is carbon in the living tree biomass, carbon in the soil due to decaying biomass on and in the forest floor, and carbon transferred out of the forest but still residing in various types of products made of paper and wood. When a tree is cut and the wood used to make products, this is not a carbon emission but a carbon transfer from one pool (the forest) to another (the products). However, these carbon pools are transitory, as the carbon will cycle between the pools over time spans of days to centuries, and will eventually return to the atmosphere. After returning to the atmosphere, the carbon is reabsorbed by growing trees and the cycle carries on. Over the long term, in a sustainably managed forest, the carbon pool within the forest remains relatively stable. Land use changes such as afforestation or deforestation would, however, lead to changes in the overall forest carbon pool. The carbon pool representing the stock of

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forest products, while currently increasing, is expected to eventually stabilize at a higher level in the long term.

However, the GHG balance changes significantly when an additional carbon pool is considered: fossil carbon whose emission is avoided when wood is used in place of other materials. When wood replaces a fossil fuel for energy, or when wood replaces a material such as steel or concrete whose use results in greater GHG emission, then the fossil emission avoided by choosing wood is a permanent (i.e., not transitory) benefit. This means that, rather than a constant balance over time when just considering the carbon cycling in the forest and wood itself, there is a continually increasing GHG benefit, assuming maintenance of a sustainable, productive forest for the purpose of providing substitutes for non-wood fuels and materials.

Wood product substitution, in other words using wood instead of other materials, is increasingly recognized as a potentially important element of a long-term strategy for mitigating climate change. The latest assessment report of the Intergovernmental Panel for Climate Change considers material substitution to be an integral part of a forest sector mitigation portfolio, and states that "in the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit" (IPCC, 2007, p. 543).

Beyond this conceptual understanding of the climate benefits of wood substitution, there is a need for quantitative analysis of the potential GHG emission reduction that can be achieved. Such analysis would guide policymakers towards more effective mitigation instruments, assist engineers and architects to reduce the climate impact of the built environment, and help determine appropriate uses for our limited supply of forestland and biomass production. Displacement factors can be useful metrics in this respect, by quantifying the climate change mitigation effect of wood substitution.

An increasing number of studies have analyzed the GHG effects of wood product uses (see Sathre and O'Connor, 2008). The studies have differed in terms of their focus (types of wood products, compared to various non-wood products), their transparency (description of analytical methods and assumptions; availability of source data), and their completeness (life cycle phases considered; analysis of multiple options or uncertainties). Some of these studies have been conducted and reported in sufficient detail to allow the calculation of displacement factors of wood substitution. A sufficient body of knowledge has now been accumulated to allow these studies to be compared and contrasted. Here we present the results of a meta-analysis in which we integrate quantitative data on displacement factors from 21 different studies of the GHG benefits of wood substitution, to draw general conclusions regarding the climate impact of wood product substitution.

2. GHG effects of wood substitution

In a review of 48 studies on the GHG impacts of wood products, Sathre and O'Connor (2008) investigated whether actively managing forests for wood products is better, worse or neutral for climate change *vs.* leaving forests in their natural states. The studies indicated several mechanisms by which wood product substitution affects GHG balances. These include the fossil energy used to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions such as from cement manufacturing; the physical storage of carbon in forests and wood materials; the use of wood by-products as biofuel to replace fossil fuels; and the possible carbon sequestration in, and methane emissions from, wood products deposited in landfills. In this section we summarize the effects of each of these mechanisms.

2.1. *Less fossil fuel consumption in manufacturing*

A general conclusion is that the manufacturing of wood products requires less total energy, and in particular less fossil energy, than the manufacturing of most alternative materials. "Cradle to gate" analyses of material production, including the acquisition of raw materials (e.g., mining or forest management), transportation, and processing into usable products, show that wood products need less production energy than a functionally equivalent amount of metals, concrete, or bricks. Furthermore, much of the energy used in wood processing is thermal energy used for drying, for which wood processing residues are commonly used. Thus, the fossil carbon emission from wood product manufacturing is generally much lower than that of non-wood products. Composite wood products, while making more efficient use of roundwood raw materials, require a relatively higher use of fossil energy than do solid wood products. This energy, used for production of resins and additives as well as for the mechanical processing of wood fibres, is still commonly less than that needed for non-wood products.

2.2. *Avoided process emissions*

Using wood products in place of cement-based products avoids the industrial process carbon emissions from cement manufacturing. CO_2 emissions are inherent to cement production, due to chemical reactions (calcination) during the transformation of raw materials into cement clinker. Avoided process emissions can be a significant part of the GHG benefits of wood products used in place of concrete and other cement-based materials. While avoided calcination reaction emissions are well quantified, there is some uncertainty regarding the net effect of cement process emissions, due to CO_2 uptake by carbonation reaction. Carbonation is a slow reaction that occurs over the life cycle of cement products, and involves reabsorption of part of the CO_2 that was initially emitted. Nevertheless, as carbonation uptake is less than calcination emission, process emissions are avoided when substituting wood in place of cement products.

