A Synthesis of Research on Wood Products & Greenhouse Gas Impacts

2nd Edition

by
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Abstract

In this review, existing scientific literature is examined to summarize consensus findings, or range of findings, addressing the net life cycle greenhouse gas footprint of wood construction products. Numerous international studies are reviewed for findings on fossil energy used in wood manufacturing compared to alternatives, the avoidance of industrial process carbon emissions as from cement manufacturing, the storage of carbon in forests and forest products, the use of wood by-products as a biofuel replacement for fossil fuels, and carbon storage and emission due to forest products in landfills. Interpretation of the various findings sought to clarify whether actively managing forests for wood products is better, worse or neutral for climate change versus leaving forests in their natural states. We discuss methodological issues in wood substitution analysis, including the definition of an appropriate functional unit and the establishment of effective system boundaries in terms of activity, time and place. Data from a subset of the reviewed studies are then used in a meta-analysis of displacement factors, that is, the quantification of greenhouse gas emission avoided per unit of wood used in place of other materials. All of the studies reviewed found that the production of wood-based materials results in less greenhouse gas emission than the production of alternatives. Over the complete life cycle of building materials, the great majority of studies also found lower total emission for wood products. End-of-life management of wood products is the single most significant variable for the full life cycle carbon profile of wood products. The few studies with scenarios in which the greenhouse gas emission of wood building materials is greater than of alternatives addressed worst-case wood disposal options. The overall consensus provides a clear carbon rationale for increasing wood substitution for other products, provided that forests are sustainably managed and that wood waste and by-products are used responsibly.

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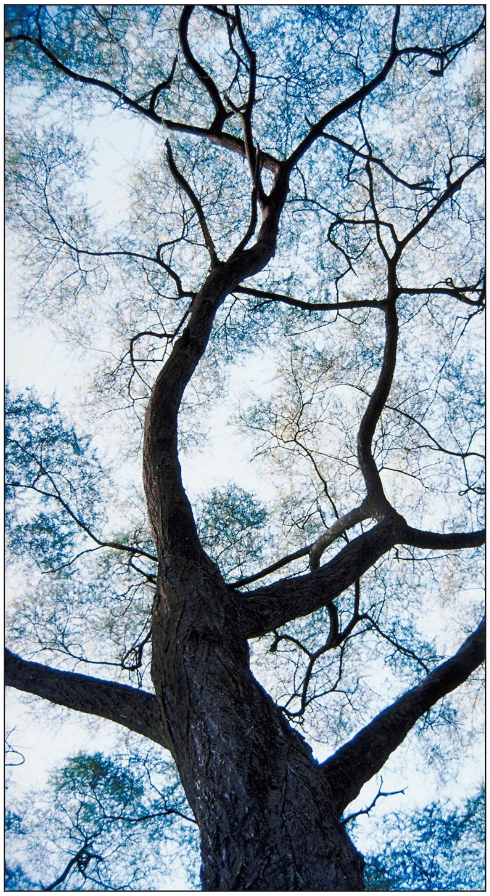

Abbreviations Used	
C	carbon
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
CH_4	methane
EJ	exajoule
GHG	greenhouse gas
GJ	gigajoule
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kV	kilovolt
m^2	square metres
m^3	cubic metres
Mt	megatonne
N_2O	nitrous oxide
NOx	oxides of nitrogen
PJ	petajoule
SOx	oxides of sulphur
t	tonne (metric ton)
tC	tonne (metric ton) carbon
Tg	teragrams
TWh	terawatt-hour

Executive Summary

The objective of this review is to summarize the consensus (or range of) opinion from scientific literature regarding the net impact on atmospheric greenhouse gases due to wood product use within a life cycle perspective. More generally, it seeks to clarify whether actively managing forests for wood production is better, worse or neutral for climate change than leaving the forest in its natural state. A further objective is to quantify, if possible, the greenhouse gas (GHG) emissions avoided per unit of wood substituted for non-wood materials.

In this review, 66 studies were examined; the literature review was confined to documents in English, Swedish or Finnish, with an emphasis on scientific, peer-reviewed articles. Of these, 49 studies presented original data and analysis on the GHG impacts of wood products. The others summarized or synthesized information from other sources. Twenty-one studies contained sufficient information to calculate the displacement factor of at least one wood product substituted for a non-wood product. The studies were 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 biofuels were not considered, although many of the studies reviewed here also included the fuel substitution effects of biofuels from wood processing residues or post-use wood products.

The studies 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). Therefore, the results of the studies themselves, and 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. Furthermore, 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.

The Role of Wood in Carbon Balances

The studies show 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 in 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. The effects of each of these mechanisms are summarized here:

- **Less fossil fuel consumption in manufacturing:** A universal 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 from 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.

- **Avoided cement 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 when wood is 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, there is still a net GHG benefit when substituting wood for cement products.

- **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, significant 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, with climate benefits accruing from the substitution effects of avoided emissions. Some wood substitution studies have covered a relatively short time frame, and have considered carbon storage to be equivalent to avoided emissions. Other studies have considered the long term carbon dynamics of wood products, and show that the substitution effect of avoiding fossil emissions is ultimately much more significant than the carbon stored in wood products.

- **Carbon storage in the forest:** 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 understanding the climate impacts of wood product use. Without exception, all of the wood substitution studies reviewed here have assumed as boundary conditions that the forests that produce the wood are managed sustainably. Over a complete rotation period of sustainable (yield) forestry, by definition the carbon content in tree biomass remains unchanged. Forest soils often store more carbon than forest biomass, and several studies suggest that soil carbon stock in managed forests 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.

- **Avoided fossil fuel emissions due to biomass 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 CO_2 emitted during the direct combustion of sustainably produced biofuel is balanced by CO_2 uptake in regrowing forests, although the quantification of GHG benefits due to the use of residues from the wood product value chain is not straightforward. Issues addressed by the studies reviewed here include the 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), soil carbon reduction due to removal of harvesting residues and uncertainties about how post-use wood products will be handled by future waste management systems. Nevertheless, many studies indicate that the recovery and combustion of the biomass by-products associated with wood products is the single most significant contributor to the life cycle GHG benefits of wood product use.

- **Carbon dynamics in landfills:** Post-use wood products are commonly landfilled in some regions, and some studies have suggested landfilling as an appropriate post-use management option for wood materials. Carbon dynamics in landfills are recognized to be quite variable, and can have a significant impact on the GHG balance of wood products. A fraction of the carbon in landfilled wood products will likely remain in (semi)permanent storage, providing climate benefits. However, another fraction may decompose into methane, which has much higher global warming potential (GWP) than CO_2. The few instances of negative displacement factors (i.e., wood use giving greater GHG emission than non-wood use) found in this review are largely the result of methane emissions from landfilled wood. 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).

Methodological Issues

Comparative analysis of the carbon balances of wood vs. non-wood products is a complex issue. Important factors are the definition of an appropriate functional unit and the establishment of effective system boundaries in terms of activity, time and place. The functional unit can be defined at the level of building component, complete building, or services provided by the built environment. GHG emissions per unit of mass or volume of material is inadequate as a functional unit because equal masses or volumes of different materials do not fulfil the same function. Activity-based system boundaries include life cycle processes such as material production, product operation, and post-use material management. If the products compared are functionally equivalent, such that the impacts occurring during the operation phase are equal, this phase may be dropped from the analysis allowing a focus on material flows. The use of wood co-products as biofuel can be analytically treated through system expansion, and compared to an alternative of providing the same energy service with fossil fuels. The assumed production of electricity used for material processing is another important energy-related issue, and using marginal production data may be more appropriate than average production. Temporal system boundaries include such aspects of the wood life cycle as the dynamics of forest growth including regeneration and carbon saturation, the availability of residue biofuels at different times, and the duration of carbon storage in products. The timing of GHG emissions and uptakes can be particularly significant to the cumulative radiative forcing, and hence the climate impact, over a given time horizon. The establishment of spatial boundaries can be problematic, because using wood-based materials instead of non-wood materials requires more land area to capture solar energy and accumulate biomass. We discuss several possible methodological approaches to meet this challenge, including the intensification of land use to increase the time rate of biomass production. Finally, we discuss issues related to scaling up an analysis of wood substitution from the micro-level to the macro-level of national, regional or global.

Displacement Factors

Data from 21 studies were used in a meta-analysis of the displacement factors of wood product substitution. A displacement factor is an index of the efficiency with which the use of biomass reduces net GHG emission. It quantifies the amount of emission reduction achieved per unit of wood use. A higher displacement factor indicates that more GHG emission is reduced; a negative displacement factor means that emission is greater when using the wood product. In this meta-analysis, the displacement factors were calculated in units of metric tons of carbon (tC) of emission reduction per tC in wood product. The calculated displacement factors ranged 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 was 2.1, meaning that for each tC in wood products substituted for non-wood products, an average GHG emission reduction of approximately two tC can be expected. In other units, this value corresponds to 3.9 t CO_{2eq} emission reduction per t of oven-dry wood used, or roughly 1.9 t CO_{2eq} emission reduction per m^3 of wood product[1]. This average number can be viewed as a reasonable estimate of the GHG mitigation efficiency of wood product use, over a range of product substitutes and analytical methodologies.

In summary, all of the studies reviewed here found that the production of wood-based materials and products results in less GHG emission than the production of functionally comparable non-wood materials and products. Over the complete life cycle of the product (including use and disposal), the great majority of the studies also found that wood products have lower GHG emissions. 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. The few cases found in this review of wood products causing greater GHG emission than non-wood products were the result of inappropriate disposal of wood products. In addition, several studies observed that the GHG impacts of the use phase of a building life cycle are generally greater than those of the construction and disposal phases. This suggests that the minimization of GHG impacts of products and buildings requires a consideration of the entire life cycle, including production, use and disposal. Over the long term, forests can best contribute to climate change mitigation through their sustainable management for the production of wood that is used efficiently in place of non-wood materials and fuels.

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[1] Assuming a wood density of 500 kg/m^3. See the meta-analysis section for further discussion.

Background

Growing concern about global climate change has turned the world's attention towards stabilizing and eventually reducing the concentration of greenhouse gases (GHG) in the atmosphere. Carbon dioxide (CO_2) is the most prominent GHG, but methane (CH_4), nitrous oxide (N_2O) and other gases are significant as well.

Strategies for mitigating climate change can include reducing GHG emissions and increasing GHG sinks. Fossil fuel combustion is the single greatest source of GHG emissions, while land use change including deforestation is also a significant source. Reducing fossil fuel use and implementing sustainable land use practices are recognized as essential steps to stabilizing atmospheric GHG concentrations. There is also growing interest in exploring opportunities to increase GHG sinks. A sink is a process or mechanism for removing GHGs from the atmosphere and storing them in a stable reservoir. For example, a young forest is a carbon sink, as it removes carbon from the atmosphere through photosynthesis and fixes it in tree biomass. An overmature or a burning forest, on the other hand, is a carbon source.

Climate change concerns are centered on the current imbalance in the earth's carbon cycle, which is the flow of carbon through the atmosphere, the oceans, forests and all other terrestrial ecosystems. Currently, more carbon, typically in the form of CO_2, is being emitted to the atmosphere than is being removed, resulting in an increasing atmospheric concentration of CO_2. Finding a way to increase the rate of carbon removal by enhancing carbon sinks may be an important tool, along with reducing our rate of emissions, in the process of reversing climate change.

Both of these strategies for mitigating climate change – reducing GHG emissions and increasing carbon sinks – have relevance to forests and forest products. Accordingly, there has been an escalating interest in scientifically examining the potential for forest products to actively contribute to the mitigation of global climate change.

The role of forests and wood in the global carbon balance is properly considered over a fairly long time span, recognizing the cyclical carbon flows involved along the full "value chain" of wood products from the forest to the post-use product, and including the avoided emissions when wood is used in place of other materials. In other words, assessing the role of wood products in GHG balances requires the consideration of numerous complex carbon flows over a long time period.

The earth's carbon is thought of in terms of the various reservoirs, or "pools" in which it resides. With respect to forests and forest products, the atmospheric carbon removed by trees is stored in several pools. There is carbon in the tree biomass (wood, leaves, roots), 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). An analogy is transferring money between bank accounts – the money is still in the bank, just in another account. However, these carbon pools are transitory. In other words, the carbon will cycle between the pools over time spans of days to centuries, and will eventually return back to the atmosphere. After the carbon is returned to the atmosphere, growing trees then reabsorb that carbon and the cycle carries on. Over the long term, in a sustainably managed forest, the carbon bank balance in the forest remains constant, because the carbon deposited and the carbon withdrawn are in equilibrium. This holds true both for a natural (i.e., unmanaged) forest and for a forest that is periodically harvested for products or for fuel. Land use changes such as deforestation or afforestation would, however, lead to changes in the overall forest carbon pool. The carbon bank balance representing the stock of forest products, while currently increasing, is expected to eventually stabilize at a higher level in the long term.

However, the carbon bank balance goes up significantly when an additional carbon pool is considered: the avoided emissions due to wood use in place of other materials. When wood replaces a fossil fuel for energy, or when wood replaces a construction material with a greater GHG footprint (such as steel and concrete), then the fossil carbon emission avoided by choosing wood is a credit in the carbon bank balance. This is a permanent (i.e., not transitory) benefit to GHG removal from the atmosphere. This means that, rather than a constant carbon pool balance over time when just considering the carbon in the wood itself, there is actually a continually increasing bank account balance, assuming maintenance of a sustainable, productive forest for the purpose of providing substitutes for non-wood fuels and materials.

To determine the most efficient uses for our limited supply of forest land and biomass production, it can be useful to develop a simplified metric for the GHG benefits of wood substitution. This metric, termed a displacement factor, is a measure of the amount of carbon emission avoided by the use of wood instead of some other material. The idea of a displacement factor 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, then there may be an interest in how much carbon emissions 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 carbon emissions would decrease if there was a widespread switch to wood. Displacement factors can be presented in a variety of formats (emission reduction per cubic metre of wood, per square metre of construction, per hectare of forest land, etc), and using a variety of methods and assumptions. The complexities, uncertainties and application limits for displacement factors are discussed further in the last section of this report.

Increasing the use of wood products in construction and for other long-lived uses, plus the use of wood by-products and wood waste as a biomass replacement for fossil fuels, contributes to atmospheric GHG stabilization because of net positive carbon impacts across all of the carbon pools. The sustainable management of forests for the production of wood products is therefore a feasible and beneficial part of an overall strategy to mitigate climate change.

List of Studies Reviewed

In this section, the 66 papers reviewed are listed alphabetically by first author. A brief synopsis of the paper is provided, along with a link to the page where the full review can be found.

1 Anonymous. 2006. **Tackle climate change: Use wood.** Published by CEI-Bois. 84 pg.

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Synopsis: Attractive 'coffee table' book produced as a marketing tool by the European wood industry. Captures a wide range of European data on the carbon role of forests and wood products, and presents the information in a non-technical, accessible manner while maintaining an image of credibility. However, readers looking for details or validation of the data will have to turn to original sources, not all of which are cited.

2 Anonymous. 2009. **Tackle climate change – Use wood.** Published by the BC Forestry Climate Change Working Group and the California Forestry Association. 75 pg.

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Synopsis: Intended for policymakers and other non-specialist audiences, this attractive booklet gives an overview of the climate benefits of wood product use. With a focus on North America, it includes discussions of sustainable forest management, wood product substitution, forest biofuels, pulp and paper, and measures to increase climate change mitigation in the forest sector.

3 Björklund, T. and Tillman, A-M. 1997. **LCA of building frame structures: Environmental Impact over the life cycle of wooden and concrete frames.** Technical Environmental Planning Report 1997:2. Chalmers University of Technology, Sweden. 156 pg.

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Synopsis: Comparative LCA of wood and concrete construction in two different building types (an apartment building and a warehouse) analyzing a range of environmental impacts. Embodied effects are clearly lower for wood, however, these effects are dwarfed by operational energy and related greenhouse gas effects, which are the same across materials.

4 Börjesson, P. and 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.

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Synopsis: Comparative analysis of wood and concrete construction in an apartment building, for both a 50-year and a 100-year life span, taking into account all carbon stocks and substitution effects, and considering various harvesting and landfill scenarios. The examination includes consideration of forest options for best GHG effects, including leaving the forest alone, using the forest for wood construction products, or using the forest only for fossil fuel substitution. In most scenarios, the wood building fares better, however GHG performance for wood in construction is highly affected by landfill methane emissions as well as the time period used in the analysis. Includes data on displacement factors.

5 Bowyer, J., Briggs, D., Lippke, B., Perez-Garcia, J. and Wilson, J. 2005. **Life cycle environmental performance of renewable materials in the context of residential building construction.** Consortium for Research on Renewable Industrial Materials. Phase I Research Report. Revised June 2005.

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Synopsis: Final report from the academic collective known as CORRIM, for the first phase of a work program that began in 1998. Much of the work reported addresses life cycle inventory development for various wood products. In addition, life cycle carbon flows are examined, using various building life span and forest rotation timelines to quantify carbon pools and to determine optimal forest management regimes from a GHG perspective. The core of this report addresses a comparative LCA of wood versus steel and concrete in typical North American houses. The wood houses show significant GHG benefits.

6 Boyd, C.W., Koch, P., McKean, H.B., Morschauser, C.R., Preston, S.B. and Wangaard, F.F. 1976. **Wood for structural and architectural purposes: Panel II Report, Committee on Renewable Resources for Industrial Materials.** Wood and Fiber, 8(1): 3-72.

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Synopsis: Findings of the first generation of CORRIM researchers, a consortium that was originally formed in 1974 (see study #4 for the findings of the second generation, which was formed in 1996 and built on this foundation). Detailed environmental inventories are developed for various structural wood products, and existing data on non-wood products are accessed in order to compare alternate designs of floors, walls and roofs. The wood elements require substantially less energy. The researchers also project that the wood industry could likely be almost fully self-sufficient for its production energy needs by using biofuel residues.

7 Brunklaus, B. and Baumann, H. 2002. Vad innebär ett ökat träbyggande i Sverige för miljön? Granskning av jämförande LCA studier av stombyggnadsmaterian i hus. (**What does increased wood construction in Sweden mean for the environment? Review of comparative LCA studies of building frame materials**). ESA Report 2002:6, Institute for Environmental System Analysis, Chalmers Technical University, Göthenburg. 17 pg. (in Swedish)

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Synopsis: A review of six studies (four Swedish and two German) on environmental impact of building materials, looking primarily at methods used. Most of the studies find that wood construction materials have the lowest embodied footprint, however, impacts of building operation are so much larger that the choice of materials is insignificant.

8 Buchanan, A.H. and Honey, B.G. 1994. **Energy and carbon dioxide implications of building construction.** Energy and Buildings, 20(3): 205-217.

See Page 32

Synopsis: Simplified comparison of embodied energy and net carbon in wood, steel and concrete buildings using several different building types in the analysis (industrial, mid-rise office, mid-rise hotel, and various single family homes). The production of the wood buildings consistently uses less energy and causes lower net C emissions.

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

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Synopsis: Using the results from Buchanan's 1994 study (see #8), the authors apply these data to calculate displacement factors, that is, the amount of carbon emission avoided when using wood instead of another material. In addition, they project total GHG and energy consumption benefits for a given increase in wood use for construction on national and global levels.

10 Cole, R.J. 1999. **Energy and greenhouse gas emissions associated with the construction of alternative structural systems.** Building and Environment, 34(3): 335-348.

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Synopsis: Analysis of energy and GHG during on-site construction only, for various wood, steel and concrete assemblies. Includes transportation of materials and workers, and operation of construction equipment. Construction energy is found to be a low proportion of total embodied energy, which calls into question the value of looking at this single component in isolation. On-site assembly of steel systems has the lowest figures for energy use and GHG emission, however, this component is a maximum of 5% of the total embodied effects for steel.

11 Cole, R.J. and Kernan, P.C. 1996. **Life-cycle energy use in office buildings.** Building and Environment, 31(4): 307-317.

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Synopsis: Calculates total energy use for wood, steel and concrete versions of a typical office building, including embodied energy, operation and maintenance energy, and end-of-life energy. The wood building has the lowest energy use, followed by concrete and then steel. All three buildings are considered to have the same operating energy consumption. Differences between the materials become much less significant as total operating energy goes up, for example, when the analysis considers a long building life span. Conversely, as energy efficiency of the building goes up, the embodied energy differences become more important.