2.3. *Carbon storage in products*

Wood material is composed of about 50% carbon by dry weight, this carbon having been drawn from the CO_2 removed from the atmosphere by the growing tree. In other words, wood products provide a physical storage of carbon that was previously in the atmosphere as a greenhouse gas. The climatic significance of carbon storage in wood products depends on the dynamics of the products pool as a whole, i.e., whether the total quantity of stored carbon is increasing, decreasing, or is stable. Atmospheric carbon concentration is affected by *changes* in the size of the wood product pool, rather than by the size of the pool itself. In the short to medium term, climate benefits can result from increasing the total stock of carbon in wood products, by using more wood products or using longer-lived wood products. In the long term as the stock of products stabilizes at a higher level, wood products provide a stable pool of carbon as new wood entering the pool is balanced by old wood leaving the pool. Consideration of the long-term carbon dynamics of wood products shows that the substitution effect of avoiding fossil emissions is ultimately much more significant than the carbon stored in wood products.

2.4. *Carbon storage in forests*

The life cycle of wood products begins with the growth of trees, so the consideration of carbon flows in forest ecosystems is essential to accurately understand the climate impacts of wood product use. A boundary condition of wood substitution studies is that the forests that produce the wood are managed sustainably. Over a complete rotation period of sustainable (yield) forestry, the carbon content in tree biomass remains unchanged, by definition. Forest soils often store more carbon than forest biomass, and soil carbon stock in managed forests generally maintains a dynamic equilibrium level over multiple rotations. This discussion of wood production in *managed* forests must be distinguished from the carbon balance effects of harvesting *primary* forests. Conversion of primary (old-growth) forests to secondary, managed forests results in a loss of stored carbon from both biomass and soils, before the forest carbon stocks again reach dynamic equilibrium. The level of the new equilibrium depends on soil characteristics, forest management intensity, and other factors. Afforestation, or the creation of forests on previously non-forested land, generally increases the carbon stock in biomass and soil as well as producing wood for product substitution.

2.5. *Avoided fossil fuel emissions due to biofuel substitution*

The wood contained in a finished forest product is only a part of the total biomass flow associated with the product. Substantial biomass residues are generated during forest thinning and harvest operations, and during primary and secondary wood processing. At the end of its service life, unless it is recycled for additional material use, the wood product itself becomes combustible residue. These by-products can be used as biofuel to replace fossil fuels, thus avoiding fossil carbon emissions. The quantification of GHG benefits due to the use of residues from the wood product value chain is not straightforward; issues include the allocation of benefits to the different biomass fractions, varying carbon intensity of the fossil fuel replaced, leakage (i.e., a unit of additional biofuel does not necessarily lead to a unit reduction of fossil fuel use), potential soil carbon stock change due to removal of harvesting residues, and uncertainties about how post-use wood products will be handled by future waste management systems. Nevertheless, the recovery and combustion of the biomass by-products associated with wood products appears to be the single most significant contributor to the life cycle GHG benefits of wood product use.

2.6. *Carbon dynamics in landfills*

Some wood products are deposited in landfills at the end of their service life. Carbon dynamics in landfills are recognized to be quite variable, and can have a significant impact on the life cycle GHG balance of the wood product. A fraction of the carbon content in landfilled wood will likely remain in (semi)permanent storage, providing climate benefits. Another fraction may decompose into methane, which has much higher global warming potential (GWP) than CO_2. However, methane gas from landfills can be partially recovered and used as a biofuel to replace fossil fuels. Thus, the landfilling option for post-use wood products carries great uncertainties, and could result in climate benefits (partial sequestration in landfills, and partial production of methane biofuel) or climate impact (emission of methane to the atmosphere).

3. Methods

A displacement factor of wood product substitution is a measure of the amount of GHG emission that is avoided when wood is used instead of some other material. It is an index of the efficiency with which the use of biomass reduces net GHG emission, and quantifies the amount of emission reduction achieved per unit of wood use. If the use of non-wood materials in a particular application results in a given amount of GHG emission, while using wood materials to fulfil the same application results in a different amount of emission, then the displacement factor is calculated as the difference in emission divided by the amount of additional wood used. A higher displacement factor indicates that more GHG emission is avoided per unit of wood used. A negative displacement factor means that emission is greater when using the wood product.

Based on a review of numerous studies of the GHG impacts of wood products (Sathre and O'Connor, 2008), supplemented by further literature search, we determined that 21 studies contain sufficient information to calculate the displacement factor of at least one wood product substituted in place of a non-wood product. The studies are restricted to analyses of wood material substitution, i.e., the use of wood instead of non-wood materials like metals, minerals and plastics. Studies of the GHG impacts of wood used exclusively as biofuel are not considered, although some of the studies also include the fuel substitution effects of biofuels from wood processing residues or post-use wood products. The studies focus on the production phase of the products, and often include the end-of-life phase, but in general do not explicitly consider the operation phase of the products. For example, comparisons of flooring materials (Jönsson et al., 1997; Petersen and Solberg, 2004) assume identical maintenance requirements for wood and non-wood flooring, and comparisons of buildings (Gustavsson et al., 2006; Lippke et al., 2004) are based on functionally equivalent buildings, thus the operation phase of the wood and non-wood buildings are identical and have no effect on the relative impacts. An exception is John et al. (2009), in which minor differences in operating energy exist between the wood and non-wood buildings, which are included in the calculated displacement factors. Differences in life spans of the materials are accounted for in the calculations of life cycle GHG emission (e.g., Jönsson et al., 1997).

Schlamadinger and Marland (1996) defined two displacement factors, one for biofuels that substitute directly in place of fossil fuels, and another for wood products whose production requires less fossil fuel than substituted products. Their analysis did not consider other potential substitution benefits not related to fossil fuel use, such as avoided process emissions or carbon sequestration in landfills. In the present meta-analysis, due to the diversity of the studies analyzed, we calculate a single displacement factor that incorporates all the GHG emission reductions reported in each study. Depending on the system boundaries of the study, these may include fossil fuel emissions from material production and transport, process emissions such as cement reactions, fossil emissions avoided due to using biomass by-products and post-use wood products as biofuel, carbon stock dynamics in forests and wood products, and carbon sequestration and methane emissions of landfilled wood materials. A summary of the system boundaries of the 21 studies is shown in Table 1. Where possible, we also break down the overall displacement factors to find the contribution of each of these system components. The data available in some studies allow the calculation of a single displacement factor, with no indication of the range of variability. Other studies report data on several scenarios or assumptions, which allow the calculation of high and low estimates of the displacement factors.

In this meta-analysis we calculate displacement factors in units of tC of emission reduction per tC in wood product. The displacement factors could also be calculated in other units, e.g., emission reduction per ton of wood product, or per m^3 of wood product, or per m^3 of roundwood, or per hectare of forestland. The inverse of the displacement factor could also be used to express the ''biomass cost,'' or the amount of wood required to achieve a unit of GHG emission reduction (Gustavsson et al., 2007). Here we use the units of tC emission reduction per tC in wood products, as these units appear to be the most transparent and comparable. In addition, because both emission reduction and wood use are expressed in the same unit (tC), the displacement factor is an elegant indicator of the ''multiplicative'' effect of using wood products for GHG mitigation. This definition of displacement factor implies that we allocate the GHG effects of all associated biomass co-products to the main wood product, which is discussed further in Section 4.

Specifically, we calculate the displacement factor (DF) as follows:

$$DF = \frac{GHG_{non\text{-}wood} - GHG_{wood}}{WU_{wood} - WU_{non\text{-}wood}}$$

where $GHG_{non\text{-}wood}$ and GHG_{wood} are the GHG emissions resulting from the use of the non-wood and the wood alternatives, respectively, expressed in mass units of carbon (C) corresponding to the CO_2 equivalent of the emissions, and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in the wood and non-wood alternatives, respectively, expressed in mass units of C contained in the wood. $WU_{non\text{-}wood}$ is non-zero in some applications, e.g., concrete-framed buildings with roof structures, doors or window frames made of wood. WU includes only the wood contained in the end-use products.

For studies that use other units to quantify the GHG emissions and wood product use, we convert both parameters to mass units of carbon (C). The carbon content of GHG emissions is calculated as 12/44 CO_2 eq. The carbon content of wood is assumed to be 50% of oven-dry weight. Unless otherwise specified in the source documents, calculations have been made assuming a wood density of 500 kg oven-dry matter per m^3, and a moisture content of 15% (mass of water per mass of oven-dry wood).

4. Results and discussion

The calculated displacement factors are listed in Table 2. The displacement factors average 2.1, and range from a low of −2.3 to a high of 15. The wide range of displacement factors is due to the inclusion of ''extreme'' scenarios in some of the studies, and differences in system boundaries between studies. The middle estimates of the displacement factors range from 0.4 to 6.0, with most lying in the range of 1.0 to 3.0. The average of the low estimates is 0.8, and average of the high estimates is 4.6. The average middle estimate of 2.1 can be viewed as a reasonable estimate of the GHG mitigation efficiency of wood product use over a range of product substitutions and analytical methodologies.

The results show several cases of negative displacement factors, in which the GHG emission of wood products are greater than that of alternatives. These are generally the result of worst-case scenarios that are unrealistic in current practice. For example, the lowest displacement factor of −2.3 is based on Börjesson and Gustavsson's (2000) scenario of landfilled wood with high methane emission, compared to a concrete building with minimal emissions. Petersen and Solberg's (2002, 2003) scenarios that result in displacement factors of −0.8 and −0.9 are based on landfilled wood with no permanent carbon storage and continuous methane emission. Gustavsson and Sathre's (2006) scenario results in a displacement factor of −0.1, based on a ''worst case'' combination of 13 parameters that were selected to give maximum GHG emissions from a wood-framed building and minimum emissions from a concrete-framed building. In contrast to these few extreme cases, most of the low estimates of displacement factors are positive, and all of the middle estimates are positive.

Over its complete life cycle, wood can be used as both a material and as a fuel. Although the focus of the studies in this meta-analysis is material substitution, many of the studies also include the use of wood as an energy source. As an end-of-life material management option, many studies consider recovery of the feedstock energy of the wood material through controlled combustion. Some studies also include energy

Table 1 – Summary of system boundaries of 21 studies of wood product substitution.