12 Ekvall, T. 2006. **Miljöaspekter på val av stommaterial i byggnader: Kompletterande kartläggning av kunskapsläget (Environmental aspects of the choice of frame material in buildings: Supplementary survey of the state of knowledge).** IVL Report B1663, Swedish Environmental Research Institute, Stockholm. 18 pg. (in Swedish)

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Synopsis: Reviews the analytical methods used by eight research groups active in the topic of environmental footprints of construction materials, particularly with respect to GHG. Focuses on the uncertainties involved in LCA studies and the resulting gap between potential and actual CO_2 emissions. Concludes that, lacking a consensus method, there is no single objective answer quantifying the CO_2 benefit of wood.

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

Synopsis: A broad system analysis of carbon stocks and flows under various forest management regimes, for a Swedish forest under a 300 year time horizon. Net carbon emissions are lowest when forests are managed intensively to produce construction materials. Removing residues (slash and stumps) reduced total soil carbon, but this was compensated ten times over when the residues were used for bioenergy instead of fossil fuel. A range of total carbon benefit (displacement factors) is provided, depending on forest fertilization, type of fossil fuel being avoided through residue biomass substitution, etc. A comparison to a non-managed forest is also provided, with the cumulative effects of wood substitution making the managed forest more and more attractive over time. Includes data on displacement factors.

14 Eriksson, P-E. 2003. **Comparative LCAs for wood construction and other construction methods: Energy use and GHG emissions.** Swedish Wood Association. 15 pg. *See Page 39*

Synopsis: Reviews twelve comparative LCA studies of wood versus non-wood, and finds all support a GHG benefit of wood construction over alternatives. Provides GHG benefits per square metre of floor area, and estimates total GHG benefit if Europe were to convert its housing stock to wood.

15 Eriksson, P-E. 2004. **Comparative LCAs for wood and other construction methods.** In: Proceedings of World Conference on Timber Engineering. Lahti, Finland. 6 pg. *See Page 40*

Synopsis: See #14, Eriksson, 2003.

16 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. 63 pg. *See Page 40*

Synopsis: Comprehensive literature review and then subsequent in-depth analysis of a subset of 13 studies regarding methods. Finds inconsistency in methods and assumptions used to track carbon through the full product life cycle, leading to different and potentially contrary conclusions. Suggests that a uniform protocol for addressing carbon flows in LCA studies is needed.

17 Frühwald, A., Welling, J. and Scharai-Rad, M. 2003. **Comparison of wood products and major substitutes with respect to environmental and energy balances.** Paper presented at seminar, Strategies for the Sound Use of Wood, 24-27 March, Poiana Brasov, Romania. 10 pg. *See Page 41*

Synopsis: See #51, Scharai-Rad, M. and Welling, J. 2002.

18 Gerilla, G.P., Teknomo, K. and Hokao, K. 2007. **An environmental assessment of wood and steel reinforced concrete housing construction.** Building and Environment, 42(7): 2778-2784.

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Synopsis: Comparison of a wood and a concrete house, looking at energy use and GHG plus other air emissions. The wood building is found to be lower in all impacts. The authors additionally calculate economic costs for the total environmental impact of both buildings. The paper also discusses the GHG benefit of extending the lifetime of buildings in order to avoid the embodied effects of new construction.

19 Glover, J., White, D. and Langrish, T. 2002. **Wood versus concrete and steel in house construction: A life cycle assessment.** Journal of Forestry, 100(8): 34-41.

See Page 42

Synopsis: Compares embodied energy in assemblies and whole houses for wood, steel and concrete. This is primarily a rework of Buchanan and Honey 1994 (see #8).

20 Gustavsson, L., Madlener, R., Hoen, H.-F., Jungmeier, G., Karjalainen, T., Klöhn, S., Mahapatra, K., Pohjola, J., Solberg, B. and Spelter, H. 2006. **The role of wood material for greenhouse gas mitigation.** Mitigation and Adaptation Strategies for Global Change, 11(5-6): 1097-1127.

See Page 42

Synopsis: Interdisciplinary look at wood and GHG based on perspectives from engineering, natural sciences and social sciences. The history and various applications of wood use are described, along with estimates of total global carbon sequestration in wood products. Assesses potential GHG benefits by increased substitution of wood for non-wood.

21 Gustavsson, L., Pingoud, K. and 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.

See Page 43

Synopsis: Life cycle CO_2 comparison of 4-storey apartment buildings, in Sweden and in Finland, in wood and concrete versions, over a 100-year life span. Addresses all substitution effects, including the use of biomass residues from harvesting, processing and building demolition in place of fossil fuel. Also considers different reference fossil fuel scenarios, reabsorption of CO_2 by concrete, and two different forest management scenarios. In all cases, building with wood results in negative net CO_2 emissions. Includes data on displacement factors.

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

See Page 45

Synopsis: Comprehensive energy and CO_2 comparison of wood versus steel in a 4-storey apartment building, focussing on the effect of varying a number of parameters such as cement manufacturing scenarios, forestry scenarios and so forth. In all cases but one, the wood building has lower energy use and net CO_2 emissions. Includes data on displacement factors.

23 Hennigar, C.R., MacLean, D.A. and Amos-Binks, L.J. 2008. **A novel approach to optimize management strategies for carbon stored in both forests and wood products.** Forest Ecology and Management, 256(4): 786-797.

See Page 46

Synopsis: This analysis uses linear programming methods to determine forest management strategies that optimize carbon stock in forests, in wood products, in both forest and products, or in forests and products as well as substitution benefits. The lowest net carbon emission occurs when combined forest and product carbon stock and substitution benefits are maximized. This entails harvest levels that are significantly greater than those that maximize carbon stock in forests.

24 Hillier, W. and Murphy, R. 2000. **Life cycle assessment of forest products: A good story to tell.** Journal of the Institute of Wood Science, 15(4): 221-232.

See Page 47

Synopsis: Examination of life cycle environmental impacts of treated wood poles versus steel, concrete and fibreglass. The wood poles have consistently lower GHG effects. The toxicity impacts due to preservatives (creosote for utility poles and CCA for cattle fencing) and the need to manage those impacts is a focus of the study.

25 Hofer, P., Taverna, R. and Werner, F. 2008. **Forest and carbon: Greenhouse gas dynamics of different forest management and wood use scenarios in Sweden.** GEO Partner AG, Zurich. 76 pg.

See Page 48

Synopsis: In a scenario analysis of climate impacts of forest management and wood use in Sweden, the calculated steady-state carbon implications of current management is an annual emission reduction of 60 million tCO_2. In other words, global emissions would be 60 million tCO_2 higher if not for the Swedish forest industry. More intensive management could raise that value to 103 million tCO_2. Most of the emission reduction occurs outside of Sweden.

26 Hung, C.P., Wei, C., Wang, S.Y. and Lin, F.C. 2009. **The study on the carbon dioxide sequestration by applying wooden structure on eco-technological and leisure facilities.** Renewable Energy, 34(8): 1896-1901.

See Page 49

Synopsis: Comparison of wood and concrete versions of several small structures including a check dam and a pedestrian bridge. Some of the wood structures use preservative treated wood. The wood versions consistently result in less net carbon emission, defined in the article as production emissions minus carbon storage in wood products.

27 John, S., Nebel, B., Perez, N. and Buchanan, A. 2009. **Environmental impacts of multi-storey buildings using different construction materials.** Research Report 2008-02, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand. 135 pg.

See Page 50

Synopsis: In this comparison of cradle-to-grave energy use and GHG emissions of four versions of an office building, as the amount of wood products increases, the life cycle GHG emissions decrease. Building operation energy and post-use material fate significantly affect life cycle energy use and climate impacts. Includes data on displacement factors.

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

See Page 50

Synopsis: LCA of solid wood flooring versus vinyl and linoleum. Energy use and CO_2 emissions are lowest with wood, along with other LCA measures. Several parameters were varied to test sensitivity and robustness of results. Includes data on displacement factors.

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

See Page 51

Synopsis: In this partial life cycle inventory comparing the production of a fiberglass-reinforced wood door and a functionally equivalent insulated steel door, the steel door produces 27 times as much GHG emissions as the wood door. The wood door also has lower energy use, waterborne wastes, and solid waste generation. Includes data on displacement factors.

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

See Page 52

Synopsis: Estimates energy and GHG implications if forest harvesting were to decrease in the US northwest and subsequently non-wood materials were used to replace wood. Uses 1976 energy data and 1985 wood production data, and considers five harvest scenarios. Finds substantial increases in energy consumption and CO_2 emissions with reduced harvests. Also addresses the carbon impacts of converting an old-growth forest to a managed forest. Includes data on displacement factors.

31 Kram, T., Gielen, D.J., Bos, A.J.M., de Feber, M.A.P.C., Gerlagh, T., Groenendaal, B.J., Moll, H.C., Bouwman, M.E., Daniels, D.W., Worrell, E., Hekkert, M.P., Joosten, L.A.J., Groenewegen, P. and Goverse, T. 2001. **Integrated energy and materials systems engineering for GHG emission mitigation.** Final Report of the MATTER Project. The Netherlands. 245 pg.

See Page 53

Synopsis: In this study of the prospects for GHG emission reduction in various industrial sectors, the use of sustainably produced wood material in place of non-wood materials is identified as the most significant single mitigation strategy in the construction materials industry. Other important wood-related actions include using renewable wood in place of unsustainable tropical hardwoods, and recovering energy from waste wood.

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

See Page 54

Synopsis: Full LCA of CCF- or CCB-treated wood utility poles versus concrete and steel. The wood poles had the lowest CO_2 emissions among other environmental measures, however ecotoxicity effects due to the preservatives were higher. Includes data on displacement factors.

33 Lenzen, M. and Treloar, G. 2002. **Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson.** Energy Policy, 30(3): 249-255.

See Page 55

Synopsis: A reanalysis of Börjesson and Gustavsson 2000 (see #4), using a different method and challenging the original results. Although this study reports energy use twice as large as in the original study, the conclusion that wood construction uses less energy and emits less CO_2 is unchanged. This paper is largely a discussion on analytical technique.

34 Lippke, B. and Edmonds, L. 2006. **Environmental performance improvement in residential construction: The impact of products, biofuels, and processes.** Forest Products Journal, 56(10): 58-63.

See Page 56

Synopsis: Building on the CORRIM results (see #5), quantifies the energy and GHG impacts through substitution of wood for non-wood in house construction, for example, wood siding to replace vinyl, wood insulation to replace fibreglass, and biomass energy to replace fossil fuel in wood manufacturing. Looks at various assemblies in different climates, comparing conventional wood systems to steel and/or concrete and showing energy and GHG benefits, and then shows substantially higher benefits with a greater level of wood replacement for non-wood.

35 Lippke, B., Wilson, J., Meil, J. and Taylor, A. 2010. **Characterizing the importance of carbon stored in wood products.** Wood and Fiber Science, 42(CORRIM Special Issue): 5-14. *See Page 56*

Synopsis: In this discussion of the climate significance of carbon stored in wood products, it is shown that more carbon is generally stored in wood products than is emitted during their manufacture. The full life cycle significance of this stored carbon will depend on its post-use management.

36 Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J. and Meil, J. 2004. **CORRIM: Life-cycle environmental performance of renewable building materials.** Forest Products Journal, 54(6): 8-19. *See Page 57*

Synopsis: See #5, Bowyer *et al*., 2005. Includes data on displacement factors.

37 Liu, G and Han, S. 2009. **Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon.** Ecological Modelling, 220(13-14): 1719-1723. *See Page 57*

Synopsis: Carbon storage in living trees and wood products is tracked over a 400-year time period for three different forest management scenarios. Total carbon storage is greatest for the scenarios with increased harvest levels. Material substitution benefits are not considered.

38 Marcea, R.L. and Lau, K.K. 1992. **Carbon dioxide implications of building materials.** International Journal of Forest Engineering, 3(2): 37-43. *See Page 58*

Synopsis: This pioneering study, one of the first to quantitatively analyze the GHG implications of wood vs. non-wood construction, compares different versions of a single-family house and an industrial building. The versions with greater wood content consistently use less energy, and emit less carbon dioxide, during their production.

39 Oneil, E.E. and Lippke, B.R. 2010. **Integrating products, emission offsets, and wildfire into carbon assessments of Inland Northwest forests.** Wood and Fiber Science, 42 (CORRIM Special Issue): 144-164. *See Page 59*

Synopsis: In this analysis of the impacts of forest management action on overall carbon flows, a more intense management regime is shown to significantly reduce net carbon emissions. Although average forest carbon stock increases under intensive management, product substitution benefits and product carbon stock increases are the main drivers of the net emission reduction. Reduced loss of forest biomass due to wildfires is also a significant benefit of intensive management.

40 Perez-Garcia, J., Lippke, B., Comnick, J. and Manriquez, C. 2005. **An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results.** Wood and Fiber Science, 37(CORRIM Special Issue): 140-148.

See Page 60

Synopsis: Comprehensive analysis of carbon dynamics associated with forest growth, wood product use, and material and energy substitution. Includes forest modeling in various management scenarios, for a US northwest forest over 165 years. LCA data on wood products and substitution effects are derived from the CORRIM work (see #5). Net carbon effects are best with intensively managed forests.

41 Petersen, A.K. and 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.

See Page 61

Synopsis: A comparison of energy use, GHG and cost of steel versus wood for the roof of an airport. A number of different manufacturing, end-of-life, and economic scenarios are considered. The wood beams result in lower CO_2 emissions in most scenarios except where landfilled wood waste causes methane emissions. Includes data on displacement factors.

42 Petersen, A.K. and 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.

See Page 62

Synopsis: An identical approach as with their 2002 study (#41) is used in this comparison of wood and stone flooring, with similar findings. Includes data on displacement factors.

43 Petersen, A.K. and 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.

See Page 63

Synopsis: Similar approach as with their previous studies (#41, #42), but with some important changes including the assumption that landfill is capped and therefore causes no emissions. Compares wood flooring with linoleum, vinyl, and two types of carpet. Concludes that wood has the lowest GHG profile. Includes data on displacement factors.

44 Petersen, A.K. and Solberg, B. 2005. **Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden.** Forest Policy and Economics, 7(3): 249-259.

See Page 64

Synopsis: Reviews 12 comparative studies of wood vs. non-wood construction products and assemblies, all of which show wood has less net GHG emissions (among other benefits), although management of wood at the end of service life has an important impact. Nine of the studies address displacement factors.

45 Pingoud, K. and 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 pg. (in Finnish, summary in English)

See Page 65

Synopsis: Estimate of potential GHG impact if Finland maximized its use of wood in construction. Finds significant net benefit with increased use of wood, particularly if wood residues and end-of-life wastes are used as a fossil fuel substitute. Also estimates the total carbon stock in existing wood products in Finland, and relates this to the total stock in Finnish forests. Includes data on displacement factors.

46 Pingoud, K., Pohjola, J. and Valsta, L. 2010. **Assessing the integrated climatic impacts of forestry and wood products.** Silva Fennica, 44(1): 155-175.

See Page 65

Synopsis: Steady-state analysis of forest management and wood use alternatives. Two climatic indicators are discussed: the combined carbon stock in forest biomass and wood products, and the avoided fossil emissions due to wood product use. Some forest management and wood use strategies can increase both indicators, for example producing more sawlogs that are used for material substitution that is recovered post-use for bioenergy.

47 Reid, H., Huq, S., Inkinen, A., MacGregor, J., Macqueen, D., Mayers, J., Murray, L. and Tipper, R. 2004. **Using wood products to mitigate climate change: A review of evidence and key issues for sustainable development.** International Institute for Environment and Development, London. 90 pg.

See Page 66

Synopsis: Multidisciplinary analysis of wood, climate change and sustainable development, addressing forest management, wood markets, and comparative GHG emissions of wood vs. non-wood. The quantitative information on GHG benefits of wood use is incomplete and without proper references.

48 Salazar, J. and 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.

See Page 67

Synopsis: In a comparison of two houses, one conventionally built and one with increased use of wood-based components, the wood house has significantly lower life cycle carbon emissions. The analysis considers forest carbon flows, industrial carbon flows from manufacturing, construction and maintenance, and end-of-life carbon flows. Includes data on displacement factors.

49 Salazar, J. and 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. *See Page 68*

Synopsis: In this life cycle assessment comparing residential window frames made of aluminum-clad wood, polyvinyl chloride (PVC) and fiberglass frames, the aluminum-clad wood frame produces fewer GHG emissions than the other frames. The aluminum-clad wood frame also compares well in other non-climate impact categories. Includes data on displacement factors.

50 Sathre, R. 2007. **Life cycle energy and carbon implications of wood-based materials and construction.** Ph.D. Dissertation, Ecotechnology and Environmental Sciences, Mid Sweden University, Östersund. 102 pg. *See Page 69*

Synopsis: Analysis of the mechanisms by which wood product substitution can affect energy and carbon balances, assessing the full life cycle of the product chain and the carbon stocks involved. Addresses the analytical challenges involved, and examines several different forest management scenarios as well as economic factors. Analysis done within the context of two case-study multi-storey apartment buildings (wood versus concrete, in two locations – see #21). Concludes that active and sustainable management of forests for products and biofuels returns the greatest potential for net CO_2 reduction.

51 Scharai-Rad, M. and Welling, J. 2002. **Environmental and energy balances of wood products and substitutes.** Food and Agricultural Organization of the United Nations. 70 pg. *See Page 70*

Synopsis: LCA comparison of wood versus non-wood in several examples: houses, unspecified multi-storey buildings, warehouses and window frames. In GHG emissions as well as other environmental impacts, the wood options are generally lower. When demolition wood from each option is considered for fossil fuel replacement, the GHG results are stronger. Includes data on displacement factors.

52 Schlamadinger, B. and Marland, G. 1996. **The role of forest and bioenergy strategies in the global carbon cycle.** Biomass and Bioenergy, 10(5-6): 275-300. *See Page 71*

Synopsis: A strong theoretical foundation for understanding the carbon dynamics of wood substitution. Modeling 16 different land use scenarios over a 100-year period, carbon is tracked in the atmosphere, forest biomass, forest soils, wood products and fossil fuels. In all scenarios, over long periods the carbon pools in trees, soil and wood products reach equilibrium and provide no further sequestration. However, the substitution effects of biomass over alternate materials dominate the carbon balance and create a continuing and cumulative carbon benefit. Discusses the definition and importance of displacement factors.

53 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. *See Page 72*

Synopsis: Calculates the total carbon stored in all US wood utility poles and estimates the total increase in CO_2 emissions if all poles were made of steel instead. Includes data on displacement factors.

54 Skog, K. and Nicholson, G. 1998. **Carbon cycling through wood products: The role of wood and paper products in carbon sequestration.** Forest Products Journal, 48(7/8): 75-83. *See Page 73*

Synopsis: Tracks carbon in US forest products from the year 1910 and carries into a projection up to 2040. Service lives of products are considered to follow a simple exponential decay pattern. Landfilled products are modeled based on previous data indicating very slow rates of wood decay in landfill, leading to high long term carbon sequestration. Results suggest that carbon in forests will decrease, carbon in products will slightly decrease, carbon in landfills will increase and carbon burned for energy will increase.

55 Suzuki, M. Oka, T. and Okada, K. 1995. **The estimation of energy consumption and CO_2 emission due to housing construction in Japan.** Energy and Buildings, 22(2): 165-169. *See Page 74*

Synopsis: Partial life cycle calculation of energy and GHG effects for wood versus steel in houses (also includes two concrete apartment buildings which are not comparable due to methodological issues). Finds substantially less energy use and CO_2 emissions with the wood buildings.

56 Taverna, R., Hofer, P., Werner, F., Kaufmann, E. and Thürig, E. 2007. **CO_2 effects of the Swiss forestry and timber industry.** In: Environmental Studies No. 0739, Federal Office for the Environment (BAFU), Bern. 102 pg. *See Page 75*

Synopsis: See #65, Werner *et al.,* 2010.

57 Taylor, J. and van Langenberg, K. 2003. **Review of the environmental impacts of wood compared with alternative products used in the production of furniture.** Project No. PN03.2103, Forest and Wood Products Research and Development Corporation, Australian Government. 16 pg. *See Page 75*

Synopsis: Review of over 20 studies of wood vs. non-wood, all of which find lower GHG emissions (among other benefits) for wood.

58 Upton, B., Miner, R. and Spinney, M. 2006. **Energy and greenhouse gas impacts of substituting wood products for non-wood alternatives in residential construction in the united states.** Technical Bulletin No. 925. National Council for Air and Stream Improvement. 42 pg.

See Page 75

Synopsis: Applies results from the CORRIM case-study houses (see #5) across all new US housing construction to derive national total avoided GHG emissions due to building houses with wood rather than steel or concrete. Uses a 100-year time horizon and comprehensively addresses forest growth dynamics, land use issues and disposal of materials at end-of-life. Finds net energy and GHG benefits due to the widespread use of wood. Includes data on displacement factors.