Reference	Energy for material production	Process reaction emissions	Biomass residues for energy	C stock in products	C dynamics in forest	End-of-life management	Time horizon
Börjesson and Gustavsson (2000)	Included	Included	Included	Discussed	Included	Landfilling, energy recovery	Cradle to grave (100-year); cradle to cradle (300-year)
Buchanan and Levine (1999)	Included	Not included	Not included	Discussed	Discussed	Not included	Cradle to gate
Eriksson et al. (2007)	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
Gustavsson et al. (2006)	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
Gustavsson and Sathre (2006)	Included	Included	Included	Discussed	Included	Energy recovery	Cradle to grave, 100-year service life
John et al. (2009)	Included	Included	Not included	Discussed	Not included	Landfilling; energy recovery	Cradle to grave, 60-year service life
Jönsson et al. (1997)	Included	Included	Not included	Not included	Not included	Energy recovery without fossil fuel substitution	Cradle to grave, 40-year service life
Knight et al. (2005)	Included	Included	For wood processing	Not included	Discussed	Not included	Cradle to gate
Koch (1992)	Included	Not included	For wood processing	Discussed	Discussed	Not included	Cradle to gate
Künniger and Richter (1995)	Included	Included	For wood processing	Not included	Not included	Energy recovery without fossil fuel substitution	Cradle to grave, 60-year service life
Lippke et al. (2004)	Included	Included	For wood processing	Discussed	Discussed	Landfilling	Cradle to grave, 75-year service life
Petersen and Solberg (2002)	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 50-year service life
Petersen and Solberg (2003)	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 45-year service life
Petersen and Solberg (2004)	Included	Included	Not included	Not included	Included	Landfilling; energy recovery	Cradle to grave, 45-year service life
Pingoud and Perälä (2000)	Included	Included	Included	Discussed	Discussed	Energy recovery	Cradle to grave, permanent transition to wood-intensive construction sector
Salazar and Meil (2009)	Included	Included	Discussed	Temporary storage, linked to disposal	Discussed	Landfilling; energy recovery	Cradle to grave, 100-year service life
Salazar and Sowlati (2008)	Included	Included	Not included	Discussed	Not included	Landfilling	Cradle to grave, 25-year service life
Scharai-Rad and Welling (2002)	Included	Included	Not stated	Not included	Not included	Energy recovery	Cradle to grave, varying service lives
Sedjo (2002)	Included	Included	For wood processing	Discussed	Discussed	Not included	Cradle to gate
Upton et al. (2008)	Included	Included	Included	Included	Included	Landfilling; energy recovery	Cradle to grave, 100-year service life
Werner et al. (2005)	Included	Included	Included	Stabilizes at higher level, no net effect	Discussed	Energy recovery	Steady-state condition assumed after 2130

Table 2 – Low, middle, and high estimates of displacement factors of wood product substitution (tC emission reduction per tC of additional wood products used) based on data from 21 studies.

References	Application	Displacement factor (tC/tC)		
		Low	Middle	High
Börjesson and Gustavsson (2000)	Apartment building	−2.3	4.3	7.4
Buchanan and Levine (1999)	Hostel building		1.0	
	Office building	1.1	1.2	1.2
	Industrial building		1.6	
	Single-family house	−0.7	3.5	15
Eriksson et al. (2007)	Apartment building	4.4	6.0	7.5
Gustavsson et al. (2006)	Apartment building (Sweden)	1.9	3.7	5.6
	Apartment building (Finland)	0.4	1.8	3.3
Gustavsson and Sathre (2006)	Apartment building	−0.1	2.3	7.3
John et al. (2009)	6-storey office building			
	Timber vs. steel	0.7	0.9	1.1
	Timber vs. concrete	0.9	1.0	1.0
	Max wood content vs. steel	1.1	1.3	1.4
	Max wood content vs. concrete	1.3	1.3	1.3
Jönsson et al. (1997)	Solid wood flooring	0.2	0.4	0.7
Knight et al. (2005)	Wood door *vs.* steel door		3.0	
Koch (1992)	Mixture of wood products		2.2	
Künniger and Richter (1995)	Roundwood utility pole	0.6	2.5	4.4
	Glulam utility pole	0.1	2.0	3.8
	400V transmission line	1.5	2.7	3.9
	20 kV transmission line	1.0	3.4	5.8
Lippke et al. (2004)	Single-family house			
	Wood vs. concrete (Atlanta)		2.2	
	Wood vs. steel (Minneapolis)		0.9	
Petersen and Solberg (2002)	Roof beams, wood *vs.* steel	−0.9	0.5	1.5
Petersen and Solberg (2003)	Flooring, wood *vs.* stone	−0.8	0.4	1.2
Petersen and Solberg (2004)	Flooring, wood *vs.* alternatives	0.1	1.9	14
Pingoud and Perälä (2000)	Finnish construction sector	0.5	1.1	3.2[a]
Salazar and Meil (2009)	Single-family house	1.4	1.9	9.0[b]
Salazar and Sowlati (2008)	Window frames	1.2	5.0	8.8
Scharai-Rad and Welling (2002)	Single-family house	2.3	2.8	3.3
	3-storey building	1.5	2.3	3.1
	Warehouse	0.7	1.2	1.8
	Window frame	1.7	3.2	4.6
Sedjo (2002)	Utility poles, wood *vs.* steel		1.6	
Upton et al. (2008)	Single-family house			
	wood vs. concrete (Atlanta)	2.8	2.8	6.6
	wood vs. steel (Minneapolis)	−0.01	0.4	2.2
Werner et al. (2005)	Swiss construction sector		1.7	
Averages		0.8	2.1	4.6

[a] Personal communication with K. Pingoud, October 2009.
[b] Calculated by authors based on data from Salazar and Meil (2009).

recovery from biomass residues associated with wood products, such as forest harvest residues and wood processing residues. Using post-use wood products and associated biomass residues as biofuel is increasingly common in some counties, such as Sweden and Finland. The use of this biofuel can reduce net GHG emissions by substituting in place of fossil fuels (see Section 2.5). Table 3 shows the displacement factors of several wood products with differing levels of biomass residue recovery used to substitute various fossil fuels. For each product use, the displacement factor increases as more biomass residues are recovered. Furthermore, the displacement factor increases when the carbon intensity of the replaced fossil fuel increases (e.g., replacing coal avoids more fossil emissions than replacing natural gas).

The results of this meta-analysis can be compared to the displacement factor when wood is used directly as biofuel to replace fossil fuel instead of being used as a material. In this case, the displacement factor would range from less than 0.5 up to about 1.0, depending largely on the type of fossil fuel replaced and the relative combustion efficiencies. When a wood product is burned as biofuel at the end of its service life, the displacement factor of the product increases by roughly

Table 3 – Summary of impacts on wood product displacement factors of using associated wood residues to replace fossil fuels.

Reference	Application	DF	Recovered biomass type				Fossil fuel replaced
			Processing residues	Harvest slash	Stumps	Post-use wood product	
Eriksson et al. (2007)	Apartment building	1.7	X			X	Natural gas
		1.9	X	X		X	Natural gas
		2.0	X	X	X	X	Natural gas
		2.2	X			X	Coal
		2.5	X	X		X	Coal
		2.7	X	X	X	X	Coal
Gustavsson et al. (2006)	Apartment building (Sweden)	4.0	X	X		X	Natural gas
		5.6	X	X		X	Coal
	Apartment building (Finland)	2.2	X	X		X	Natural gas
		3.3	X	X		X	Coal
Gustavsson and Sathre (2006)	Apartment building	1.5					Coal
		2.8	X				Coal
		2.0		X			Coal
		2.6				X	Coal
Petersen and Solberg (2002)	Roof beams	0.5				X	70% hydro, 30% oil
		0.8				X	Oil
Petersen and Solberg (2003)	Floor material	0.4				X	70% hydro, 30% oil
		0.7				X	Oil
Pingoud and Perälä (2000)	Finnish construction sector	0.5					None
		1.1	X				Oil
		2.5	X	X			Oil
		1.2				X	Oil
		3.2[a]	X	X		X	Oil
Salazar and Meil (2009)	Single-family house	1.9				X	67% coal, 33% natural gas
		4.9[b]	X			X	67% coal, 33% natural gas
		9.0[b]	X	X	X	X	67% coal, 33% natural gas
Scharai-Rad and Welling (2002)	Single-family house	2.3					None
		3.3				X	Unspecified fossil fuel
	3-storey building	1.5					None
		3.1				X	Unspecified fossil fuel
	Warehouse	1.0					None
		1.5				X	Unspecified fossil fuel
Werner et al. (2005)	Swiss construction sector	1.1					None
		1.3	X				Oil
		1.7	X			X	Oil

[a] Personal communication with K. Pingoud, October 2009.
[b] Calculated by authors based on data from Salazar and Meil (2009).

this amount (Table 3), as the GHG benefits of both material substitution and fuel substitution accrue.

In this analysis we calculate displacement factors based on the quantities of carbon contained in the final wood product, although the reported GHG emissions reductions often include the use of associated biomass residues from forestry and wood processing that are not contained in the finished product. Thus, we are *allocating* all the GHG impacts of the wood products chain to the final product, including the emissions from forest management, harvest, transport and processing, as well as all avoided emissions due to material and fossil fuel substitution. The method used for allocation within life cycle analyses of wood products can have a significant impact on the results (Jungmeier et al., 2002). Using other allocation methods, a separate displacement factor could be calculated for a main product and for each by-product, accounting for all GHG impacts directly related to that product plus a portion of common impacts. Allocation of common impacts could be made on a mass or an economic basis, where impacts are attributed to the main product and by-products based on their relative masses or economic values. A drawback of calculating separate displacement factors for by-products is that the GHG impacts of by-products could mistakenly be considered to occur in isolation, when in reality these impacts would likely not have occurred had the main product not been produced. In their analysis of wood construction materials, Salazar and Meil (2009) suggested that over 90% of revenue is gained from the main wood product, with less than 10% gained from other biomass co-products. Similarly, Sathre and Gustavsson (2009) showed that the average economic value added per hectare of forestland is over 40 times greater for main products made from sawlogs than for harvest residues. Thus, it is unlikely that trees will be harvested solely to produce these low-value products; instead, trees are harvested to produce high-value main products, and by-products are generated simultaneously.

On the other hand, a drawback of calculating a single displacement factor for main products that includes the GHG impacts of by-products, as we do in this analysis, is that the total GHG impact is quantified not in terms of the total biogenic carbon flow from the forest, but only the carbon in the main product. Thus, a main product with relatively inefficient wood material use, i.e., with a small amount of wood in the end product compared with the amount of harvested biomass, could potentially have a higher displacement factor than an identical product made with a more efficient process. Per unit of product, both products have the same GHG benefits from the product itself, while the GHG benefits from the allocated by-products are greater for the inefficiently made product due to its larger by-product flows. It is therefore possible that a displacement factor defined in this way might not indicate the most efficient way, from a climate change mitigation perspective, to use the total biomass resource. This issue does not affect our conclusions regarding the GHG impacts of wood *vs.* non-wood products, but is important for optimizing overall biomass use patterns. Defining the displacement factor differently, for example in units of reduced GHG emission per m^3 of roundwood or per hectare of forestland harvested, could be useful in this wider context.