59 Upton, B., Miner, R., Spinney, M. and 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.

See Page 77

Synopsis: See #58 Upton *et al.*, 2006.

60 Upton, B., Miner, R. and Vice, K. 2007. **The greenhouse gas and carbon profile of the canadian forest products industry.** Report No. 07-09, National Council for Air and Stream Improvement. 27 pg.

See Page 77

Synopsis: Quantifies and discusses the net effect on atmospheric carbon due to the Canadian forest sector, looking at emissions, sequestration and avoided emissions, for the years 1995 and 2005. Carbon profile has improved over that time period, largely due to substantial reduction in fossil fuel consumption in pulp and paper mills. Includes comprehensive carbon tracking from forest to product to landfill.

61 Valsta, L. 2007. **Sequester or harvest: The optimal use of forests to mitigate climate change.** Report No. 46, Department of Forest Economics, University of Helsinki, Finland. 23 pg.

See Page 78

Synopsis: An economic modeling approach to the question, should more wood be harvested to substitute for other materials and thereby avoid C emissions, or should less wood be harvested to increase C in the forests? Values for avoided C due to substitution are taken from other studies, and a managed Finnish forest is the context. Economic values are assigned to carbon emissions and storage, with interest rate emerging as an important variable in the equation, particularly with respect to the benefit of using wood for biofuel. Using wood for construction is seen as generally more economically beneficial.

62 Werner, F. and Richter, K. 2007. **Wooden building products in comparative LCA: A literature review.** International Journal of Life Cycle Assessment, 12(7): 470-479.

See Page 79

Synopsis: Review of over 40 wood vs. non-wood LCA studies, with an in-depth analysis of 13 of those meeting the methodological standards of the authors. In almost all studies, wood had a lower GHG impact and generally favourable performance in other categories as well.

63 Werner, F., Taverna, R., Hofer, P. and 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.

See Page 80

Synopsis: Estimates the GHG effect if Switzerland were to increase its use of wood by 30%. Uses data from other LCA studies and applies broad assumptions regarding product mix, service lives, and use of all residues and waste as biofuel, over a 130-year timeframe. Results show that carbon stocks in wood products initially rise and then reach equilibrium, while the C benefits of substitution continue to accumulate. Energy recovery from wood residues makes an important contribution. Includes data on displacement factors.

64 Werner, F., Taverna, R., Hofer, P. and Richter, K. 2006. **Greenhouse gas dynamics of an increased use of wood in buildings in Switzerland.** Climatic Change, 74(1-3): 319-347.

See Page 81

Synopsis: See #63, Werner *et al.*, 2005.

65 Werner, F., Taverna, R., Hofer, P., Thürig, E. and Kaufmann, E. 2010. **National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment.** Environmental Science and Policy, 13(1): 72-85.

See Page 81

Synopsis: In this analysis of climate impacts of various forest management and wood use regimes in Switzerland, the greatest long-term reduction in GHG emission occurs when forests are harvested at their maximum sustainable level, the wood is used for long-lived products, and post-use wood is used for energy generation. Other management regimes result in greater short-term emission reductions. 20-30% of the emission reduction occurs outside of the national border.

66 Wilson, J.B. 2006. **Using wood products to reduce global warming.** Chapter 7 in: Forests, Carbon and Climate Change: A Synthesis of Science Findings. Oregon Forest Resources Institute.

See Page 82

Synopsis: A general overview of the climate advantage of using wood products, based on CORRIM data. Discusses the interactions between forest growth, carbon storage in trees and wood products, and substitution of fossil fuels and materials.

Individual Summaries of Study Findings

1 Anonymous. 2006. **Tackle climate change: Use wood.** Published by CEI-Bois. 84 pg. http://www.trada.co.uk/techinfo/asset/send/990/content/TackleClimateChange/index.html

- Conclusion: This attractive and colourful booklet provides non-technical information about using wood products as a means to mitigate climate change. It contains good introductory descriptions of the role of forests in the global carbon cycle, and of the life cycle of wood products. Quantitative data on the climatic benefit of product substitution are given, but discussion of uncertainties and the effect of analytical assumptions is lacking.
- This booklet is published by The European Confederation of Woodworking Industries (CEI-Bois).
- This booklet describes, in accessible and non-technical terms, the climate benefits of using wood products. The information is well-presented, and the booklet contains many figures and colourful photographs.
- The booklet begins with a basic description of the causes and effects of climate change. The role of forests and wood products in the global carbon cycle is briefly described. Two ways that wood use can reduce net CO_2 emissions are described: by reducing fossil emissions through material and fuel substitution, and by storing carbon in forests and wood products.
- The booklet discusses forest management, and distinguishes between the deforestation occurring in some regions and the efforts made toward sustainable forest management in Europe. Statistics are provided saying that European forest area is increasing by 510,000 hectares annually, and that only 64% of the net annual growth increment is harvested. The authors argue that marginally increasing forest harvest in Europe will increase forest vigour and reduce the susceptibility to damage from insects, disease, storms and fire.
- The authors describe the life cycle stages of wood products, and discuss the climate change impacts at each stage. Figures are given, based on data from various sources, showing that wood products emit less CO_2 over their life cycle than non-wood construction materials, per unit volume. Additional figures are given comparing the CO_2 emissions from several functionally equivalent buildings or building elements: window frames, flooring, beams, walls and houses. Data from earlier life cycle assessments are used. Some include only production-related emissions, some include the carbon stock in the wood materials, and some include post-use management. In all cases shown, the wood-based materials are said to have lower CO_2 emission than the non-wood materials.
- In general, the presentation is quite simplistic, and does not discuss the uncertainties associated with the analyses from which data are taken. Methodological issues such as the time dynamics of carbon emissions are not discussed in detail, and (temporary) carbon stock in materials is presented as being equivalent to (permanent) avoided emissions due to material and fuel substitutions. Comparisons are shown of emissions per unit volume of different materials, without acknowledging that equal volumes of different materials do not fulfill the same function.
- End-of-life options for wood products are discussed, including re-use, recycling and use as biofuel. The authors argue for a “balance between energy and product use.”
- The booklet concludes with statistics on the European wood products industry, including employment, economic value added and quantities of production of various products.

2 Anonymous. 2009. **Tackle climate change – Use wood.** Published by the BC Forestry Climate Change Working Group and the California Forestry Association. 75 pg. http://www.bcclimatechange.ca/docs/Book_Tackle_Climate_Change_Use_Wood_eVersion.pdf

- Conclusion: Intended for policymakers and other non-specialist audiences, this attractive booklet gives an overview of the climate benefits of wood product use. Based primarily on North American data, it discusses sustainable forest management, wood product and fuel substitution, and barriers and opportunities for increased mitigation activities in the forest sector.
- The document is published by the BC Forestry Climate Change Working Group and the California Forestry Association, in cooperation with WoodWorks.
- This booklet was developed by the U.S. and Canadian forest industries, and is targeted towards policymakers and architects to encourage the use of sustainably-produced forest products for climate change mitigation. It is based on the 2006 report with the same title published by CEI-Bois, but with updated information and focused on North American forestry instead of European forestry.
- The booklet is attractively-illustrated, and describes in non-technical terms the current and potential roles of forestry and forest products in reducing GHG emissions. It begins with a brief description of the causes and effects of climate change. The global carbon cycle is described, with a focus on the role of forests and forest products. A distinction is made between sustainable forestry, with continual cycling of carbon between forests and the atmosphere, and unsustainable forestry, which is said to contribute 17% of global CO_2 emissions.
- The climate impact of wood product substitution is discussed, using data from CORRIM research results (see #5, 39, 40). Emphasis is placed on the carbon stored in wood products and the reduced fossil energy use for wood product manufacture compared to non-wood products. No mention is made of the potential climate benefits of avoided process emissions. Carbon storage in wood products is treated somewhat inconsistently. For example, on pg. 24 it is stated simplistically that "for every metric ton of wood used, 1.9 tons of carbon dioxide equivalent is stored *indefinitely*." On the following page, however, more thorough information is given (based on #48) showing the climate significance of post-use wood management, with different life cycle emissions if wood is landfilled or recovered for energy.
- The use of forest biomass for bioenergy is then discussed. Most processing residues in the U.S. and Canada are already used for either energy or wood products, but it is estimated that at least 9 million dry tons per year go unused. Harvest residues are less commonly used, and it is estimated that 42 million dry tons could be recovered and used. Recoverable thinnings from overly dense and insect-killed stands is estimated at over 74 million dry tons per year.
- Efforts within the pulp and paper sector to reduce GHG emissions are then discussed. In recent decades, both the absolute emissions as well as the emission intensity (i.e., emissions per unit of production) of Canadian and U.S. pulp and paper producers have decreased substantially. At the same time, the recovery rate for waste paper has increased to about 56% in the U.S. and 65% in Canada.
- The authors discuss the barriers to more widespread use of wood products for climate change mitigation, and ways to overcome them. Carbon storage in wood products and GHG emissions avoided through substitution are not currently included in mitigation policy instruments. Various national and regional governments, however, have implemented policies to encourage greater use of sustainably-produced wood materials and biofuels.

- Five case-study buildings are presented, and estimates are given of the GHG emission reduction achieved by using wood-based construction instead of non-wood materials. A distinction is made between carbon stored temporarily in wood products, and avoided emissions due to material substitution. For four of the buildings, the substitution benefits are estimated using the average displacement factor found in the meta-analysis section of the present report (1st edition).

3 Björklund, T. and Tillman, A-M. 1997. **LCA of building frame structures: Environmental impact over the life cycle of wooden and concrete frames.** Technical Environmental Planning Report 1997:2. Chalmers University of Technology, Sweden. 156 pg.

- Conclusion: In a life cycle assessment of buildings made with wood or concrete frames, the energy use and CO_2 emission is clearly lower for construction of the wood buildings. The wood buildings performed better than the other materials in other environmental impact categories as well. Impacts during the operation phase dominate over those of the construction phase, making the life cycle differences less pronounced.
- The authors are from Chalmers University of Technology, in Sweden.
- The authors conduct a comparative life cycle assessment of wood-framed buildings and reinforced concrete-framed buildings. Two types of buildings are analyzed: a multi-storey apartment building and a warehouse building. The functional unit of the apartment building is 1 m^2 of floor area. The functional unit of the warehouse is a 6 m long section of a structure 18 m wide.
- Construction of the wood versions of both buildings required less total energy, and less fossil energy, than construction of the concrete versions.
- Significantly less GHG is emitted during construction of the wood version of both buildings. Per m^2 of the apartment building, the pre-cast concrete version emits 110.7 kg CO_{2eq}, the cast-in-place concrete version emits 97.1 kg CO_{2eq}, and the wood version emits 39.3 kg CO_{2eq}. Per functional unit of warehouse building, one pre-cast concrete version emits 9.11 t CO_{2eq}, another pre-cast concrete version emits 3.43 t CO_{2eq}, and the wood version emits 1.92 t CO_{2eq}.
- Electricity used for production of the materials is accounted for only as the amount used, and the environmental impacts of generating the electricity (e.g., CO_2 emissions if it is generated in fossil fuel-fired plants) are not included. Production of wood buildings uses less electricity than production of the concrete buildings. For construction of 1 m^2 of the apartment buildings, the pre-cast concrete version, the cast-in-place concrete version and the wood version use 268, 232, and 168 MJ of electricity, respectively. For construction of a functional unit of the apartment buildings, the two pre-cast concrete versions and the wood version use 26.1, 11.8, and 9.9 GJ of electricity, respectively. Depending on the source of the electricity, this may further increase the relative GHG advantage of the wood flooring.
- Demolition of the wood versions of both buildings required less energy, and emitted less GHG, than demolition of the concrete versions.
- The authors calculate energy use and GHG emission during the operation phase of the apartment building. The differences in operational energy and GHG emission are insignificant between the different versions of the building. GHG emissions from the operation phase are the dominant part of the life cycle emissions (80 to 85% for the concrete versions).

- The authors also assess other environmental impact categories of the buildings, including resource use, air pollution emissions, water pollution emission and waste generation. The overall environmental impact of the buildings is assessed using three common LCA assessment methods (Environmental Priority Strategies, Environmental Theme and Ecological Scarcity). The wood versions of both buildings are consistently found to have substantially lower environmental impacts during the construction phase than the concrete versions. For the apartment building, environmental impact during the operation phase is also calculated, and is approximately the same for all three materials. Because the impact during the operation phase is greater than the impact during the construction phase, the reduced impacts of the wooden material becomes less pronounced when seen in a life cycle perspective.

4 Börjesson, P. and Gustavsson, L. 2000. **Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives.** Energy Policy, 28(9): 575-588. http://dx.doi.org/10.1016/S0301-4215(00)00049-5

- Conclusion: In a comparison of life cycle GHG emissions of a wood- and a concrete-framed building, wood has lower emissions than concrete in almost all scenarios. GHG performance for wood structures is highly affected by methane emission from landfilled wood, as well as the time period used in the analysis. If wood is not landfilled or if methane gas is collected, wood construction consistently has lower GHG emission than concrete. Using forests for building material production, rather than carbon storage, becomes increasingly advantageous as the time perspective lengthens.
- The authors are from Lund University, Sweden.
- The authors perform an assessment of energy and GHG balances in a life cycle perspective (from resource extraction to demolition) of a 4-storey apartment building, built with either a wood-frame or concrete-frame. They assume a building life span of 50 years and 100 years. Building operation energy is not included, as the authors assume it will not differ between the 2 buildings.
- Their carbon accounting method takes as an emission fossil fuel used in product manufacturing, and also includes net process emission from cement manufacture. Credit (i.e., negative emission) is counted for avoided fossil fuel use when wood residue and landfill gas are used for energy, and wood fractions that remain sequestered in landfills. Carbon stocks in building materials and forests are tracked, but have no net change over the complete building life span and rotation period.
- They believe it’s necessary to use a long time perspective when considering GHG balances, due to long term processes like forest growth, cement carbonation, decomposition of landfilled wood, etc. They conduct analyses over the 100-year life span of the building (coinciding with the rotation period of the forest), and over a period of 300 years encompassing 3 consecutive forest rotations and building life spans.
- Carbon stock in the wood building is 44 tC. The authors estimate that twice that amount, or 88 tC, is contained in the roundwood removed from the forest. An additional 22 tC is contained in recoverable logging residues.
- Demolition wood is assumed to be either burned for energy, re-used or landfilled (currently 90% of Swedish demolition wood goes to landfill). For the landfill emissions, they assume 20% of the wood will eventually decay and 80% will remain sequestered. Landfill gas is estimated to be 60% methane and 40% CO_2. Seventy percent of the landfill gas is assumed to be collected and used to replace fossil fuels. The fossil fuel replaced by burning wood residues and landfill methane is coal, oil or natural gas.

- The re-use scenario assumes that 50% of demolition wood is recovered for re-use, and 50% is burned for energy. When wood is re-used, forest harvest and energy use for processing is reduced in the construction of subsequent buildings.
- The authors assume no net CO_2 emission due to cement process emissions. They assume 70% of calcinations' emissions from cement manufacture will be re-absorbed by the concrete in the first 100 years due to carbonation (a.k.a. carbonization), and the remaining 30% in the second 100 years.
- The lowest net life cycle GHG emission occurs for the wood building, when half the demolition wood is re-used and half is burned. The net emission in this case ranges from 0 to –10 tC, depending on the fossil fuel replaced by residues. If all demolition wood is burned, the net emission is around zero. If the demolition wood is landfilled and no methane is collected, the net emission is about 40 tC. If landfill gas is collected, the net emission is about 5 tC.
- The life cycle emission of the concrete building is higher. Depending on whether natural gravel or crushed gravel (which required more energy to produce) is used, net emission is 20 to 35 tC. If uptake of CO_2 by cement carbonation is disregarded, the net emission rises to 60 to 75 tC.
- The authors define an index of land-use efficiency for GHG mitigation, which is the amount of GHG emission reduction per 2 hectares of forest land. This area is the forest land required to supply raw materials, including energy, for the production of the wood-frame building. Less wood material is needed if the building is made with concrete-frame, and the remaining forest land can be used to produce biofuels or can be left to sequester carbon.
- The authors ask, in the context of their case-study building, how the forest can be used to best advantage for GHG mitigation – for example, alternatives would be leaving it untouched as a carbon sink, or building with concrete and using the wood directly as fuel. The results vary depending on assumptions, and the dynamics change over time. As the time perspective lengthens, the options that involve leaving the forest alone become less attractive, because the uptake of carbon in biomass decreases as the forest matures. In a 300-year perspective, net GHG emission is higher for the wood building than the concrete building if, and only if, the wood waste is landfilled, there is a high rate of decomposition and methane gas is not collected.
- When the building life span is reduced to 50 years, wood remains more attractive than concrete except when demolition waste is landfilled. For wood options involving landfill, with or without methane recovery, the concrete option that leaves wood in the forest is better over 100 years but not necessarily for 300 years. When demolition wood is not landfilled, the wood building has lower GHG emissions than the concrete building in both the 100- and 300-year time perspectives.
- The average GHG mitigation efficiency over a 100-year perspective is 2 to 3 times better for the wood building than the concrete building. Over a 300-year perspective the mitigation efficiency is 3 to 5 times higher with the wood building than concrete.

5 Bowyer, J., Briggs, D., Lippke, B., Perez-Garcia, J. and Wilson, J. 2005. **Life cycle environmental performance of renewable materials in the context of residential building construction. consortium for research on renewable industrial materials. Phase I Research Report.** Revised June 2005. http://www.corrim.org/reports/2006/final_phase_1/index.htm

Summarized in: Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J. and Meil, J. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Products Journal, 54(6): 8-19. http://www.corrim.org/reports/pdfs/FPJ_Sept2004.pdf

- Conclusion: In a comparison of houses made with wood frames and non-wood frames, the wood construction resulted in about 16% lower total energy use and 28% less GHG. The wood-framed versions also performed better than, or similar to, the non-wood versions in other environmental performance indices (air emissions, water emissions and solid waste). In a life cycle perspective, energy use and emissions from building construction were relatively small compared to energy use and emissions from building operation. Dynamic modeling of carbon flows shows that intensified forest management provides lower net CO_2 emissions, due to increased potential for material and fuel substitution, with the effect becoming more pronounced as the time horizon becomes longer.
- The authors are from the University of Minnesota, University of Washington, Oregon State University, and ATHENA™.
- This report presents the finding of Phase I research of the Consortium for Research on Renewable Industrial Materials, composed of 15 research institutions in North America. The goals of the CORRIM project are to create a database of environmental performance measures of the life cycle of wood and non-wood construction materials, to develop an analytical framework for evaluating the environmental and economic impacts of alternative building materials, and to diffuse the resulting information to interested parties.
- Phase I research focuses on forest management in the Pacific Northwest and the Southeast regions of the USA, and construction of typical houses in cold weather and warm weather areas. Two case-study buildings are analyzed: a house in Minneapolis with 2 storeys plus basement made with either wood or steel framing, and a single-storey house in Atlanta made with either wood or concrete framing.
- Primary data were collected by CORRIM researchers on the inputs and outputs associated with the production of a range of wood-based construction materials, based on surveys of mills in the processing regions. Secondary data were gathered and analyzed regarding forest regeneration, growth and production.
- Energy use and environmental impacts were calculated for the resource extraction/production, processing, transport and construction of the wood and non-wood versions of the buildings. Production of the wood houses required 17% and 16% less total energy, for the Minneapolis and Atlanta houses, respectively.
- Global warming potential, including the impacts of CO_2, CH_4 and N_2O, was 26% and 31% lower for the wood-framed versions of the Minneapolis and Atlanta houses, respectively.
- In the other environmental performance indices (air emissions, water emissions and solid waste) the wood-framed versions performed either better than, or similar to, the non-wood versions.
- Because the wood and non-wood versions of the buildings have many elements that are identical, various subassemblies were analyzed to better understand the sources of the performance differences of the complete buildings. The above-grade walls of

the buildings, which had significantly different designs and material composition, had environmental performance differences greater than those of complete buildings. The construction of the above-grade walls of the wood houses required 18% and 38% less total energy than those of the non-wood houses, for the Minneapolis and Atlanta houses, respectively. Global warming potential was 33% and 80% lower for the wood-framed versions of the Minneapolis and Atlanta houses, respectively.