Among the studies examined in this meta-analysis, landfilling was the second most common end-of-life management option after energy recovery. Table 4 shows the displacement factors of landfilled wood products from those studies that provide details on landfill assumptions. The average displacement factor of these landfilled wood products is 1.1, significantly lower than the average of 2.1 for the group of studies as a whole. In addition, a greater share of the landfilled wood products has negative displacement factors. A hypothetical permanent landfill storage of 100% of the carbon content of a wood product, as assumed by Petersen and Solberg (2004), would increase the displacement factor by 1.0 over the same product that decays or is burned without energy recovery. Such a hypothetical situation is unlikely, however, as carbon dynamics in landfills are quite variable and are affected by e.g., moisture content, temperature, pH, waste processing, and landfill design and operation (Micales and Skog, 1997). Generally, there is a lack of consistency in the methods and assumptions regarding the calculation of carbon sequestration and methane generation in landfills (Franklin Associates, 2004). The uncertainty regarding landfill processes and the variety of assumptions used in the studies lead to different and potentially contradictory conclusions. In general, however, disposal in a well-managed landfill facility in which wood decomposition is discouraged and methane is recovered and used to replace fossil fuels will result in a higher displacement factor than disposal in a poorly managed landfill.

As discussed in Section 2.3, carbon stored in wood products affects the atmospheric carbon concentration only by changes in the size of the wood products pool as a whole, i.e., the difference between new wood products entering service and old wood products that decay or burn and release their stored carbon into the atmosphere. The temporary storage of carbon in products, whether long- or short-lived, should therefore not be included in the calculation of a displacement factor of an individual product, but instead should be considered at the macro-level of whether the total quantity of stored carbon is increasing, decreasing, or stable. Depending on the time scale of interest, it may be beneficial to postpone the release of carbon stored in products. Inclusion of temporary carbon storage would increase the displacement factor of a wood product by 1.0, by definition. As indicated in Table 1, many of the studies in this meta-analysis discuss the issue of carbon storage in products; however this temporary storage is generally not used in the determination of GHG emission reduction. Salazar and Meil (2009) account for carbon stored in products as an avoided emission, but later account for a corresponding emission depending on the end-of-life fate of the product. Werner et al. (2005) show the increasing carbon storage in products in their scenario of greater use of wood products, but also show this effect levelling off in the future, after which carbon storage has no additional climatic effect. Of the studies included in this meta-analysis, only Upton et al. (2008) include carbon storage in products in the GHG emission figures used to calculate the displacement factors. Given the boundary conditions of their study, carbon is still stored in products during the selected time frame. They also include carbon stored in "surplus forest" that is not harvested if non-wood products are used. Given a longer time horizon, the displacement factor of the Upton et al. (2008) study would decrease when the wood products are retired from service, but would increase when the surplus forest matures or is disturbed naturally. In the long term, the effects of carbon storage in products and forests become less significant, as the recurring material substitution benefits accumulate.

A displacement factor is valid only for wood used *instead* of non-wood materials. The displacement factors calculated here should not be misinterpreted to suggest that a GHG emission reduction will result from each and every piece of wood used, regardless of how it is produced and used. The use of wood in applications for which wood is typically used will

Table 4 – Displacement factors of wood products that are landfilled at the end of service life.

Reference	Application	DF	Landfill assumptions
Börjesson and Gustavsson (2000)	Apartment building		
	Landfill, best case	3.8	90% permanent storage, methane recovery to replace fossil fuel
	Landfill, worst case	−1.3	60% permanent storage, no methane recovery
John et al. (2009)	6-storey office building		
	Timber vs. steel	1.1	82% permanent storage, partial flaring of methane
	Timber vs. concrete	1.0	82% permanent storage, partial flaring of methane
	Max wood content vs. steel	1.4	82% permanent storage, partial flaring of methane
	Max wood content vs. concrete	1.3	82% permanent storage, partial flaring of methane
Petersen and Solberg (2002)	Roof beams, wood *vs.* steel	−0.9	11-year half-life of landfilled wood; methane production of 168 kg CH_4 per ton of wood
Petersen and Solberg (2003)	Flooring, wood *vs.* stone	−0.8	11-year half-life of landfilled wood; methane production of 168 kg CH_4 per ton of wood
Petersen and Solberg (2004)	Flooring, wood *vs.* alternatives	1.7	100% permanent storage, no GHG emission
Salazar and Meil (2009)	Single-family house	1.4	76% permanent storage, partial methane capture to replace fossil fuels.
Upton et al. (2008)	Single-family house (Atlanta)		
	Landfill, best case	2.5	85% permanent storage, 0.02 $year^{-1}$ rate constant for methane generation
	landfill, worst case	2.3	50% permanent storage, 0.04 $year^{-1}$ rate constant for methane generation
	Single-family house (Minneapolis)		
	Landfill, best case	1.2	85% permanent storage, 0.02 $year^{-1}$ rate constant for methane generation
	Landfill, worst case	1.0	50% permanent storage, 0.04 $year^{-1}$ rate constant for methane generation
Average		1.1	

not result in a GHG emission reduction, except to the extent that emission would have been greater *if* non-wood materials were used instead. Thus, depending on the context, a displacement factor can be a measure of either the GHG emission that is avoided because something is made of wood when it could have otherwise been made of non-wood materials, or of the potential reduction in GHG emission if something made of non-wood materials were instead made of wood. Effective GHG displacement can also occur if wood from sustainably managed forests is used in place of unsustainably harvested wood.