- The wood and non-wood versions of the houses were designed with identical thermal resistance, so operation was assumed to be the same. Assuming a 75-year life span, the energy for construction, maintenance and demolition averaged 10% and 12% of the total heating and cooling energy of the Minneapolis and Atlanta houses, respectively.
- Life cycle carbon flows, including fossil fuel emissions, carbon accumulation in regrowing forests, carbon stored in wood materials, and avoided emissions due to material and fuel substitutions, were tracked over multiple building life spans and forest rotation periods. This time series analysis shows that carbon stocks in managed forests maintain a stable long term average level, carbon stocks in products continue to increase, but over time the substitution of forest products for emission-intensive fuels and materials dominates the cumulative carbon flow impacts.
- Intensified forest management, with shorter rotation periods and greater average annual wood production, result in increased net emission reduction due to the increased potential for material and fuel substitution. This effect becomes more pronounced as the time horizon becomes longer.

6 Boyd, C.W., Koch, P., McKean, H.B., Morschauser, C.R., Preston, S.B. and Wangaard, F.F. 1976. **Wood for structural and architectural purposes: Panel II Report, Committee on Renewable Resources for Industrial Materials.** Wood and Fiber, 8(1): 3-72. Web-accessible at http://www.treesearch.fs.fed.us/pubs/7976

Summarized in: Boyd, C.W., Koch, P., McKean, H.B., Morchauser, C.R., Preston, S.B. and Wangaard, F.F. 1977. Highlights from “Wood for structural and architectural purposes”. Forest Products Journal, 27(2): 10-20. Web-accessible at http://www.treesearch.fs.fed.us/pubs/24226

- Conclusion: In a comprehensive study of the US forest sector, the energy needs of the forest product industries are found to be potentially mostly fulfilled by biofuel residues produced during wood product manufacture. A comparison of the energy needed to produce wood-based construction elements shows that 2 to 10 times more energy is needed to make comparable elements with non-wood materials.
- The authors are from various academic, governmental and forest industry institutions in the USA.
- The authors report the findings of Panel II of the Committee on Renewable Resources for Industrial Materials (CORRIM 1), formed in 1974 by the US National Research Council. The Committee’s mission was “to assess the interchangeability of renewable and nonrenewable resources, to define the limits on supply and utilization of renewable resources, and to forecast the possible consequences of increased demand for renewable resources on energy consumption, society and the environment.” Panel II focused on wood use for structural and architectural purposes.
- The report quantify the flows of woody biomass in the US in 1970, from annual growth of standing trees, natural mortality levels, harvest of various types of timber and destination of roundwood removed from forests. The authors make projections of wood flows in 1985 and 2000, along with several scenarios for demand for wood products.

- The study makes detailed material balances for the production of a variety of structural products made of solid and composite wood. They calculate the labour, capital depreciation, mechanical energy and heat energy need to produce a unit weight of each product. The system boundaries include forestry activities, harvest and transport of roundwood, processing into products and transport to building sites. They calculate that the energy needed to manufacture most wood products can come from the biomass residues produced during manufacture.
- Similar data on comparable materials made of non-wood materials are gathered from census reports and a government laboratory databank. Comparisons are then made of a number of alternate designs for floors, walls and roofs made with different materials but providing a similar function. The basis of comparison is 100 ft^2 of building element. The study does not consider building maintenance. Building operation energy is not included, as the function of the building elements (including thermal resistance) is comparable.
- Production of the wood construction elements requires substantially less energy than the non-wood elements. In roofs, a design using steel rafters uses twice the energy of wood rafters. Exterior walls made with brick or concrete block use 7 to 8 times more energy than wood construction. Walls made with steel or aluminum framing uses twice the energy of wood-framed walls. Floor construction with concrete slabs or steel joists use 10 times more energy as a wood floor system.
- Comparisons of individual building components show even greater differences in energy requirements; up to 50 times more energy is needed to make some components of non-wood materials instead of wood.
- The labour requirements and capital depreciation are not appreciably different between most wood-based and non-wood designs.
- Although this study does not consider GHG emissions, the significant difference in total production energy use between wood and non-wood materials, as well as the potential for many wood product industries to satisfy their energy needs with CO_2 neutral biomass residues, point to significant GHG benefits from using wood products.
- This study was later updated and expanded by the CORRIM 2 research project.

7 Brunklaus, B. and Baumann, H. 2002. Vad innebär ett ökat träbyggande i Sverige för miljön? Granskning av jämförande LCA studier av stombyggnadsmaterian i hus. (**What does increased wood construction in Sweden mean for the environment? Review of comparative LCA studies of building frame materials**). ESA Report 2002:6, Institute for Environmental System Analysis, Chalmers University of Technology, Gothenburg. 17 pg. (in Swedish) http://www.esa.chalmers.se/Publications/PDF-files/TR/ESA20026.pdf

- Conclusion: In a review of six studies of environmental impacts of different construction materials, most of the studies show that wood has less environmental impact than non-wood materials during the construction phase. Over the complete life cycle, however, the impacts from building operation were much more significant, and independent of the construction material. The authors conclude that efficiency improvements in the building operation phase will have more effect on life cycle environmental impacts than will the choice of building material.
- The authors are from Chalmers University of Technology, in Sweden.
- The authors review six studies that analyze various aspects of environmental performance of building materials. The studies are reviewed in terms of their coverage of environmental impacts in a life cycle perspective, the suitability of their functional comparisons between wood and non-wood materials, the appropriateness of their input data, and other methodological issues that affect the validity of their results. Four of the

studies are from Sweden, and two are from Germany. Two studies analyze complete apartment buildings, two analyze single-family houses, and two analyze structural systems.

- The authors find methodological irregularities with several of the studies, including non-equivalent functional units, lack of transparency and inconsistent input data.
- One of the studies focuses only on toxicological impacts. That study concludes that there is no inherent impact difference between wood and non-wood construction, the impact arising from paints, solvents, putties, etc. that are used regardless of the primary construction material.
- Of the other five studies, four conclude that during the construction phase, wood material has slightly or significantly less environmental impact than non-wood material. Most of the studies find that over the entire life cycle, the advantages that wood may have during the construction phase are overwhelmed by the impacts occurring during the operations phase. Thus, most of the studies conclude that in a life cycle perspective, there is no significant difference in environmental impacts between wood-based and non-wood-based construction.
- The authors conclude that efficiency improvements in the building operation phase (space heating, electricity, water heating) are more important than building material choice, to achieve reductions in life cycle energy use and CO_2 emissions.
- In specific response to external arguments that wood construction is more environmentally friendly, the authors say that: the advantage of wood being a renewable resource depends on the sustainability of forestry practices; the advantage of energy recovery from post-use wood products depends on the waste handling and energy supply systems that will exist at the time of future demolition; the advantage of reduced CO_2 emission depends on carbon storage in forests and wood products, and on the relative CO_2 emissions of alternative energy supplies.

8 Buchanan, A.H. and Honey, B.G. 1994. **Energy and carbon dioxide implications of building construction.** Energy and Buildings, 20(3): 205-217. http://dx.doi.org/10.1016/0378-7788(94)90024-8

- Conclusion: In a comparison of several different building types made with wood, steel and reinforced concrete, the production of wood buildings is consistently found to use less energy and have lower CO_2 emissions. At both the level of individual building elements as well as when comparing entire buildings, using wooden materials instead of other materials resulted in lower net carbon emission in all cases.
- The authors are from the University of Canterbury in Christchurch, New Zealand.
- This article is a summary of a larger report published by the Department of Civil Engineering, University of Canterbury, New Zealand.
- The authors analyze several buildings, quantifying the energy used and carbon emitted during production of the buildings. The buildings include: a single-storey industrial building built of either wood or steel; a five-storey office building built of wood, steel or reinforced concrete; a six-storey hotel built of either wood or reinforced concrete; and three single-storey, single-family houses each built in a different way (most common, greatest energy requirement and lowest energy requirement).
- The authors calculate the energy used to manufacture the materials in each building type, based on production energy data from a 1983 New Zealand study, with minor updates made by the authors. The paper contains an appendix with production energy figures for a variety of materials.

- They calculate the carbon emissions released to the atmosphere during the material production, originating from fossil fuel combustion and cement production. Two scenarios are offered for the carbon intensity of electricity used for material production: average and marginal. The average intensity assumes current average New Zealand electricity production of 75% hydropower and 35% fossil-fired thermal power stations. The marginal intensity assumes 100% fossil-fired thermal power stations, and is said to represent the carbon emission impacts of marginal changes in electricity use. The paper contains an appendix with “carbon coefficients” for a variety of materials, under the two scenarios.
- Although the authors have data on the amounts of different types of fossil fuels (coal, oil, natural gas) used in the production of the materials (listed in Appendix 1 of the article), they aggregate all fossil fuel use and assume an average carbon intensity of 20 kg C per GJ of fossil energy. Greater precision would have resulted from using different carbon intensities specific to each fuel type.
- They also calculate the quantity of carbon stored temporarily in the materials of each building, and calculate “net carbon emission” as the difference between the carbon emitted during production and the carbon stored in the materials. The significance of this index as a long term means to mitigate climate change is not discussed by the authors. They acknowledge that the storage of carbon in materials is temporary, but do not explicitly consider the entire life cycle of the materials, and the climate impacts of the post-use management of the materials.
- The authors compare the calculated “net carbon emission” of building elements (structural frame, floor, wall cladding, roof covering, window frame) made of different materials, and also entire buildings made using different materials. In all cases, using wooden materials instead of other materials (steel, concrete, brick, aluminum) results in lower net carbon emission.
- The authors observe that a significant increase in global wood product use, as a means to mitigate climate change, will require more intensive forest management. They suggest that increasing the area of sustained-yield forest plantations may be required.

9 Buchanan, A.H. and Levine, S.B. 1999. **Wood-based building materials and atmospheric carbon emissions.** Environmental Science and Policy, 2(6): 427-437. http://dx.doi.org/10.1016/S1462-9011(99)00038-6

- Conclusion: In a comparison of several different building types made with wood, steel and reinforced concrete, the production of wood buildings is consistently found to use less energy and have lower CO_2 emissions. For each m^3 of additional wood products used in construction, carbon emissions are reduced by 260 to 3700 kg C.
- The authors are from the University of Canterbury in New Zealand, and Hart/Howerton Ltd. in USA.
- The paper begins with a good general overview of the role of forests and forest products in the global climate system, and a quantitative breakdown (based largely on FAO data) of global energy and carbon flows associated with forest products industries.
- The authors then analyze several buildings, quantifying the energy used and carbon emitted during production of the buildings. The buildings include: a single-storey industrial building built of either wood or steel; a five-storey office building built of wood, steel or reinforced concrete; a six-storey hotel built of either wood or reinforced concrete; four different single-storey, single-family houses each built with a different mix of materials (wood, brick, steel, concrete, aluminum, etc.).
- The authors calculate the energy used to manufacture the materials in each building type, using data sets for production energy specific to New Zealand. They calculate the carbon emissions released to the atmosphere during the material production, based on

an assumed carbon intensity of 20 kg C per GJ of fossil energy. They also calculate the quantity of carbon stored temporarily in the materials of each building.

- They then used these data to calculate displacement factors for the various construction alternatives, defined as the ratio of decreased carbon emission to increased carbon storage in wood construction material. For the industrial building, using wood instead of steel gave a displacement factor of 1.6 kg C emission avoided per kg C additional wood material (= 400 kg C emission avoided per m^3 of wood product, with the conversion factors used by the authors). For the office building, using wood instead of concrete gives a displacement factor of 1.1 (= 280 kg C per m^3 additional wood), while using wood instead of steel gives a displacement factor of 1.2 (= 300 kg C per m^3 additional wood). For the hotel building, using wood instead of concrete gives a displacement factor of 1.05 (= 260 kg C per m^3 additional wood). For the single-family houses, comparisons of the various alternatives gave different displacement factors, with the highest being 15 (= 3700 kg C per m^3 additional wood) when wood replaced brick in exterior cladding and wood replaced aluminum in window frames.
- Based on the analyses of individual building types, the authors present a scenario of increased wood use in New Zealand construction. They calculate that a 17% increase in wood use could result in a 20% reduction in both energy use and carbon emission from building material production. This would be a 1.8% decrease in New Zealand's total carbon emission. The authors also make a scenario analysis of increased wood use on a global level, with similar results.

10 Cole, R.J. 1999. **Energy and greenhouse gas emissions associated with the construction of alternative structural systems.** Building and Environment, 34(3): 335-348. http://dx.doi.org/10.1016/S0360-1323(98)00020-1

- Conclusion: In a study of the energy use and GHG emission due to the on-site construction of structural assemblies, steel structures had the lowest energy use and emissions, followed by wood structures, then concrete structures which had much higher energy use and emission. Transportation of construction workers to and from the building site caused a large share of the energy use and emissions for many of the structural assemblies studied. When worker transportation is included, the share of construction energy to total initial embodied energy is 2 to 5% for steel assemblies, 6 to 16% for wood assemblies, and 11 to 25% of concrete assemblies.
- The author is from the School of Architecture, University of British Columbia, Canada.
- The author studies the energy use and GHG emission associated with the on-site construction of buildings made of wood, steel and reinforced concrete. The analysis covers the transportation of construction workers to and from the building site, the transportation of materials from a distribution center to the building site, the transportation of construction equipment to and from a central depot to the building site, the use of on-site construction equipment, and supporting processes such as formwork and temporary heating.
- The analysis was conducted not on the basis of entire buildings but on a variety of structural assemblies (walls, beams, columns, etc.) made predominantly of wood, steel, or concrete. Data on materials and labour needed to construct 1 m^2 of each assembly were used as a basis for comparison.
- GHG emissions are expressed in CO_2 equivalents, over a time horizon of 20 years. Emissions from electricity generation are based on Canadian average electricity production.
- The steel assemblies required the least energy and produced the least GHG emission. Energy use for most of the steel assemblies ranged from 3 to 7 MJ/m^2, and GHG emission from 0.4 to 1.0 kg CO_{2eq}/m^2. The wood assemblies followed, with energy

use ranging from 8 to 20 MJ/m^2, and GHG emission from 0.8 to 2.5 kg CO_{2eq}/m^2. The concrete assemblies required the most energy and produced the most GHG emission, ranging from 20 to 120 MJ/m^2 and from 5 to 20 kg CO_{2eq}/m^2, respectively. Among the concrete assemblies, cast-in-place assemblies had the highest energy and emissions, followed by tilt-up walls and then precast assemblies.

- Energy analyses conducted according to IFIAS guidelines[2] generally exclude worker transportation. However, the author states that while materials manufacturing is energy and machinery intensive, on-site construction is often labour intensive. The transportation of workers to and from the construction site contributed between 5% and 85% of the total calculated energy use and GHG emissions of the various assemblies.
- The author states that a common assumption is that construction activities use between 7% and 10% of total initial embodied energy of construction. He calculates that when worker transportation is included, the share of construction energy to total initial embodied energy is 2 to 5% for steel assemblies, 6 to 16% for wood assemblies, and 11 to 25% of concrete assemblies. When worker transportation is not included, the share of construction energy to total initial embodied energy is 1 to 3% for steel assemblies, 2 to 9% for wood assemblies, and 5 to 15% of concrete assemblies.
- Because the functional unit of comparison of the various assemblies is not the same (i.e., different functions, load capacities, heat transmission properties, etc.), the quantitative results of particular assemblies should not be compared against each other. Nevertheless, because the study analyzes a large number of assemblies (39) made of different materials, the overall trends observed by the author appear to be valid.

11 Cole, R.J. and Kernan, P.C. 1996. **Life-cycle energy use in office buildings.** Building and Environment, 31(4): 307-317. http://dx.doi.org/10.1016/0360-1323(96)00017-0

- Conclusion: In a study of life cycle energy use of a building with a wood, steel or concrete structural frame, the wood building had the lowest energy use. Construction of the structural system of the concrete structure required up to 1.39 times more energy, and the steel structure up to 1.82 times more energy, than the wood structure. In a life cycle perspective, including building operation energy and recurring maintenance energy over the full life span, the difference between the structural systems becomes much less significant. Energy efficiency measures taken to reduce operation energy increase the relative importance of the lower energy use for producing wood structural systems.
- The authors are from the School of Architecture, University of British Columbia, Canada.
- This study compares energy use over the life cycle of a three-storey office building made with either a wood, steel, or concrete structural frame. Two versions of the building are considered: with or without an underground parking facility. The authors distinguish between energy used for the initial production of the building, the recurring energy used for maintenance, the energy used for building operation, and the energy used for demolition and disposal of the materials.
- The energy used to construct the structural system of the building is lowest when built with wood. The concrete structure requires 1.27 times more energy, and the steel structure requires 1.61 times more energy, in the building version without an underground parking facility. With the parking facility, the concrete structure requires 1.39 times more energy than the wood structure, and the steel structure requires 1.82 times more energy.

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[2] International Federation of Institutes of Advanced Study. 1974. *Energy analysis workshop on methodology and conventions.* http://petroleum.berkeley.edu/papers/Biofuels/IFIASConference1973v.pdf

- The energy used to construct the complete building is also lowest when built with wood, although the differences are less because many non-structural materials are the same in all the buildings. The concrete structure requires 1.05 times more energy, and the steel structure requires 1.13 times more energy, in the building version without an underground parking facility. With the parking facility, the concrete structure requires 1.06 times more energy than the wood structure, and the steel structure requires 1.14 times more energy.

- The level of recurring energy use (e.g., for paint, carpeting, electrical and mechanical systems, interior partitions) depends strongly on the service life of the building. With a 25-year life span, the recurring energy use for the wood building is 56% of the initial production energy. With a 50-year life span it is 144% of initial energy, and with a 100-year life span it is 325% of initial energy. The recurring energy use is slightly lower for the wood building than for the steel and concrete buildings.

- Operating energy is assumed to be the same, irrespective of the structural material. Two scenarios for operating energy are given: 1.05 $GJ/m^2/yr$ if the building is in Vancouver, and 1.761 $GJ/m^2/yr$ if the building is in Toronto.

- Due to the relatively low energy inputs needed for building demolition, and the uncertainties regarding the differences between the different structural materials, the authors choose to exclude the energy impacts of the demolition phase. By doing so they disregard the potential effects on the life cycle energy use that would result from burning wood demolition materials and recovering the energy.

- The service life of the building has a strong impact on the relative weights of the one-time initial production energy, the recurring maintenance energy, and the continuous operation energy. Over a 50-year life span, the operation energy is 80 to 90% of total life cycle energy, and initial production energy and recurring maintenance energy are each about 7 to 10% of the total. A shorter life span results in greater relative importance of the initial production energy.

- Energy efficiency measures taken to reduce operation energy increase the relative importance of initial production and recurring maintenance energy. If operating energy is reduced to 25% of base level, the operating energy falls to 55 to 65% of total life cycle energy use.

- In the case-study building under current conditions, the energy use differences among structural systems of wood, steel or concrete make very little difference in a life cycle perspective. However, as efforts are made to reduce building operating energy use, the reduced energy use of wood structural systems will become more significant.

- While this study addresses the life cycle energy use of the buildings, it is interesting from a climate change perspective because of the links between fossil fuel use and GHG emission. Additional GHG issues are beyond the scope of this study, e.g., calcination emission from cement manufacture, and CO_2-neutral biofuels used in the forest products industry.

12 Ekvall, T. 2006. Miljöaspekter på val av stommaterial i byggnader: Kompletterande kartläggning av kunskapsläget (**Environmental aspects of the choice of frame material in buildings: Supplementary survey of the state of knowledge**). IVL Report B1663, Swedish Environmental Research Institute, Stockholm. 18 pg. (in Swedish) http://www3.ivl.se/rapporter/pdf/B1663.pdf

- Conclusion: In a review of the methods and results of eight research groups that have studied the CO_2 emissions of using different types of building materials, most of the studies showed that wood-frame construction leads to lower CO_2 emission than non-wood materials. There are many inherent uncertainties regarding such studies, and there can be a significant difference between the potential and the actual CO_2 emission benefits of using wood materials. The author suggests that an analytical methodology be developed with the input of academic researchers and representatives from diverse industries.