Displacement factors can be considered within two different contexts. In a scenario where wood is widely used in an application, for example single-family housing in North America, there may be an interest in how much GHG emission would *increase* if the houses were instead constructed of concrete or steel. Alternatively, in a scenario where non-wood materials are dominant, for example apartment buildings in Europe, the calculation of interest is how much GHG emission would *decrease* if there were a widespread switch to wood.

Variability is inherent in the determination of displacement factors. Each study shows a unique result, which varies with physical factors like the type of forestry and wood product, the type of non-wood material it is compared against, and the post-use fate of the wood. It may also vary with the analytical methodology and assumptions used in the analysis, which adds additional uncertainty. The studies in this meta-analysis cover a wide range of wood product types and materials substituted, and use data specific to different geographic regions. Some studies include only the production phase of the product life cycle, while others take into account the entire life cycle and consider land use issues and various post-use management options. The studies vary in scale, from micro-level studies of individual building elements, to meso-level studies of complete buildings, to macro-level studies covering wood product usage in a country or region.

The analytical rigour of the studies varied, with some using well-developed methods and well-justified assumptions, while others used less-complete models and data sources. Some studies incorporated established life cycle assessment (LCA) protocols, although there exist additional methodological challenges when comprehensively analyzing the GHG impacts of wood product use (Perez-Garcia et al., 2005). This heterogeneity of study methodologies and assumptions brings advantages and disadvantages to the meta-analysis. While making inter-study comparisons more difficult, it adds to the robustness of the overall results by showing displacement factors for a range of different product substitutions and analytical methodologies. Due to the diversity of the studies, the quantitative values of the displacement factors calculated in this meta-analysis should not be compared with each other. Instead, they should be seen generally to represent the range of expected GHG performance of wood product substitution, depending on the specific products compared and analytical methods employed. We have endeavoured to deconstruct each study as much as possible in order to understand the relative contributions of different parameters to the displacement factors, thus allowing us to draw more general conclusions.

Not all of the studies examined here are completely independent analyses; some data are shared between more than one study. For example, Sedjo (2002) uses GHG emission data from Künniger and Richter (1995), and Upton et al. (2008) use building material data from Lippke et al. (2004). Nevertheless, each study offers some new perspective on the issue, by analyzing the data with differing system boundaries or methodological assumptions.

Policies that provide incentives to use wood in place of other, GHG-intensive materials may have additional beneficial climate effects beyond those quantified by displacement factors. A greater global demand for wood products may increase the value of productive forestland, relative to its conversion to other uses, and thereby reduce the rate of deforestation in the tropics (Aulisi et al., 2008). This potential effect is not considered here.

5. Conclusions

In this analysis we integrate data from 21 different studies in a meta-analysis of the displacement factors of wood products substituted in place of non-wood materials. Calculated in consistent units of tons of carbon (tC) of emission reduction per tC in wood product, the displacement factors range from a low of −2.3 to a high of 15, with most lying in the range of 1.0 to 3.0. The average displacement factor value is 2.1, meaning that for each tC in wood products substituted in place of non-wood products, there occurs an average GHG emission reduction of approximately 2.1 tC. Expressed in other units, this value corresponds to roughly 3.9 t CO_2 eq emission reduction per oven-dry t of wood product, or 1.9 t CO_2 eq emission reduction per m^3 of wood product.

There is some uncertainty associated with the results of each individual study, and of the meta-analysis as a whole. The studies cover a wide range of wood product types and materials substituted, use data specific to different geographic regions, and employ different methodological techniques and assumptions. Collectively, however, the 21 studies provide a consensus that wood product substitution reduces GHG emission. The positive sign of the "base-case" displacement factor of each study shows that under normal conditions, using wood products results in less GHG emission than using functionally equivalent non-wood products. Post-use management of wood products appears to be the single most significant source of variability in the GHG impacts of the wood product life cycle. Responsible management of end-of-life wood products, as well as of other biomass residues generated along the wood product value chain, is thus critical to ensuring high GHG displacement from wood products. The use of these residues as biofuel to substitute for fossil fuels will result in reduced GHG emission. Disposal of wood waste in well-managed landfills will also result in reduced GHG emission, but at the expense of a potentially significant source of renewable energy.

The range of displacement factors among the various studies suggests that some types of wood product substitution provide greater GHG reduction than others. The limited sample size of this meta-analysis, and the inconsistencies between the studies, do not allow us to draw firm conclusions regarding specific wood uses to maximize GHG benefits. Additional research should be conducted to determine which types of wood products or building systems should replace which non-wood products to produce the highest possible GHG displacement.

By quantifying the range of GHG benefits of wood substitution, this meta-analysis provides a clear climate rationale for using wood products in place of non-wood materials, provided that forests are sustainably managed and that wood residues are used responsibly. An effective overall strategy to mitigate climate change and transition to a carbon-neutral economy should therefore include the sustainable management of forestland for the continuing production and efficient use of wood products.

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REFERENCES

Aulisi, A., Sauer, A., Wellington, F., 2008. Trees in the Greenhouse: Why Climate Change is Transforming the Forest Products Business. World Resources Institute.