- The author is from the Swedish Environmental Research Institute.
- The author reviews the analytical methodology used, and the results obtained, by eight research groups that have studied the environmental impacts of using different types of building frame materials. The focus of the review is on CO_2 emissions over the life cycle of the buildings.
- The results of most of the studies reviewed have shown that wood-frame construction leads to lower CO_2 emission. The significance of the emission difference varies between studies. Some studies have concluded that in a life cycle perspective, the difference in emissions attributable to the frame material is insignificant in relation to the much larger emissions due to the operation of the building. The operation phase of the building life cycle is not affected by the choice of frame material, in the studies reviewed.
- The author finds that broad system aspects associated with the choice of frame material can have a significant impact on CO_2 emissions. These aspects include the effects of harvest on forest carbon dynamics, the use of wood residues (including the post-use building material) as a biofuel to replace fossil fuel, and the fate of the non-harvested forest in case non-wood materials are used in construction. In this broad system perspective, the use of wood-frame construction has a significant potential to reduce CO_2 emission.
- There can be a large difference between the potential and the actual CO_2 emission benefits of using wood materials instead of non-wood materials. There are inherent uncertainties involved in life cycle analyses involving future actions (e.g., the fate of materials from buildings demolished decades in the future). At the present time, it is uncertain whether future demolition materials will be landfilled or burned with energy recovery, and if the latter, what type of energy source will be replaced by the recovered demolition material.
- Other types of uncertainties regarding the CO_2 emission impact of choice of frame material are: whether recycled steel replaces ore-based or scrap-based steel; how waste-handling systems will develop in the future; how changes in demand for wood material affects forest management; how energy systems develop in the future; and the role of combustible waste in future energy systems.
- Because of the various uncertainties involved in the analysis, the author believes that there is no single objective answer quantifying the CO_2 emission benefit of wood-frame construction. Instead, he suggests that an analytical methodology be developed with the input of academic researchers and representatives from diverse industries, including the wood products and concrete industries. Such an analysis, in spite of the inherent uncertainties involved, would provide a robust basis for policy decisions.

13 Eriksson, E., Gillespie, A., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R. and Stendahl, J. 2007. **Integrated carbon analysis of forest management practices and wood substitution.** Canadian Journal of Forest Research, 37(3): 671-681. http://dx.doi.org/10.1139/X06-257

- Conclusion: In a broad system analysis of carbon stocks and flows in trees, soil, wood products, and substitutable materials and fuels, net carbon emissions were lowest when forests were managed intensively to produce construction materials. The substitution effect of using wood instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues for use as biofuel led to avoided fossil emissions that were ~10 times greater than the reduced soil carbon stock. Different forest management and product use scenarios resulted in avoided carbon emissions ranging from 0.6 to 3.7 tC per hectare per year.

- The authors are from the Swedish University of Agricultural Sciences, Purdue University, and Mid Sweden University.
- The authors conduct a broad system analysis of the carbon stocks and flows associated with forest management and forest product usage. They model forest growth under 3 management regimes (traditional, intensive and fertilized) to determine the carbon stocks in trees and soil, the production levels of harvestable biomass and the fossil emissions associated with each regime. Three scenarios are considered for slash management: no removal, removal of harvest slash, and removal of harvest slash and stumps. Roundwood is used either as biofuel to replace fossil fuels, or as construction material in place of non-wood materials. Two reference fossil fuels are considered: coal and natural gas.
- The modeled forest is a Norway spruce stand in central Sweden. The analysis is conducted on a unit hectare of forest land. The time horizon of the study is 300 years, over multiple forest rotation periods.
- The mean carbon stock in standing tree biomass is greatest in the intensive management regime. However, the biomass production is greatest in the fertilized regime, which is 6% and 42% greater than the intensive and traditional regimes, respectively.
- Soil carbon levels increased rapidly in all 3 regimes during the first 100 years, and then asymptotically approached a level that was highest for the fertilized regime. Soil carbon fluctuated over time due to litter inputs followed by decomposition, but eventually reached stable long-term mean levels.
- Removal of slash and stumps caused a reduction in soil carbon levels, but also led to increased fossil fuel substitution from its use as biofuel. The decreased fossil fuel emission is in the order of 10 times greater than the decreased soil carbon stock.
- The product use (i.e., whether the biomass is used as biofuel or is used as construction material) has the single greatest effect on the overall carbon balance. Avoided net carbon emissions are 60% to 100% greater when wood is used for construction, because the wood replaces carbon-intensive concrete in a building, and later replaces fossil fuel when the demolition wood is recovered at the end of the building service life.
- The highest level of avoided net carbon emission occurs with fertilized forest management, removals of slash and stumps, stemwood used as construction material, and with coal as the avoided fossil fuel. This scenario resulted in 3.7 tC per hectare per year avoided carbon emission. The lowest level of avoided net carbon emission occurs with traditional forest management, slash and stumps remaining on-site, stemwood used as biofuel, and with natural gas as the avoided fossil fuel. This scenario resulted in 0.6 tC per hectare per year avoided carbon emission.
- The authors discuss the forest management regimes in comparison to an option of non-management and non-use of forest land. They observe that in the long term, the carbon stock in unmanaged forest biomass and forest soil will reach a dynamic equilibrium, where carbon stock increases due to tree growth will be balanced by decreases due to respiration and decomposition. Because no forest products are produced, other non-wood materials and fossil fuels will be used instead, resulting in relatively greater net carbon emissions. Because the substitution benefits of forest products are cumulative, while the carbon sink in forest biomass and soils is limited, the managed use of forests becomes more attractive as the time horizon lengthens.

14 Eriksson, P-E. 2003. **Comparative LCAs for wood construction and other construction methods: Energy use and GHG emissions.** Swedish Wood Association. 15 pg.

Summarized in: Eriksson, P-E. 2004. Comparative LCAs for wood and other construction methods. In: Proceedings of World Conference on Timber Engineering. Lahti, Finland. 6 pg. http://www.ewpa.com/Archive/2004/jun/Paper_032.pdf

- Conclusion: In a review of 12 comparative life cycle assessments of building construction, wood construction was consistently found to have lower energy use and GHG emission than non-wood construction materials. The author estimates that the increased use of wood construction in Europe could reduce GHG emissions by 35 to 50 Mt CO_{2eq} per year.
- The author is from the Swedish Wood Association.
- The author reviews and summarizes 12 life cycle assessments that compare the energy use and GHG emission of wood structures to that of steel or concrete structures. The studies are not completely comparable with each other, because some compare complete buildings and others compare only the structural differences between the wood and non-wood constructions. However, the author selects eight studies which, although the absolute numbers for energy use and GHG emissions should not be compared, the differences between the wood and non-wood options should be "reasonably comparable."
- The author calculates the energy use difference and GHG emission difference between each of the wood and non-wood buildings, per m^2 of floor area. All the energy use differences except one are positive, meaning that the wood buildings use less energy than the non-wood buildings. The one case with a negative difference results from a methodological inconsistency in which the feedstock energy value of the wood raw material is counted as an energy use, but the heat content in the same material at the end of the building life cycle is not credited as an energy source.
- The GHG emission difference between the wood and non-wood buildings is positive in every study, meaning that the wood buildings result in less GHG emission than the non-wood buildings. The differences range from 60 to 400 kg CO_{2eq} per m^2 floor area, with most being in the range of 150 to 200 kg CO_{2eq} per m^2.
- The author states, "Thus the conclusion for GWP is even clearer; regardless of system boundary conditions applied in the different studies, a building with a primary wood structure will give a lower GWP than the alternatives."
- The author discusses the system boundaries used in the different studies, in particular the varying inclusion of raw material feedstock energy and recovery of heat energy from post-use wood. He concludes that it is more appropriate to not include the feedstock energy of the wood material (because it is harvested for use as a structural material, and would not economically be harvested for use as biofuel), and to include the energy content of the post-use wood (because it is a resource that is available at the end of the building's service life).
- The author estimates the GHG emission reduction potential of using wood construction material on a European scale. Based on an annual production of 1.8 million housing units, 95% of which are made of non-wood materials, and an average size of 100 m^2/unit, and a GHG emission reduction of 200 to 300 kg CO_{2eq}/ m^2, the total reduction would be about 35 to 50 Mt CO_{2eq} per year. This is about 0.9 to 1.3% of total annual European emissions. This would require an additional annual use of 35 million m^3 of sawn softwood, compared to current use of roughly 100 million m^3 per year.

15 Eriksson, P-E. 2004. **Comparative LCAs for wood and other construction methods.** In: Proceedings of World Conference on Timber Engineering. Lahti, Finland. 6 pg.

- See #14, Eriksson, 2003.

16 Franklin Associates. 2004. **An analysis of the methods used to address the carbon cycle in wood and paper product cla studies.** Report No. 04-03, National Council for Air and Stream Improvement. 63 pg. Available online at http://www.ncasi.org/publications/Detail.aspx?id=2628

- Conclusion: In a review of 13 LCA studies of wood and paper products, the authors find a lack of consistency in the methods and assumptions used to track carbon during the product life cycle. Particularly with regard to carbon sequestration and methane generation in landfills, but also regarding carbon accounting during forest growth and product use, a wide variety of methods and assumptions were used in the studies, leading to different and potentially contrary conclusions. The authors conclude that a uniform protocol for addressing carbon flows in LCA studies is needed.
- The authors are from Franklin Associates, a private firm in Kansas, USA that provides consulting services in solid waste management and life cycle assessment.
- This report, commissioned by NCASI, reviews and synthesizes LCA literature to determine the methods used to characterize carbon sequestration or landfill emission from forest products in their use and post-use phases. The report identifies 66 LCA studies of wood and paper products. Most of these studies do not track carbon throughout the life cycle of the products. Some consider the fixation of atmospheric carbon into tree biomass through photosynthesis. Most studies do not consider the fate of carbon in products at the end of their service life, for example sequestration in, or methane emission from, landfills. Where biomass carbon is included it is usually, but not always, considered to be “global warming neutral.”
- The authors conduct an in-depth review of 13 of the studies. Issues to which the authors pay particular attention are: system boundaries and data sources; types of paper and wood products covered by the study; time-in-use (i.e., service life) of each product type; effects of recycling on effective service life; fixation of atmospheric carbon during tree growth; amount and duration of carbon sequestration in landfills; amount and timing of methane generated from landfills; amount and timing of CO_2 generated from landfills; and assumptions about collection and burning of landfill methane.
- In these 13 studies there was very little uniformity in the methodology and assumptions regarding the fate of carbon during the life cycle of the products. The studies covered a diverse range of forest product (various types and grades of paper and wood products), though even different studies of the same types of products used different methodologies and assumptions. The system boundaries of the studies varied substantially, including the treatment (or not) of carbon sequestration during forest growth. Treatment of carbon flows in landfills was very diverse. The studies generally used simplified assumptions that were not backed up by empirical data, for example that all organic matter decays in landfills, or that no organic matter decays in landfills. Some studies offered several different scenarios, or uncertainty analyses, to show the significance of the assumptions made.
- The report does not specifically address other options for end-of-life management of forest products besides landfilling, for example re-use or burning with energy recovery. The authors note that several of the reviewed studies do consider these options, though there is no discussion in the report of which end-of-life management option is most beneficial from a climate change mitigation perspective. There is also no analysis or discussion of suitable system boundaries regarding forest growth and regrowth.

17 Frühwald, A., Welling, J. and Scharai-Rad, M. 2003. **Comparison of wood products and major substitutes with respect to environmental and energy balances.** Paper presented at the seminar, Strategies for the Sound Use of Wood, 24-27 March, Poiana Brasov, Romania. 10 pg.

- See #51, Scharai-Rad, M. and Welling, J. 2002.

18 Gerilla, G.P., Teknomo, K. and Hokao, K. 2007. **An environmental assessment of wood and steel reinforced concrete housing construction.** Building and Environment, 42(7): 2778-2784. ttp://dx.doi.org/10.1016/j.buildenv.2006.07.021

- Conclusion: In a comparison of houses made with wood and reinforced concrete, the wood building is found to have lower emissions of CO_2, NOx, SOx, and suspended particulate matter than the concrete building. Seventy-nine percent of total CO_2 emissions occur during the operation phase, and 12% during the construction phase. The wood building has lower overall environmental impact (based on the impact categories analyzed by the authors), and lower external costs.
- The authors are from the Department of Civil Engineering at Saga University in Japan, and Arsenal Research in Austria.
- The authors study the energy use and atmospheric emissions (CO_2, NOx, SOx, and suspended particulate matter) over the life cycle of houses made of wood or reinforced concrete. The houses have 150 m^2 floor area and an assumed life span of 35 years. Impacts due to construction, maintenance, operation and disposal of the buildings are distinguished.
- Impacts due to construction, maintenance and disposal are derived with a hybrid input-output model using data from input-output tables for the Japanese economy, unit prices of the various materials, and assumptions about life span and maintenance needs. Energy use during the operation phase is estimated based on a questionnaire survey of domestic energy consumption.
- Life cycle CO_2 emission was lower for the wood building than for the concrete building. Emission for the wood building was about 2.1 tC/year, and for the concrete building was about 2.6 tC/year. For both building types, 79% of the total emissions occurred during the operation phase. Twelve percent of the life cycle emissions occurred during the construction phase; less than 9% occurred due to maintenance. Energy use for disposal was very small. The authors apparently do not consider the potential for energy recovery from post-use wood material.
- Emission of NOx, SOx and suspended particulate matter are lower for the wooden building than for the concrete building.
- Overall environmental impact of the two building types is analyzed by multiplying the quantities of the various emissions by an equivalency factor for each type of emission, based on the CML method. The results show total environmental impact to be lower for the wooden building (5,977 units) than for the concrete building (7,252). This analysis is incomplete, however, because not all impact categories are included in this analysis.
- The economic costs of the environmental impacts are estimated based on damage cost factors from the ExternE study. Emissions from the wood building are estimated to cost 110,000 Yen, and those of the concrete building are estimated to cost 122,000 Yen.
- The authors analyze potential reductions to the environmental impacts of the buildings. They calculate that average annual CO_2 emission will decrease by about 2% for every

5-year increase in the design life of the building, because the one-time emissions occurring during construction will be a smaller proportion of total life cycle emissions. However, there appears to be no dynamic element in the calculations that would factor in the possible increased emissions needed to build the building to have longer life spans. The authors also calculate the reduction in life cycle energy use if the building operation phase uses solar energy.

19 Glover, J., White, D. and Langrish, T. 2002. **Wood versus concrete and steel in house construction: A life cycle assessment.** Journal of Forestry, 100(8): 34-41.

- Conclusion: Based on analysis and reconfiguration of data from several earlier studies, the authors conclude that wood-based construction is generally less energy intensive than concrete or steel construction.
- The authors are from the Department of Chemical Engineering, University of Sydney, Australia.
- This paper reviews several earlier studies of the energy needed to produce building materials and houses made of wood, steel and concrete. The authors point out that the different studies are not completely comparable due to differing methodologies, assumptions and system boundaries. Nevertheless, the authors list production energy data from the studies, in units of MJ/kg, for products made of steel, concrete and wood. They observe the range of energy values needed to make various products, but note that the values cannot be compared because the materials do not serve the same function per unit mass of material.
- The authors then compare production energy values for building components (e.g., walls, floors, roofs) made predominantly of wood, steel or concrete, based on data from 2 earlier studies. They find that wood-based components generally use less energy.
- They then compare entire houses made with wood, steel or concrete frames, based on data from Buchanan and Honey (1994), repeating the earlier findings that production of the wood house uses less energy.
- The authors make some supplemental calculations of the uncertainty of the results presented by Buchanan and Honey (1994), using the ranges of material production energy found in the other studies reviewed by the authors. They find that wood construction has a range of energy use from 185 to 280 GJ, concrete from 265 to 521 GJ, and steel from 457 to 649 GJ. Thus wood construction will generally use less energy than other materials, although the high end of the range of wood construction energy overlaps with the low end of the range of concrete construction.
- This study is relevant to the question of climate impacts of building construction due to the link between fossil energy use and GHG emission. However, it may underestimate the climate advantage of wood construction because it does not consider calcinations' emissions of cement production and the use of climate-neutral bioenergy in the wood products industry.

20 Gustavsson, L., Madlener, R., Hoen, H.-F., Jungmeier, G., Karjalainen, T., Klöhn, S., Mahapatra, K., Pohjola, J., Solberg, B. and Spelter, H. 2006. **The role of wood material for greenhouse gas mitigation.** Mitigation and Adaptation Strategies for Global Change, 11(5-6): 1097-1127. http://dx.doi.org/10.1007/s11027-006-9035-8

- Conclusion: This is an interdisciplinary study of the current and potential use of wood material substitution for GHG mitigation, based on perspectives from engineering, natural sciences and social sciences. The authors consider wood substitution to mean "increasing the transformation of forest biomass into wood products in order to replace products emitting more GHGs per functional unit." The focus of the study is on using wood instead of other materials, but the use of wood instead of fossil fuels is also considered due to the characteristics of wood and its multiple uses over its life cycle.

- The authors briefly describe the history of wood use, from its preindustrial use as the predominant fuel and material, to its declining use as other industrial materials and fossil fuels largely replaced wood. They suggest that wood use may again increase in relative importance, due to future scarcity of non-renewable materials and fuels.
- The various material uses of wood are reviewed, as well as the non-wood materials that compete with wood for different uses. The authors note that the share of houses built with wood-based construction ranges from <20% in UK, Germany and France, to >80% in USA, Canada and the Nordic countries. The share of window frames made of wood ranges from <30% in southern Europe, to >60% in the Nordic countries. The authors offer several reasons for the wide variation in wood product use, including building standards, building traditions, perceived concerns about wood performance and about forest sustainability, and a lack of knowledge of wood among architects and engineers.
- The authors quote studies estimating that carbon sequestration in wood products is on the order of 0.026 to 0.139 GtC per year, and substitution benefits are on the order of 0.25 GtC per year. They believe that there is significant potential for decreasing GHG emissions by increasing the use of wood products. They distinguish among different potentials for GHG mitigation, which are (from highest to lowest): physical, technological, socioeconomic, economic and market potential.
- The authors describe the general approach to quantifying GHG benefits of wood substitution, based on a comparison of the life cycle emissions of functionally equivalent products. They provide data from three case studies, including two apartment buildings in Sweden and Finland made with either wood or concrete frames (see #21), and roof beams in Norway made of glue-laminated wood or steel (see #41).
- Recommendations are given regarding knowledge gaps that should be filled to allow more efficient GHG mitigation through wood substitution. Recommendations include: a need for studies that integrate material and energy substitution; optimize wood substitution in terms of GHG emission and costs; understand the sources and extent of variation; a need for implementation studies, including adoption, diffusion, and econometric studies; and dissemination of practical information to construction professionals, legislators, and consumers.

21 Gustavsson, L., Pingoud, K. and 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. http://dx.doi.org/10.1007/s11027-006-7207-1

- Conclusion: In a comparison of the energy use and CO_2 emission of apartment buildings with wood or concrete frames, wood buildings are found to have lower energy use and emission. More energy is available from biomass residues from logging, processing, construction, and demolition than is used to produce the wood buildings. Because of reduced fossil and process emissions during material production, and the substitution of fossil fuels by biomass residues, the wood buildings have lower life cycle net CO_2 emissions than the concrete buildings. Per m^3 of additional wood product used to make a wood building instead of a concrete building, life cycle net emission is reduced by 0.68 to 1.14 tC.
- The authors are from Mid Sweden University in Sweden, and Finnish Forest Research Institute in Finland.
- The authors compare the net CO_2 emissions over the life cycle apartment buildings made

with either a wood frame or reinforced concrete frame. The accounting of CO_2 emissions includes fossil emissions from the production and transport of material, calcination emissions from cement manufacture, atmospheric carbon fixed during tree growth and released during wood combustion or decay, and avoided fossil emissions due to the use of biofuels instead of fossil fuels.

- They analyze two case-study buildings, one in Sweden and one in Finland. Both are four-storey apartment buildings built with wood structural frames. The authors compare each building to a functionally identical building made with reinforced concrete frames. They assume a 100-year life span for all buildings. They assume that energy for operation and maintenance is the same for the wood-frame and concrete-frame buildings, thus they do not include it in the analysis.
- Based on the quantity of wood-based materials in each wood-framed building, the authors calculate the quantity of roundwood that must be harvested to produce the materials. Based on biomass expansion factors for boreal tree species, and assumptions about reasonable residue recovery rates, they calculate the quantities of biomass residues from harvesting, processing and construction that are associated with each building type. They assume that 90% of wood material in the buildings is recovered at the end of the service life of the buildings, and that all recovered residues are used as substitute for fossil fuels. All non-recovered residues are assumed to decay and release CO_2 to the atmosphere.
- The authors consider two “reference fossil fuels,” coal and natural gas, that are replaced by biomass residues, and that produce the electricity used for material production.
- Production of materials for the wood-frame buildings requires less energy than for the concrete-frame building. For the Swedish building, the wood building uses 2330 GJ and the concrete building uses 2972 GJ. For the Finnish building, the wood building uses 2907 GJ and the concrete building uses 3207 GJ. A greater proportion of the energy used to make the wood-frame materials comes from biofuels, while the concrete materials use more fossil fuels.
- The total amount of bioenergy recovered over the life cycle of the wood buildings is greater than the energy used to produce the materials in the wood buildings. For the Swedish building 3209 GJ of biofuels are recovered, and for the Finnish building 4700 GJ of biofuels are recovered.
- The system boundaries for the wood and the concrete buildings each contain the same area of forest land, which is the area required to make the wood materials for the wood-frame building. As the concrete building uses less wood, there is some “surplus forest” that is not used for building materials. The authors consider 2 scenarios for the biomass from this forest: it is left untouched to sequester carbon, or it is harvested to use as biofuel. If it is harvested for bioenergy, the total amount of bioenergy recovered over the life cycle of the concrete buildings is 3178 GJ for the Swedish building and 4565 GJ for the Finnish building. If it is left standing, the total bioenergy from the concrete buildings is 2087 GJ for the Swedish building and 916 GJ for the Finnish building.
- The authors assume that 8% of the CO_2 released by calcination reactions during cement production will be reabsorbed by carbonation reactions over the life cycle of the buildings.
- The life cycle net CO_2 emission of the wood buildings is –41 tC for the Swedish building and –76 tC for the Finnish building, when the reference fossil fuel is coal. The net CO_2 emission is negative because more emission has been avoided by using biofuel to substitute for fossil fuel, than has been released during the life cycle. If natural gas is the reference fossil fuel, the life cycle net CO_2 emission is –12 tC for the Swedish building and –31 tC for the Finnish building.
- The life cycle net CO_2 emission of the concrete buildings depends on the reference fossil

fuel and the use of the surplus forest, and range from –7 to +37 tC for the Swedish building and –35 to +75 tC for the Finnish building. In all cases the emissions of the wood buildings were less than those of the concrete buildings.

- The carbon stock in the building materials of the wood frame buildings is 40.3 tC for the Swedish building and 59.5 tC for the Finnish building. While temporarily significant, over the complete life cycle of the carbon stock change is zero.
- With coal as reference fuel, and not including the surplus forest, 1 m^3 of additional wood product used to make a wood building instead of a concrete building reduces life cycle net emissions by 1.14 tC in the Swedish building, and 0.68 tC in the Finnish building.

22 Gustavsson, L. and Sathre, R. 2006. **Variability in energy and carbon dioxide balances of wood and concrete building materials.** Building and Environment, 41(7): 940-951. http://dx.doi.org/10.1016/j.buildenv.2005.04.008

- Conclusion: In a study of the variability of energy use and CO_2 emission of buildings with wood or concrete frames, wood buildings are found to have lower energy use and emission over a wide range of parameter variation. Recovery of biomass residues, particularly demolition wood, has the single greatest effect on the energy and carbon balances of both the wood and concrete buildings. Land use issues and concrete production parameters also had significant effects. In all cases but one (a combination of parameters giving the worst performance of the wood building), the wood building has lower energy use and net CO_2 emissions than the concrete building.
- The authors are from Mid Sweden University in Sweden.
- The authors calculate the life cycle “energy balance” and “CO_2 balance” of a case-study 4-storey apartment building made with a wood frame and a reinforced concrete frame. They vary a number of system parameters including clinker production efficiency; blending of cement; crushing of aggregate; recycling of steel; lumber drying efficiency; material transportation distance; carbon intensity of fossil fuel; recovery of logging, sawmill, construction and demolition residues for biofuel; and growth and exploitation of surplus forest not needed for wood material production. For each parameter variation they determine the effect on energy use and CO_2 emission of the buildings.
- The energy balance is calculated as the primary energy expended to extract, process and transport the materials, minus the heat values of the fraction of finished materials and process by-products that can be recovered and made available for external use throughout the life cycle of the wood building materials. Data on energy use for material production is based on the average of 3 European studies. Biomass byproduct recovery is assumed to be 70% of logging residues and 100% of processing, construction and demolition residues.
- The CO_2 balance is calculated as CO_2 emissions to the atmosphere due to fossil fuel combustion and industrial process reactions, minus CO_2 emission avoided by replacing fossil fuel with recovered biofuels, minus increased (or plus decreased) carbon stock in materials and forests.
- The reference case is the combination of parameters that gives the lowest energy and CO_2 balances. The reference energy balance is 260 GJ for the concrete building and –1110 GJ for the wood building. The negative energy balance for the wood-frame building means that more usable energy in the form of biofuel is made available during the life cycle of the materials than is used during the production of materials. The reference CO_2 balance is –44.2 tC for the wood building and –16.5 tC for the concrete building. The negative energy balance means that more fossil emissions are avoided due to substitution by biofuels and carbon stock change than are emitted from fossil fuel combustion and cement reactions.

- Recovery of demolition wood has the single greatest effect on the energy and carbon balances of both the wood and concrete buildings. If demolition wood is not recovered and used as biofuel, the energy balance increases by 1450 GJ and 1000 GJ for the wood and concrete buildings, respectively. The CO_2 balance increases by 43.8 tC and 30.8 tC, respectively.

- Collectively, recovery of logging, processing and construction residues is also very significant. If these residues are not recovered and used, the energy balance increases by 1860 GJ and 1100 GJ for the wood and concrete buildings, respectively. The CO_2 balance increases by 56.8 tC and 33.9 tC, respectively.

- The 3 parameters regarding concrete production (cement clinker production efficiency, blending of cement, and crushed vs. natural concrete aggregate) have greater impact on the concrete building than the wood building. These 3 parameters taken together affect the energy balance by 130 GJ and 840 GJ in the wood and concrete buildings, respectively. They affect the CO_2 balance by 5.2 tC and 31.1 tC, respectively.

- Other parameters having significant effects include transport distances, carbon intensity of the fossil fuel replaced by biofuels and whether steel is recycled or ore-based.

- Land use issues regarding the difference in forest area required to produce the wood-based materials for the 2 buildings can also significantly affect the energy and CO_2 balances. In the reference case this “surplus forest” is assumed to remain standing and increase by 50% in carbon stock during the building life cycle. If instead it is harvested and used as biofuel, the energy balance of the concrete building decreases by 1090 GJ and the CO_2 balance of the building decreases by 6.8 tC. If instead it remains standing but does not increase in carbon stock (e.g., as in a mature forest), the CO_2 balance of the concrete building increases by 25.6 tC, while the energy balance is unaffected.

- Two worst-case combinations of parameters are analyzed that give the highest energy and carbon balances for the 2 buildings. With the combination giving the poorest results for the concrete building, the energy balances increased by 1720 GJ and 640 GJ for the concrete and wood buildings, respectively. The CO_2 balance of the concrete building increased by 78.1 tC and gave the highest CO_2 balance encountered in this study. The CO_2 balance of the wood building increased by 17.6 tC. With the combination giving the poorest results for the wood building, the energy balance of the wood-frame building increased by 3240 GJ, giving the highest energy balance encountered in this study. The energy balance of the concrete building increased by 900 GJ. The CO_2 balances increased by 100.4 tC and 71.5 tC for the wood and concrete buildings, respectively. This was the only scenario in which the energy and CO_2 balances of the wood-frame building were higher than those of the concrete-frame building.

23 Hennigar, C.R., MacLean, D.A. and Amos-Binks, L.J. 2008. **A novel approach to optimize management strategies for carbon stored in both forests and wood products.** Forest Ecology and Management, 256(4): 786-797. http://dx.doi.org/10.1016/j.foreco.2008.05.037

- Conclusion: Optimal forest management strategies will differ depending on whether the desired outcome is maximum carbon stock in forests, in wood products, in both forests and products, or in forests and products as well as substitution benefits. The lowest net carbon emission occurs when combined forest and product carbon stock and substitution benefits are maximized. More efficient substitution encourages greater harvest levels.

- The authors are from the University of New Brunswick, in Canada.

- The authors use the STAMAN growth and yield model and the CBM-CFS3 forest carbon budget model to generate scenario data that are then optimized for various objective functions using the Woodstock linear programming model. The time horizon in the analysis is 300 years. A 30,000 ha hypothetical forest in New Brunswick, Canada is analyzed

- The authors consider five alternate objective functions to be maximized: 1) wood volume harvested; 2) carbon storage in wood products; 3) carbon storage in forests; 4) carbon storage in wood products and forests; and 5) carbon storage in wood products and forests, and substitution benefits of wood product use.
- Carbon storage in wood products includes storage of landfilled post-use wood, using landfill decay data from Upton *et al*. (2007). Carbon storage in forests includes living tree biomass, litter, snags, coarse woody debris and soil organic matter.
- The authors estimate substitution benefits based on a literature review. Substitution rates (analogous to “displacement factors” described in the meta-analysis section of this report) used in the modeling are 0.125, 0.25, 0.5 and 1.0, in units of tC of avoided emissions per m^3 of wood product used. For comparison, the average displacement factor found in the meta-analysis section of this report was 2.1 tC of avoided emissions per tC in wood products used, which corresponds to a substitution rate of approximately 0.5 tC of avoided emissions per m^3 of wood product used, assuming a wood density of 500 kg/m^3.
- The authors consider three initial age structures for the forest: young, even-aged, and old. In the results, the initial age structure has very little effect on long-term forest management, though it did affect harvest levels and carbon storage during the first 50-100 years.
- Optimal forest management strategies are significantly different, depending on which of the objective functions are to be maximized. Maximization of harvest volume and maximization of carbon storage in wood products both results in high harvest levels and low carbon storage in forests. Maximization of carbon storage in forest results in low harvest level and low carbon storage in products. Maximization of carbon storage in both products and forest results in intermediate harvest level, and maintains relatively high carbon storage in forest.
- The lowest net carbon emission results from maximization of combined carbon storage in wood products and forests, and substitution benefits of wood product use. As the modeled “substitution rate” increases from 0.125 to 1.0 tC avoided emissions per m^3 of wood product used, the optimal harvest level increases and the overall net carbon emission decreases. Thus, more efficient substitution encourages greater harvest levels, and the resulting decrease in forest carbon stock is “leveraged” to produce lower overall carbon emissions.

24 Hillier, W. and Murphy, R. 2000. **Life cycle assessment of forest products: A good story to tell.** Journal of the Institute of Wood Science, 15(4): 221-232.

- Conclusion: In a life cycle analysis of preservative-treated wooden poles compared to non-wood poles, the wood poles consistently had lower global warming potential (GWP) than the other materials. Toxicity impacts of the wooden poles were relatively high due to the preservative treatment, unless the poles were burned in a controlled manner with ash and energy recovery.
- The authors are from Imperial College, London.
- The authors discuss the application of life cycle assessment to forest products, and give results of assessments of 2 preservative-treated wood products in comparison with non-wood products. The main focus of the study is the severity and management of the toxicological impacts of the preservative treatments, in relation to the other impacts caused by the wood and non-wood materials. GWP results from the life cycle assessment are presented, but are not extensively discussed by the authors.

- The first comparison is of an electricity-distribution line using poles made of steel, concrete, fibreglass or creosote-treated wood. The wood poles had significantly lower GWP than any of the other materials. The wood poles were rated relatively poorly in impact categories of “ecotoxicity” and “human toxicity” due to the use of creosote preservative.
- The second comparison is of a cattle fence using poles made of concrete, steel or CCA-treated wood. Two end-of-life options were considered: open burning of the wood poles, and controlled burning with energy recovery. Under both disposal options, the wood poles had significantly lower GWP than either of the other materials. When the wooden poles were burned in the open, they were rated relatively poorly in impact category of “human toxicity” due to the release of the CCA preservative. When burning was controlled and the ashes were recovered, the wood poles were rated with lower human toxicity impact than either of the other materials.

25 Hofer, P., Taverna, R. and Werner, F. 2008. **Forest and carbon: Greenhouse gas dynamics of different forest management and wood use scenarios in Sweden.** GEO Partner AG, Zurich. 76 pg.

- Conclusion: The calculated steady-state carbon implication of current management of forest management and wood use in Sweden is an annual emission reduction of 60 million tCO_2. Most of the emission reduction occurs outside of Sweden, due to the large volume of exports. More intensive management could raise that value to 103 million tCO_2.
- The authors are from GEO Partner AG and Werner Environment and Development, in Switzerland.
- The study examines the effects of different forest management and wood use scenarios on the carbon stocks in the forest, the carbon stocks in wood products, the substitution effects resulting from the use of wood materials in place of more energy-intensive materials, and the substitution effects of using forest biofuels in place of fossil fuels. GHG flows occurring within Sweden are distinguished from those occurring in other countries, to analyze political implications of the increased wood use.
- The authors develop three main scenarios: 1) Baseline regular, based on actual trends of forest management, harvesting, and wood products utilization, projected into the future until 2035, after which all parameters are kept constant; 2) Baseline full potential, the same as scenario 1 plus extra harvest of logging residues and stumps for use as energy; and 3) Increased increment, where forest growth is increased by means of fertilization, genetic improvement of tree species and intensified forest management. A fourth scenario focuses on forests managed by the Swedish forest company Sveaskog.
- The authors combine several models, including the HUGIN forecast model for forest yield and harvest, a model of the Swedish wood products industry (adapted from the authors’ earlier analysis of the Swiss wood products industry, see Taverna *et al*., 2007), and a model of wood substitution effects (also based on Taverna *et al*., 2007).
- Harvested sawlogs are assumed to be used for a variety of construction applications in place of non-wood materials. The wooden components and their substitutes were selected based on the results of a survey among architects and building commissioners in Switzerland and adapted to Swedish conditions if necessary. The GHG emissions from using the wood and non-wood materials are determined by comparative life cycle assessments.
- No substitution effects are defined for pulp and paper, although emissions from production processes are included. Imports and exports of paper products results in production emissions shifting across national borders.

- Forest harvest residues, wood processing residues, and post-use wood products are used as biofuel to replace oil, coal and natural gas, weighted on the basis of their share of total energy consumption. The authors allocate the avoided fossil emissions based on where they would have occurred, i.e. combustion emissions and some refining emissions would have occurred in Sweden, while other refining emissions and exploration, extraction and long-distance fuel transport emissions would have occurred outside of Sweden.
- The authors track carbon flows over time, but focus on the steady-state conditions that will occur after all system changes specific to each scenario have made their effects on carbon flows. For the Baseline regular scenario, the authors conclude that the Swedish forest and timber industry is responsible for, under eventual steady-state conditions, an annual emission reduction of about 14 million tCO_2 within Sweden, and 46 million tCO_2 outside of Sweden. In other words, if the Swedish forest industry did not exist, global emissions would be 60 million tCO_2 greater. This compares to a total annual CO_2 equivalent emissions of Sweden of about 66 million t.
- For the Baseline full potential, the steady-state conditions result in an annual emission reduction of 19 million tCO_2 within Sweden, and 47 million tCO_2 outside of Sweden, for a total annual global emission reduction of 66 million tCO_2. For the Increased increment scenario, the steady-state conditions result in an annual emission reduction of 38 million tCO_2 within Sweden, and 64 million tCO_2 outside of Sweden, for a total annual global emission reduction of 103 million tCO_2.

26 Hung, C.P., Wei, C., Wang, S.Y. and Lin, F.C. 2009. **The study on the carbon dioxide sequestration by applying wooden structure on eco-technological and leisure facilities.** Renewable Energy, 34(8): 1896-1901. http://dx.doi.org/10.1016/j.renene.2008.12.015

- Conclusion: In a comparison of several different small outdoor structures made of either wood or concrete, the wood versions consistently result in less carbon emissions.
- The authors are from Nan Kai University of Science and Technology, and the National Taiwan University, in Taiwan.
- The structures analyzed include a check dam, a small bridge, a viewing platform and a pedestrian trail. Drawings and photos are shown of the check dam and platform. Information is provided on volumes and species of all woods used in the structures.
- The method of determining the quantities of materials used in the wood and non-wood versions of each structure appears somewhat uncertain. For example, the wooden check dam is reported to use 8.69 m^3 of wood, and substitutes a dam with 55.68 m^3 of concrete. For the other three structures, however, the authors assume “for conservative comparison, the same volume of concrete” as wood is used in each structure. The basis of this equal volume assumption is not explained, however, as the check dam uses 6 times more concrete than wood.
- A variety of softwoods were used in the structures. The check dam, for example, was made of Japanese cedar (Cryptomeria japonica). The wood in the check dam was treated alkaline copper quaternary (ACQ) preservative. It appears that the wood used in the other structures is untreated.
- The authors calculate the carbon emission of each structure as the emissions during material processing minus the carbon stored in the material. They do not discuss the temporary nature of the storage in materials, except within the context of wood preservation which is said to extend the lifespan of wood check dam material from 2-3 years without ACQ preservative to 30-40 years with preservative.

- For all of the structures, the wood alternative resulted in substantially less carbon emissions than the concrete alternative.
- The authors use an efficient writing style and succeed in putting many useful details into a short article. They conclude poetically by stating "The more utilization of wood, the more reduction of carbon dioxide is."

27 John, S., Nebel, B., Perez, N. and Buchanan, A. 2009. **Environmental impacts of multi-storey buildings using different construction materials.** Research Report 2008-02, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand. 135 pg. http://www.nzwood.co.nz/images/uploads/multi-storey_building_report.pdf

- Conclusion: Life cycle GHG emissions of a six-storey office building decrease as the amount of construction wood increases. The operation energy and the end-of-life fate of wood materials are significant to the life cycle GHG balance.
- The authors are from the University of Canterbury, Scion, and Victoria University of Wellington, in New Zealand.
- The authors model the performance of four similar design versions of a six-storey 4,200 m^2 office building: Concrete, Steel, Timber and TimberPlus. The Concrete and Steel buildings used conventional structural design and construction methods. The Timber building used a post-tensioned timber structure with laminated veneer lumber. The TimberPlus design used additional wood in architectural features such as exterior cladding, windows and ceilings. All four buildings are designed for a 60 year life span.
- The life cycle GHG emission of the TimberPlus building is consistently lowest, followed by that of the Timber building, followed by either the Concrete or Steel building depending on end-of-life material fate. Comparison of the four building designs shows that as the amount of wood products increases, the life cycle GHG emissions decrease.
- The TimberPlus version has the lowest life cycle energy use. The building operation energy varies slightly between the different versions of the building, with the annual operation energy use of the wood-based buildings being up to 5% higher than that of the non-wood-based buildings. This affects the life cycle energy use ranking, as the Timber version with the highest operation energy uses more life cycle energy that the Concrete version with the lowest operation energy. The operation phase dominates life cycle energy use, thus improving operating efficiency is important for all building types.
- The post-use fate of building materials is shown to be important to the life cycle carbon balance. Landfilling of wood waste, assuming a very low decomposition rate of 18%, is slightly more beneficial than burning of wood waste for energy to replace natural gas and average New Zealand electricity supply. Using the recovered energy to replace more carbon-intensive fuels, such as coal, would improve the position of post-use energy recovery.

28 Jönsson, Å., Tillman, A-M. and Svensson, T. 1997. **Life cycle assessment of flooring materials: Case-study.** Building and Environment, 32(3): 245-255. http://dx.doi.org/10.1016/S0360-1323(96)00052-2

- Conclusion: In a life cycle assessment of flooring materials made of solid wood, linoleum and vinyl, the energy use and CO_2 emission is clearly lower for the wood flooring. Per m^2 of flooring per year of service, the wood flooring emits 0.011 kg CO_2, the linoleum emits 0.064 kg CO_2, and the vinyl flooring emits 0.21 kg CO_2. The wood flooring performed better than the other materials in other environmental impact categories as well.

- The authors are from Chalmers University of Technology in Sweden.
- The authors conduct a life cycle assessment of three types of flooring materials: vinyl, linoleum and solid wood. The functional unit of comparison is 1 m^2 of flooring for one year of service. The life span of the material is assumed to be 20 years for vinyl, 25 years for linoleum and 40 years for solid wood.
- All three flooring materials are assumed to be incinerated with energy recovery at the end of their service lives. Following LCA methodology, the feedstock heat energy value of raw materials is accounted as an energy cost. The heat recovered at the end of the service life is accounted as an energy gain.
- Total energy use is lowest for the wood flooring. Per m^2 of flooring per year of service, the wood flooring uses 1.6 MJ of energy, the linoleum uses 2.3 MJ and the vinyl flooring uses 2.8 MJ. Fossil fuel use was very much lower for the wood flooring than for the other materials.
- CO_2 emission of the wood flooring is significantly lower than for the other 2 materials. Per m^2 of flooring per year of service, the wood flooring emits 0.011 kg CO_2, the linoleum emits 0.064 kg CO_2, and the vinyl flooring emits 0.21 kg CO_2.
- Electricity used for production of the materials is accounted for only as the amount used, and the environmental impacts of generating the electricity (e.g., CO_2 emissions if it is generated in fossil fuel-fired plants) is not included. Production of wood flooring uses less electricity (0.21 MJ/ m^2/yr) than the linoleum (0.65 MJ/ m^2/yr) and the vinyl (0.91 MJ/ m^2/yr). Depending on the source of the electricity, this may further increase the relative GHG advantage of the wood flooring.
- The study also assesses other environmental impact categories of the flooring materials, including resource use, environmental toxin emissions, air pollution emissions and waste generation. The overall environmental impact of the flooring is assessed using 3 common LCA assessment methods (Environmental Priority Strategies, Environmental Theme and Ecological Scarcity). The wood flooring is consistently found to have lower overall environmental impacts than the other materials.
- The authors vary several parameters to determine the robustness of the results. Reduced transport distances (e.g., from localized sourcing of raw materials) do not change the conclusions. The use of revised data for pigment production reduces the impacts of linoleum production, and makes it comparable with wood flooring in some categories. The revision of the function unit to include load-bearing (i.e., a structural element in addition to a floor covering) improved the relative environmental performance of the solid wood flooring material.