Börjesson, P., Gustavsson, L., 2000. Greenhouse gas balances in building construction: wood versus concrete from lifecycle and forest land-use perspectives. Energy Policy 28 (9), 575–588.

Buchanan, A.H., Levine, S.B., 1999. Wood-based building materials and atmospheric carbon emissions. Environmental Science and Policy 2 (6), 427–437.

Eriksson, E., Gillespie, A., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R., Stendahl, J., 2007. Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research 37 (3), 671–681.

Franklin Associates, 2004. An Analysis of the Methods Used to Address the Carbon Cycle in Wood and Paper Product LCA Studies. Report No. 04-03, National Council for Air and Stream Improvement. p. 63.

Gustavsson, L., Holmberg, J., Dornburg, V., Sathre, R., Eggers, T., Mahapatra, K., Marland, G., 2007. Using biomass for climate change mitigation and oil reduction. Energy Policy 35 (11), 5671–5691.

Gustavsson, L., Pingoud, K., Sathre, R., 2006. Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. Mitigation and Adaptation Strategies for Global Change 11 (3), 667–691.

Gustavsson, L., Sathre, R., 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Building and Environment 41 (7), 940–951.

IPCC (Intergovernmental Panel for Climate Change), 2007. Climate Change 2007: Mitigation of Climate Change. Web-accessed at http://www.ipcc.ch.

John, S., Nebel, B., Perez, N., Buchanan, A., 2009.In: Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials. Research Report 2008-02. Christchurch, New Zealand. Department of Civil and Natural Resources Engineering, University of Canterbury.

Jönsson, Å., Tillman, A.-M., Svensson, T., 1997. Life cycle assessment of flooring materials: case study. Building and Environment 32 (3), 245–255.

Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C., Richter, K., 2002. Allocation in LCA of wood-based products: experiences of cost action E9. Part I. Methodology. International Journal of LCA 7 (5), 290–294.

Knight, L., Huff, M., Stockhausen, J.I., Ross, R.J., 2005. Comparing energy use and environmental emissions of reinforced wood doors and steel doors. Forest Products Journal 55 (6), 48–52.

Koch, P., 1992. Wood versus nonwood materials in U.S. residential construction: some energy-related global implications. Forest Products Journal 42 (5), 31–42.

Künniger, T., Richter, K., 1995. Life cycle analysis of utility poles: a Swiss case study. In: Proceedings of the 3rd International Wood Preservation Symposium. Cannes-Mandelieu, France, 6–7 February 10 pp.

Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J., Meil, J., 2004. CORRIM: life-cycle environmental performance of renewable building materials. Forest Products Journal 54 (6), 8–19.

Micales, J.A., Skog, K.E., 1997. The decomposition of forest products in landfills. International Biodeterioration and Biodegradation 39 (2–3), 145–158.

Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J.B., Boyer, J., Meil, J., 2005. The environmental performance of renewable building materials in the context of residential construction. Wood and Fiber Science 37 (CORRIM special issue), 3–17.

Petersen, A.K., Solberg, B., 2002. Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction. Case: beams at Gardermoen airport. Environmental Science and Policy 5 (2), 169–182.

Petersen, A.K., Solberg, B., 2003. Substitution between floor constructions in wood and natural stone: comparison of energy consumption, greenhouse gas emissions, and costs over the life cycle. Canadian Journal of Forest Research 33 (6), 1061–1075.

Petersen, A.K., Solberg, B., 2004. Greenhouse gas emissions and costs over the life cycle of wood and alternative flooring materials. Climatic Change 64 (1–2), 143–167.

Pingoud, K., Perälä, A.-L., 2000. Studies on greenhouse impacts of wood construction. 1. Scenario analysis of potential wood utilisation in Finnish new construction in 1990 and 1994. 2. Inventory of carbon stock of wood products in the Finnish building stock in 1980, 1990 and 1995. Publication 840, Technical Research Centre of Finland, VTT Julkaisuja, Espoo. 72 pp. (in Finnish, summary in English).

Salazar, J., Meil, J., 2009. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. Journal of Cleaner Production 17 (17), 1563–1571.

Salazar, J., Sowlati, T., 2008. Life cycle assessment of windows for the North American residential market: case study. Scandinavian Journal of Forest Research 23 (2), 121–132.

Sathre, R., Gustavsson, L., 2009. Process-based analysis of added value in forest product industries. Forest Policy and Economics 11 (1), 65–75.

Sathre, R., O'Connor, J., 2008. A Synthesis of Research on Wood Products and Greenhouse Gas Impacts. Technical Report No. TR-19. FPInnovations-Forintek, Vancouver, Canada.

Schlamadinger, B., Marland, G., 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 10 (5–6), 275–300.

Scharai-Rad, M., Welling, J., 2002. Environmental and Energy Balances of Wood Products and Substitutes. Food and Agricultural Organization of the United Nations, 70 pp.

Sedjo, R.A., 2002. Wood material used as a means to reduce greenhouse gases (GHGs): an examination of wooden utility poles. Mitigation and Adaptation Strategies for Global Change 7 (2), 191–200.

Upton, B., Miner, R., Spinney, M., Heath, L.S., 2008. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy 32 (1), 1–10.

Werner, F., Taverna, R., Hofer, P., Richter, K., 2005. Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: first estimates. Annals of Forest Science 62 (8), 889–902.

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