29 Knight, L., Huff, M., Stockhausen, J.I. and Ross, R.J. 2005. **Comparing energy use and environmental emissions of reinforced wood doors and steel doors.** Forest Products Journal, 55(6): 48-52. http://www.treesearch.fs.fed.us/pubs/20937

- Conclusion: From raw material acquisition to the door factory gate, an insulated steel door produces 27 times as much GHG emissions as a functionally equivalent fiberglass-reinforced wood door. The steel door also had higher energy use, waterborne wastes, and solid waste generation.
- The authors are from ERG Inc. and from USDA Forest Service, in the USA.
- The authors conduct a partial life cycle inventory comparing two products: a fiberglass-reinforced wood door, and a functionally equivalent insulated steel door. They describe in some detail the production process for both doors.

- The analysis covers the pre-manufacturing and manufacturing phases, i.e. from raw material acquisition to the door factory gate. Post-use fate of the products is not considered. Life cycle energy and emissions data come from the Franklin Associates LCI database.
- The authors report aggregate results on 44 atmospheric emissions and 32 waterborne wastes, which were significantly lower for the wood door than the steel door. Solid waste generation is also estimated to be much lower for the wood door.
- Emissions of five greenhouse gases are quantified: fossil carbon dioxide, methane, nitrous oxide, methylene chloride, and carbon tetrachloride. Non-fossil carbon dioxide is assumed to have zero GHG impact.
- The reinforced wood door is estimated to produce 5.25 kg CO_{2eq} while the steel door produces 141 kg CO_{2eq}, or 27 times as much GHG emissions.
- The reinforced wood door is reported to use 0.10 GJ of energy, while the steel door uses 2.17 GJ, or 21 times the amount of energy (including both fossil and bio fuels). However there appears to be an inconsistency in the authors' energy accounting: The feedstock energy of the petroleum and natural gas used to produce polystyrene insulation in the steel door core is included, because "this use as a feedstock removes those fuels from the pool of resources available for energy production." The same analytical treatment is not applied to the feedstock energy of wood used in the reinforced wood door.

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

- Conclusion: This analysis considers the CO_2 emission implications of a proposed reduction in forest harvest, and the consequent use of non-wood products instead of wood. CO_2 emission increases are calculated for the substitution of steel, concrete, brick and other non-wood materials in place of wood products. For each billion board feet (Scribner) reduction in annual roundwood harvest, the author estimates that net CO_2 emission will increase by about 7.5 million tons.
- The author is from Wood Science Laboratory, Inc. in USA.
- This study estimates the energy and GHG implications of a proposed decrease in forest harvest in the northwest USA. It considers five harvest scenarios: the average roundwood harvest level in the region for the years 1983 to 1987 of 13.85 billion board feet per year, and four additional scenarios of reduced harvest, down to a minimum harvest of 5.6 billion board feet per year.
- Based on the 1985 distribution of harvested roundwood to various wood product classes (e.g., lumber, plywood, pulp), and the product-to-roundwood yield ratios of the various conversion processes, the author calculates the reduced annual production of each type of product for each of the four scenarios with a harvest reduction.
- The author discusses the potential societal responses to a reduced availability of new wood products from the region, such as foregoing the services provided by the products, increasing the recycling rate of post-use products, and increasing the import of roundwood or wood products from other countries. He concludes that the most likely response will be an increased use of non-wood materials to provide the services that the wood products would have provided.
- The author uses data from the first CORRIM study (see #5) to estimate the energy use implications of the use of non-wood materials in place of the reduced production of wood products. The data cover the energy used to extract, process and transport the

materials, and also account for energy made available from wood processing residues. Comparisons are made for various product substitutions, such as wood vs. steel studs, wood vs. concrete floors, plywood vs. aluminum siding and wood vs. steel posts.

- The increased total energy demand is then calculated for the four harvest reduction scenarios. The scenario with the greatest harvest reduction gives an increased energy use of about 140 million barrels of oil per year.
- The CO_2 emission impacts of the scenarios are then calculated. The increased emissions due to the increased energy use are calculated, based on the carbon intensity of fuel oil. The emissions from biofuels that would have been used in the manufacture of wood products, but is not used because of the reduced harvest, are deducted. The result is the increased net emission of CO_2 due to the decreased harvest, and equals 61.6 tons of CO_2 per year in the scenario with the lowest wood harvest.
- For each billion board feet (Scribner) reduction in annual roundwood harvest, the author estimates that net CO_2 emission will increase by about 7.5 million tons.
- The author discusses the effect that changing forest management intensity may have on the carbon stock in the forest biomass. He believes that as long as the harvested wood is used in long-lived products (>75 years), conversion of an old-growth forest to a managed production forest with a regular harvest rotation period will have no significant impact on total carbon storage.

31 Kram, T., Gielen, D.J., Bos, A.J.M., de Feber, M.A.P.C., Gerlagh, T., Groenendaal, B.J., Moll, H.C., Bouwman, M.E., Daniels, D.W., Worrell, E., Hekkert, M.P., Joosten, L.A.J., Groenewegen, P. and Goverse, T. 2001. **Integrated energy and materials systems engineering for GHG emission mitigation.** Final Report of the MATTER Project. The Netherlands. 245 pg. ftp://ftp.ecn.nl/pub/www/library/report/2001/c01017.pdf.

- Conclusion: The use of sustainably produced wood material in place of non-wood materials is the most significant single CO_2 mitigation strategy within the construction materials industry. Other important actions include using renewable wood in place of unsustainable tropical hardwoods, and recovering waste wood for energy recovery.
- The authors are from ECN policy Studies, Groningen University, Utrecht University, and Free University of Amsterdam, in The Netherlands.
- The authors analyze the potential scope and the cost of GHG emission reduction resulting from changes in production and use of industrial materials in the OECD-Europe region. The industrial sectors covered include iron and steel, petrochemicals, packaging, buildings and infrastructure, road vehicles, agriculture, and forestry.
- Chapter 7 focuses on the construction sector, while Chapter 10 addresses forestry and agriculture. The authors estimate that the ratio between “direct” energy use in buildings (for e.g. heating and other operational uses) and “indirect” energy use (for material production) in OECD-Europe is around 4:1. However, with increasing levels of insulation and other measures to cut operational energy use, they estimate this will decrease to 3:1 or even 2:1 in the coming decades. Because materials production energy is to a greater extent based on coal (with high CO_2 emissions), while residences are generally heated with energy carriers like oil and natural gas (with lower CO_2 emissions), the ratio of indirect and direct CO_2 emissions is higher than the ratio of energy use.
- The authors consider two categories of mitigation options in the building materials industry. The first category is “efficiency improvements” such as increased resource efficiency (less natural resources to yield the same amount of material), increased materials efficiency (less material in the finished product), and increased product efficiency (less products to fulfill the same final service). The second category is

"substitution" and includes both resource substitution (e.g. blast furnace slag to replace cement clinker) and material substitution (e.g. using wood instead of bricks).

- The authors identify several priority actions for reducing GHG emissions in the construction sector, including substituting non-renewable tropical timber with sustainably produced wood, improving cement production, enhancing the quality of construction materials, re-designing building structures, and increasing waste recovery including energy recovery from wood waste. They identify substitution of concrete and ceramic products by renewable wood products as the most significant single action.
- The authors estimate that using an additional 50 million t of wood products per year to substitute for non-wood materials in OECD-Europe has the potential to reduce annual GHG emissions by 50 million tCO_2. This is based on a displacement factor of 1 tCO_2 per t wood. This displacement factor corresponds to a relatively low 0.55 tC/tC in the units used in the meta-analysis section of the present report. An additional carbon sequestration in wood products of 75 million tCO_{2eq} per year would occur. The estimated cost for this substitution ranges from negative cost (i.e. economic benefit) up to 1000 Euros per tCO_2.
- The authors estimate that substituting non-renewable tropical hardwood with sustainably produced wood has the potential to reduce annual emissions by 25 million tCO_2 by 2020, at a cost of 0 to 500 Euros per tCO_2. Using waste wood for electricity production has an estimated emission reduction potential of 5 million tCO_2 per year. The authors also provide estimates of mitigation potential and costs for a range of other actions within the building materials industry.
- Data are provided from a case study of life cycle CO_2 emissions of a 137m^2 single family house in Austria built with either a wood or brick frame, excluding operation emissions. The wood version produces 28.1 tCO_2 while the brick version emits 39.4 tCO_2. About two-thirds of the emissions are due to materials production. Energy recovery from wood waste is not considered.
- The authors estimate that a high carbon tax will raise the cost of structural elements of a building by less than 10%. They suggest that such a limited cost impact will be an insufficient incentive to switch from current building practices to less carbon-intensive practices, thus other policy measures like legislation or voluntary agreements might be needed to initiate a transition to more sustainable construction.

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

- Conclusion: In a study comparing environmental impacts caused over the life cycle of utility poles made of preservative-treated wood, reinforced concrete and tubular steel, the wood poles were found to have significantly lower global warming potential than the poles made of other materials. The wood poles also had lower impacts in most other environmental categories, but showed higher levels of ecotoxicity due to the preservative treatment.
- The authors are from the Swiss Federal Laboratories for Materials Testing and Research (EMPA).
- The study followed standard life cycle assessment methodology including goal definition and system boundary establishment, data inventory and impact assessment. Comparison was made on the basis of a single utility pole, a 0.4 kV distribution line and a 20 kV distribution line. A service life of 60 years was assumed, and the wooden poles were assumed to have a life span of 30 years, thus needing to be replaced once during the service life. Both solid roundwood poles and glue-laminated wood poles were

analyzed, and the wood poles were treated with CCF or CCB preservative. The wooden poles were incinerated at the end of their service life; the heat energy was recovered, but it is not stated whether it was used as a substitute for fossil fuels.

- The poles were compared in terms of global warming potential as well as several other environmental categories including acidification, nutrification, photochemical ozone creation and primary energy consumption.
- Individual utility poles 11 m long were compared. In the impact category "global warming potential," round wooden poles had an emission of 34 kg CO_{2eq}, glulam wood poles had 134 kg CO_{2eq}, concrete poles had 167 kg CO_{2eq} and steel poles had 1040 kg CO_{2eq}.
- The wooden poles performed better than the other materials in most other environmental impact categories. In some categories (photochemical ozone, ecotoxicity, primary energy consumption) the concrete poles had lower impacts. The primary energy consumption was higher for wooden poles than for concrete poles because the feedstock heat value of the input materials are included in the calculations. The steel poles had the highest environmental impacts in all categories.
- A 0.4 kV distribution line 1 km long with 35 m spans, constructed with poles of either concrete, steel or solid roundwood, was analyzed. In the impact category "global warming potential," the wooden poles had an emission of 3831 kg CO_{2eq}, concrete poles had 17287 kg CO_{2eq}, and steel poles had 38268 kg CO_{2eq}. The wooden poles performed better than the other materials in all other environmental impact categories except photochemical ozone and toxicity, for which concrete had lower impact.
- A 20 kV distribution line 1 km long with 120 m spans, constructed with poles of either concrete, steel, or solid roundwood, was analyzed. In the impact category "global warming potential," the wooden poles had an emission of 11834 kg CO_{2eq}, concrete poles had 16748 kg CO_{2eq}, and steel poles had 39161 kg CO_{2eq}. The wooden poles performed better than the other materials in all other environmental impact categories except ecotoxicity, in which concrete had lower impact, and solid waste, for which steel had lower impact.

33 Lenzen, M. and Treloar, G. 2002. **Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson.** Energy Policy, 30(3): 249-255. http://dx.doi.org/10.1016/S0301-4215(01)00142-2

- Conclusion: Using a top-down approach rather than a bottom-up approach, this study reanalyzes material production energy use data from Börjesson and Gustavsson (2000) in an Australian context. Energy use is estimated to be twice as much as originally estimated, but the conclusion that wood construction uses relatively less energy and emits less CO_2 than concrete construction is unchanged.
- The authors are from the University of Sydney and Deakin University, in Austrailia.
- The authors analyze the building material data from the Börjesson and Gustavsson (2000) study that compared a wood-frame building to a reinforced concrete-framed building. In contrast to the production energy intensity data based on a bottom-up process analysis of Scandinavian industry used by Börjesson and Gustavsson (2000), the authors use energy intensities obtained from a hybrid input-output technique using Australian data. They estimate energy use based on top-down economic analysis of sectoral monetary transactions, tied to specific materials in terms of the economic value of materials based on prices in Australia.
- By including economy-wide energy use associated with the production of materials, the authors estimate that the total energy used to produce the building materials is about twice as high as that estimated by Börjesson and Gustavsson (2000).

- The authors reached the same conclusion, namely that wood construction uses less energy and emits less CO_2 than concrete construction.
- The analysis is limited to the production energy of the buildings. The authors do not consider land-use issues, process CO_2 emissions or post-service life material management.

34 Lippke, B. and Edmonds, L. 2006. **Environmental performance improvement in residential construction: The impact of products, biofuels, and processes.** Forest Products Journal, 56(10): 58-63. http://www.corrim.org/reports/2006/fpj_oct_2006/FPJproductSubs.pdf

- Conclusion: In an analysis of potential changes in construction systems, the authors find that increasing the use of wood-based products in place of non-wood products improves the building's environmental performance. Increasing the use of biofuels in wood processing industries further reduces GHG emissions.
- The authors are from the University of Washington, USA.
- This study analyzes the environmental performance of various construction subassemblies. Expanding on the results of CORRIM Phase I research (Bowyer *et al.*, 2005 – see #5), the authors examine potentials for further reducing environmental impact of building construction. The authors compare four types of cold-climate wall construction, two types of warm-climate wall construction, and four types of floor construction. Each construction option uses a different mix of wood-based and non-wood materials. The function, including thermal efficiency, of each subassembly is identical, allowing comparison.
- For the cold-climate wall construction, a "conventional" wood-framed wall system uses 76% of the fossil fuel, and produces 69% of the GHGs of a steel-framed wall system. A different wall system using increased amounts of wood products (e.g., wood plywood instead of vinyl siding, wood-fibre insulation instead of fibreglass insulation, plywood paneling instead of gypsum wallboards, and biomass residues instead of fossil fuels for wood processing energy) uses 29% of the fossil fuel, and produces 32% of the GHGs of a steel-framed wall system.
- For the warm-climate wall construction, a wood-framed wall system uses 39% of the fossil fuel, and produces 23% of the GHGs of a concrete-framed wall system.
- For the floor construction, a composite-wood floor system uses 65% and 25% of the fossil fuel of a concrete and a steel floor system, respectively. The wood system produces 22% and 14% of the GHGs of a concrete and a steel floor system, respectively.
- The authors point out that not only do conventional wood construction systems use less fossil energy and emit less GHG than comparable non-wood systems, there exist many potential avenues for significantly reducing still further the energy use and GHG emissions of wood-based construction systems.

35 Lippke, B., Wilson, J., Meil, J. and Taylor, A. 2010. **Characterizing the importance of carbon stored in wood products.** Wood and Fiber Science, 42(CORRIM Special Issue): 5-14. http://www.corrim.org/pubs/index.asp

- Conclusion: More carbon is generally stored in wood products than is emitted during their manufacture. The full life cycle climate significance of this stored carbon will depend on its post-use management.

- The authors are from the University of Washington, Oregon State University, University of Tennessee in the USA, and from the Athena Sustainable Materials Institute in Canada.
- The authors discuss the climate significance of carbon stored in wood products, which they say is an often overlooked benefit of wood product use. The initial CORRIM research protocol did not consider stored carbon as an emission offset, but the protocol has now been changed to consider the effects of the stored carbon
- The authors use CORRIM data to compare fossil carbon emissions, biogenic carbon emissions, and biogenic carbon storage for a range of construction materials. Wood products consistently have lower fossil emissions than non-wood products. When carbon stored in wood products is also included, the net emission of wood product manufacture is generally negative, meaning more carbon is stored in the product than was released during manufacture.
- When looking at the full life cycle of a material, the authors suggest four end-of-life fates for wood products: 1) recycling into other wood products, thus extending the carbon storage time, 2) burning the wood product, resulting in immediate carbon release, 3) controlled incineration of the wood product, with energy recovery that substitutes fossil energy, and 4) landfilling the wood product, which results in partial long-term storage of carbon and partial emission in the form of methane. The authors do not attempt to compare these fates in terms of their climate impacts.
- The authors lament that the precision of available data on post-use carbon dynamics is lower than the precision of CORRIM data on wood product production. This is especially true of landfill dynamics. Nevertheless, the authors point out that sustainable forest management will result in a continuing flow of carbon from harvested forests into the wood products pool, which eventually enters the post-use products pool, resulting in continuing emission offsets even if the post-use carbon storage is incomplete.
- The authors suggest that an increase in non-wood products has occurred in the historical context of low fossil fuel prices, and as fossil fuel prices rise or as a value is placed on carbon emissions, a shift towards greater wood use should take place.
- The authors suggest that “carbon-negative” buildings can be built, using enough wood products to result in net negative carbon emissions during manufacture. Over the full life cycle, however, the post-use fate of the stored carbon will need to be considered. If wood products are subject to appropriate post-use management, it may be possible for life-cycle carbon negative buildings to be made.

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

- See #5, Bowyer *et al.*, 2005.

37 Liu, G and Han, S. 2009. **Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon.** Ecological Modelling, 220(13-14): 1719-1723. http://dx.doi.org/10.1016/j.ecolmodel.2009.04.005

- Conclusion: Total carbon storage in living trees and wood products is highest in forest management scenarios with increased harvest levels. A management scenario with no harvest leads to low average carbon storage because natural disturbances cause the loss of carbon stocks in living trees.
- The authors are from the Institute of Applied Forest Science, in China, and Forest Ecosystem Solutions, Ltd., in Canada.

- The authors model forest carbon flows over a 400-year time horizon, in living trees and in wood products, for three forest management scenarios: 1) no-harvest, where a forest stand remains standing until natural disturbance, 2) harvest at age of maximum mean annual increment (MAI), and 3) harvest at age after maximum MAI but before the occurrence of a natural disturbance.
- Two forest models are used: FORECAST, a management-oriented stand-level forest growth simulator, and FSOS, a landscape-level model that evaluates the effects of harvesting, silvicultural practices, and natural disturbances. The modeled region is northern British Columbia, Canada.
- On a landscape level, carbon storage in living biomass is highest for the no-harvest scenario. However, total carbon storage, including in living biomass and in wood products, is highest for the harvest scenarios.
- Total carbon storage reaches a dynamic equilibrium after about 150 years, after the wood products stock reaches its maximum level and some wood products begin to reach the end of their service life. The authors consider two different product life spans, 50 years and 100 years. The total equilibrium carbon stock is about 10% lower if the product life span is 50 years instead of 100 years, because the carbon stock in the wood products pool is lower when the product life span is shorter.
- With a 100 year product life span, the total equilibrium carbon storage is about 560 million metric tons for the "harvest after maximum MAI" scenario, about 545 million metric tons for the "harvest at maximum MAI" scenario, and about 440 million metric tons for the "no-harvest" scenario.
- The carbon storage is more stable in the two harvest scenarios than in the no-harvest scenario, because carbon is shifted from the living tree pool to the wood products pool. In the no-harvest scenario, carbon accumulated in living trees is lost to the atmosphere due to natural disturbances, resulting in greater fluctuations in carbon stock.
- The authors conclude that long-term, stable carbon storage can be achieved by a combination of improved forest management and efficient transfer of carbon into wood products.
- The authors do not include substitution benefits of wood product use, though they state that "we believe that it is necessary to account for the carbon emissions associated with the manufacturing and use of other materials such as steel, aluminium, and concrete." If such substitution benefits were included in the analysis, the carbon differences between the harvest and no-harvest scenarios would be even greater.

38 Marcea, R.L. and Lau, K.K. 1992. **Carbon dioxide implications of building materials.** International Journal of Forest Engineering, 3(2): 37-43. http://www.lib.unb.ca/Texts/JFE/backissues/pdf/vol3-2/marcea.pdf

- Conclusion: In an early comparison of different building types made with wood, steel, brick, aluminum and concrete, the production of wood buildings is consistently found to use less energy and have lower CO_2 emissions.
- The authors are from MacMillan Bloedel Research, in Canada.
- The authors analyze two different buildings, each designed in several variations with differing quantities of wood vs. other materials. One building is a 215 m^2 two-storey, single-family house, designed predominantly with either wood, brick, aluminum or concrete material. The second building is an 11,000 m^2 industrial building designed with either a wood or steel structure. The comparison between the wood and steel versions of the industrial building is not exact, but the authors suggest it is accurate to within ± 5%.

- The authors calculate the energy used to manufacture the materials in each building type, based on data on US industries. The paper contains a table with specific energy requirements for producing a variety of materials.
- The analysis is limited to energy and cement process emissions from manufacturing and assembling the materials. Energy for producing replacement materials during a 50-year service life is also included. Forest-related and end-of-life energy use and carbon flows are not included.
- The authors calculate a mixture of energy sources used for manufacturing each material, and then calculate carbon emissions from producing each material. Electricity used for material production is assumed to come from a mix of hydro, nuclear, coal-, oil- and natural gas-fired sources.
- For the residential building, the wood version used the least energy and emitted the least carbon dioxide. The brick version emitted 1.9 times more, the concrete version emitted 1.4 times more, and the aluminum version emitted 1.3 times more carbon dioxide than the wood version.
- For the industrial building, the steel version used 2.8 times more energy and emitted 3.1 times more carbon dioxide than the wood version.

39 Oneill, E.E. and Lippke, B.R. 2010. **Integrating products, emission offsets, and wildfire into carbon assessments of Inland Northwest forests.** Wood and Fiber Science, 42(CORRIM Special Issue): 144-164. http://www.corrim.org/pubs/index.asp

- Conclusion: Active management of forest land, and use of forest biomass in long-lived products, results in reduced net carbon emissions. Carbon stored in forests is vulnerable to loss due to wildfire, and can be secured and leveraged into greater net carbon emission reductions by harvesting the trees and using them for wood products.
- The authors are from the University of Washington, in the USA.
- This is a landscape-level analysis of Inland Northwest forests in the states of Idaho, Montana and eastern Washington. A 100-year time horizon is considered. Distinction is made between national forests (63% of total) and state- and privately-owned forests (37% of total), due to their different management objectives.
- Four carbon pools are tracked over time for each scenario: forest biomass, wood products, displacement of fossil fuel emissions due to biofuel use, and reduced emissions due to substituting wood in place of GHG-intensive non-wood products.
- The authors consider the effects of natural disturbances such as wildfire and insect outbreaks, which play an important role in the carbon dynamics of forests in the region. In particular, the suppression of wildfires during the past century has led to a change in forest structure, making them particularly vulnerable to wildfire and consequent loss of stored carbon to the atmosphere.
- The authors employ two forest management scenarios: base case, which describes current management intensities and harvest rates for all owner groups, and alternate case, which increases the management intensity on state and private forests and extends thinning treatments to a greater area of national forest.
- The authors used a material substitution displacement factor of 2.0 metric tons of fossil carbon emission reduction per tonne of carbon in long- and medium-lived wood products (based on the present report, 1st edition). Short-lived products such as chips and pulp and paper were assumed to decompose rapidly without substitution benefits.

- Results from state and private forests under base case management show an increase in average carbon stock in forest biomass from 44 t/ha at the beginning of the study period to 74 t/ha after 100 years. This increase, however, is minor compared to the increase in material substitution benefits and wood product carbon stock. The total in all carbon pools at the end of the 100 year period is 294 t/ha of avoided carbon emission. The continuous shift of carbon from living biomass to wood products results in an average emission reduction of 2.3 t/ha-yr over the 100 year period.
- State and private forests under the alternate case management show a slightly lower increase in average carbon stock in forest biomass, but a higher total average emission reduction over the 100 year period of 2.5 t/ha-yr.
- Results from national forests show that increasing the thinning activities leads to reduced net carbon emissions, mainly due to reduced wildfire loss and to a lesser extent due to increased production and use of long-lived forest products.
- The authors do not consider soil carbon stock changes, arguing that normal forest management actions have minimal impact on average soil carbon stock. They point out, however, that severe wildfires can reduce soil carbon by 25%, thus reducing wildfires may have a greater carbon impact than the results indicate.
- The authors conclude that net carbon emissions can be reduced, under both current and future climate conditions, by managing forests to maximize long-lived wood products and by minimizing the risk of severe wildfires. Relying on the forest solely as a carbon sink (i.e. biological carbon sequestration) would be less effective at reducing carbon emissions, and would carry the risk of significant carbon emissions due to wildfire.

40 Perez-Garcia, J., Lippke, B., Comnick, J. and Manriquez, C. 2005. **An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results.** Wood and Fiber Science, 37(CORRIM Special Issue): 140-148. http://www.corrim.org/reports/2005/swst/140.pdf

- Conclusion: In a study of the carbon dynamics of forests, wood products, and material and energy substitution, the system-wide net carbon emission is lowest when forests are managed more intensively. Although shorter harvest rotations reduce average carbon stock in forests, this reduction is more than compensated for by increased carbon storage in wood products, and by decreased emissions from avoided non-wood products.
- The authors are from the University of Washington, USA.
- The authors model the carbon dynamics associated with forest growth, wood product use, and material and energy substitution. The time horizon of the analysis is 165 years.
- Forest conditions are specific to the Pacific Northwest regions of the USA. Forest modeling accounts for growth, mortality and decomposition. Four management regimes of varying intensity are modeled, with harvest rotation periods of 45, 80 and 120 years as well as a no-harvest scenario.
- Quantities of biomass harvested from the forest are inputs for a forest products model. Current data on forest products industries (see #5) are used to determine product yield and energy flows. Comparative data on wood vs. non-wood building construction were used to estimate the effects of material substitution on net carbon flows, taking into account avoided emissions of fossil carbon when less energy-intensive materials are used.
- The results of the forest modeling show that increasing the harvest frequency reduces the average carbon stock in the forests. In the no-harvest scenario, carbon stock increases asymptotically (assuming no natural disturbance).

- When product use is considered, the results are reversed. As the rotation period length increases, the total system-wide carbon emission increases. This is because shorter harvest cycles produce more wood products, thereby reducing the use of fossil fuel-intensive non-wood products.
- The decreased carbon storage in forests is more than compensated for by increased carbon storage in wood products, and by decreased emissions from avoided non-wood products. Intensifying forest management creates "positive carbon leakage" through greater use of wood products in the market place.
- The authors observe that meaningful analyses of the carbon emission impacts of forestry must extend beyond the forest land itself, and include the impacts of the usage of forest products.

41 Petersen, A.K. and 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. http://dx.doi.org/10.1016/S1462-9011(01)00044-2

- Conclusion: In a study comparing energy use, GHG emission and costs for roof beams made of steel and glue-laminated wood, manufacturing steel beams is found to use two to three times more energy and six to twelve times more fossil fuels than manufacturing glulam beams. In the "most likely scenario," steel beam manufacturing causes five times more GHG emission than manufacture of glulam beams. The post-use management of the wood beams has a significant effect on life cycle GHG emissions: burning the wood to substitute fossil fuels significantly decreases net GHG emissions, and landfilling results in increased GHG (methane) emissions. The authors calculate that 0.24 to 0.31 metric tons CO_{2eq} emission is likely to be avoided per m^3 of sawn wood used to make glulam beams.
- The authors are from the Agricultural University of Norway.
- The paper is a case-study of the roof structure of a new airport constructed in Oslo, Norway. Two options are compared: steel beams and glue-laminated spruce wood beams. The functional unit is 1 m^2 of roof.
- A number of alternative scenarios are compared to determine a range of uncertainties in the calculations. The base case assumes that: steel beams are manufactured from a mix of scrap and ore; electricity for steel production comes from hydropower; wooden beams at the end of their service life are burned to substitute current average Norwegian energy supply (70% hydropower and 30% oil); steel beams at the end of their service life are recycled to substitute scrap.
- The authors calculate a "discounted global warming potential" that gives different importance to GHG emissions that occur at different times. The discount rates used by the authors range from 0% to 8%. The 0% discount rate corresponds to the commonly used assumption that all emissions have equal weight independent of when they occur. The higher the discount rate, the less weight is given to emissions occurring in the future.
- The global warming analysis includes emissions of CO_2, CH_4, and N_2O, converted to CO_2 equivalents.
- The energy and GHG emission calculations are limited to the manufacture and disposal of the beams. The authors assume that energy and emissions from construction, use and demolition of the roof structures are the same for steel and glulam beams, hence these life cycle phases are not included.

- Manufacture of the glulam beams requires 140 kWh of energy per functional unit (1 m^2 of roof), of which 32 is fossil fuel, 16 is electricity, and 92 is bioenergy. Manufacture of the steel beams requires 279 kWh of energy per m^2 of roof, of which 201 is fossil fuel and 78 is electricity. If the steel beams are made of primary steel from ore (rather than recycled steel as assumed in the base scenario), their manufacture requires 455 kWh of energy.
- If the wooden beams are burned at the end of their service life, more energy can be recovered than was used to manufacture the beams.
- In the base scenario, using wooden beams instead of steel beams reduces life cycle GHG emission by 57 kg CO_{2eq} per m^2 of roof. This figure varies slightly in alternate scenarios, but is generally positive (i.e., wooden beams cause lower GHG emissions than steel beams).
- However, landfilling of wooden beams at the end of their service life is calculated to cause methane emissions that result in greater GHG emissions than the steel beams. The authors use landfill decomposition data from Norwegian Pollution Control Authorities, which assume exponential decay with a half-life of 11 years.
- Per m^3 of sawn wood used for manufacture of glulam beams, the GHG emission reduction from using wood instead of steel beams is 0.312 metric ton CO_{2eq}, in the base scenario.
- One alternative scenario that the authors consider is to expand the system boundaries to include the regeneration of the forest harvested to make the beams. This results in a significant reduction in net GHG emission. However, such a system expansion should have also considered the GHG balance effects of the initial harvest, not only the post-harvest regeneration.
- The cost of the glulam wooden beams is estimated to be slightly lower than the cost of the steel beams.
- Using discount rates greater than zero result in less significance placed on future emissions, thus the various alternatives for end-of-service-life management of the beams become less important.
- The authors used a value of 550 kg/m^3 for the dry density of spruce wood, which appears to be excessively high. The significance of this parameter value on the study results is unclear.

42 Petersen, A.K. and 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. http://dx.doi.org/10.1139/x03-020

- Conclusion: This study compares energy use, GHG emission and costs for flooring made of natural stone and solid oak wood, using methodology similar to the same authors' 2002 article. Manufacturing the wooden floor requires 1.6 times more energy, but produced only one-third of the GHG emission, compared to manufacturing the stone floor. The post-use management of the wood flooring material has a great effect on life cycle GHG emissions: burning the wood to substitute fossil fuels significantly decreases net GHG emissions, and landfilling results in increased GHG (methane) emissions. The authors calculate that 0.4 metric tons CO_{2eq} emission is likely to be avoided per m^3 of wood materials in the wooden floor.
- The authors are from the Agricultural University of Norway.
- The analytical methodology is virtually identical to the same authors' 2002 article comparing wood and steel roof beams.

- The wooden floor is made of 0.02 m thick solid oak boards, on top of 0.036 m thick plywood. The stone flood is natural stone (thickness not specified) set in cement mortar. The floors are assumed to be placed on identical underlay materials, which are not included in the analysis. The life span of the floors is assumed to be 45 years.
- The monetary cost of the two floors is considered to be nearly identical.
- Manufacture of the wood flooring requires 79 kWh of energy per functional unit (1 m^2 of floor), of which 30 is fossil fuel, 20 is electricity and 29 is bioenergy. Seventy-four percent of this energy is used to make the plywood; only 12% is used to make the oak floorboards. Manufacture of the stone floor requires 49 kWh of energy per m^2 of floor, of which 36 is fossil fuel and 13 is electricity.
- Manufacture of the wood flooring produces 6 kg CO_{2eq} per m^2 of floor. Manufacture of the stone floor produces 16 kg CO_{2eq} per m^2 of floor, two-thirds of which is due to cement production.
- In the base scenario, using wooden flooring instead of stone flooring reduces life cycle GHG emission by 22 kg CO_{2eq} per m^2 of floor. In alternative scenarios (except when wood is landfilled), the emission reduction ranged from 17 to 71 kg CO_{2eq} per m^2 of floor. If the wood is landfilled it is calculated to produce 47 kg CO_{2eq} more emission per m^2 of floor than the stone flooring.
- Per m^3 of sawn oak wood and plywood used in the wood flooring, the GHG emission reduction from using wood instead of stone is 0.396 t CO_{2eq}, in the base scenario.

43 Petersen, A.K. and 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. http://dx.doi.org/10.1023/B:CLIM.0000024689.70143.79

- Conclusion: This study compares the GHG emission and costs for flooring made of solid oak wood, linoleum, vinyl, polyamide carpet and wool carpet. The methodology is similar to the same authors' 2002 article, with some significant changes. The wood floor results in less life cycle GHG emissions than the other materials. Depending on the material replaced, the authors calculate that 0.5 to 8.4 t CO_{2eq} emission is likely to be avoided per m^3 of wood materials in the wood floor.
- The authors are from the Agricultural University of Norway.
- The analytical methodology is similar to the same authors' 2002 article comparing wood and steel roof beams. Significant differences include assuming no GHG emissions from landfilled materials ("if they are placed in a capped landfill there will be no emissions"), and an alternative scenario with expanded system boundaries to include carbon flows in the forest trees both before and after harvest.
- The analysis is made over an assumed building life span of 45 years. The different flooring materials are placed on identical underlay materials, which are not included in the analysis. The wood floor is made of 0.02m thick solid oak boards, and has a life span of 45 years. The linoleum is assumed to have a life span of either 22.5 or 15 years (i.e., replaced either once or twice during the building's life span). The vinyl is assumed to have a life span of either 22.5 or 9 years. The carpets (polyamide and wool) have assumed life spans of 9 years.
- The monetary cost of the various flooring materials are very different, ranging from 13 Euros/ m^2 for linoleum to 72 Euros/m^2 for oak wood flooring.
- At 0% discount rate, the life cycle GHG emissions for the wood flooring were 10 to 168 kg CO_{2eq} lower per m^2 floor, compared to the other materials. The wool carpeting had the highest GHG emission, due to emissions from raising sheep.

- At higher discount rates, the emission differences among the materials became less. This is because emissions occurring in the future, when the non-wood materials are replaced during the building's life cycle, are given less weighting.
- The authors appear to erroneously consider the landfilling of materials (with assumed zero emission) to be climatically equivalent to burning the materials without energy recovery. However, landfilling under the assumed conditions would result in permanent sequestration of the carbon, while burning the materials would result in the emission of the carbon as CO_2. This apparent error applies to only one scenario in the analysis, and does not affect the general conclusions.
- Per m^3 of sawn oak wood used in the wood flooring, the GHG emission reduction from using wood instead of other materials ranges from 0.5 to 8.4 metric tons CO_{2eq}, in the most likely scenario with 0% discount rate.

44 Petersen, A.K. and Solberg, B. 2005. **Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden.** Forest Policy and Economics, 7(3): 249-259. http://dx.doi.org/10.1016/S1389-9341(03)00063-7

- Conclusion: In a review of 12 Scandinavian studies comparing wood and non-wood products, all the studies found that wood products had lower GHG emissions than other materials. Of nine studies that include sufficient data to allow the calculation of displacement factors, the average GHG emission reduction was 0.66 tC emission avoided per tC in wood products used. Few studies considered the economics of material substitution, but those that did found wood to have similar or lower cost than non-wood material.
- The authors are from the Agricultural University of Norway.
- The authors review 12 studies conducted in Norway or Sweden that analyze the environmental impact of wood product use compared to non-wood product use. The products include building frames, beams, walls, flooring material and railroad ties. All the studies use life cycle analysis methodology, but with varying system boundaries. All the studies include raw material extraction and processing, but the remaining life cycle stages are included in only some of the studies. Some studies consider end-use electricity, while others consider primary energy used to produce electricity. The studies vary in their treatment of end-of-life material management. Thus, the authors note that the results of the studies should not be directly compared with each other.
- All of the studies show that wood has less net GHG emission than the comparable non-wood products, as long as the wood is not landfilled after use. The management of the wood at the end of its service life has a significant impact on the GHG emission.
- The studies show that wood has lower energy consumption, emission of SO2, waste generation and use of non-renewable resources. Preservative-treated wood can have high toxicological impacts.
- Of the 12 studies reviewed, the authors select nine studies that include sufficient data to calculate the GHG emission avoided per m^3 of wood. The calculated displacement factors of the nine studies average 0.66, ranging from a low of -0.88 (due to methane emission from landfilled wood) to a high of 3.02.
- Few of the studies considered the relative economic costs of the wood and non-wood alternatives. The few studies that considered economics found the wood alternatives to have equal or slightly lower costs than the non-wood alternatives. The authors feel that economic analysis should be combined with life cycle environmental analysis, to produce information on material substitution that is more policy-relevant.

45 Pingoud, K. and 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 pg. (in Finnish, summary in English) http://www.vtt.fi/inf/pdf/julkaisut/2000/J840.pdf

- Conclusion: This analysis of the potential for wood substitution in the Finnish construction sector found that the use of wood-based products could increase by almost 70%. Each kg of additional wood product used could result in a 3.6 kg reduction in the use of masonry products and 0.12 kg reduction in metals use. On a national level, this would reduce CO_2 emission by 0.165 Mt C per year due to reduced emissions from material manufacture. The use of associated wood residues to replace fossil fuels could result in a total emission reduction of up to 1.5 Mt C per year.
- The authors are from VTT Technical Research Centre of Finland.
- The authors compared the total amount of new building construction in Finland in 1990 to a scenario in which the same buildings were built in a way that maximized wood use. The total amount of materials actually used in 1990 in 11 main building elements in nine building types was estimated. The commercial potential (less than or equal to the technical potential) for increasing wood use in each building element was then assessed.
- The results show that the use of wood-based products could have increased by almost 70% over the actual amount. The carbon stock in wood products would have been 0.37 Mt C larger. An additional 1.5 Mt C forest biomass would have to be harvested to provide the raw materials.
- Per kg of additional wood material used, there would be a reduction in use of 3.6 kg of concrete, bricks and tiles, 0.12 kg of metals, and 0.005 kg of other materials.
- The primary energy used for material production would decrease from 8.8 TWh to 7.7 TWh. The CO_2 emission from fossil fuel use and process emissions would decrease by 0.165 Mt C.
- Additional amounts of biofuel would be produced in association with the additional production of wood construction materials. If this biofuel were used to replace light fuel oil, 0.24 Mt C of fossil carbon emission would be avoided. If all above-ground wood biomass were used as biofuel, including wood products after demolition, 1.5 Mt C of fossil carbon emission could be avoided.
- The analysis was also conducted using data for construction in 1994. Total building construction was lower in 1994 than in 1990, but the proportional results were very similar to those of 1990.
- The authors estimate the total carbon stock of wood products in Finland in 1995 to have been 16.5 Mt C. About one-third of the total stock was in detached houses. The carbon stock in wood products was approximately 2.4% of the carbon stock in Finnish forest biomass.

46 Pingoud, K., Pohjola, J. and Valsta, L. 2010. **Assessing the integrated climatic impacts of forestry and wood products.** Silva Fennica, 44(1): 155-175. www.metla.fi/silvafennica/full/sf44/sf441155.pdf

- Conclusion: In a steady-state analysis of forest management and wood use alternatives, maximizing the total annual biomass production does not necessarily give the highest substitution benefits. Managing forests for high sawlog production results in more avoided fossil emissions. Lengthening the rotation and increasing the density generally resulted in higher carbon stocks in forests and in wood products, and also resulted in lower annual fossil emissions due to greater biomass substitution.

- The authors are from the VTT Technical Research Center and the University of Helsinki, in Finland.
- The analysis assumes steady-state conditions in both the forest, where growth equals removals, and also the wood products pool, where new input equals old output. The forest model thus covers the landscape level rather than individual stands; the authors assume the forest area "is composed of even-age, fully-stocked stands representing a balance of age classes, such that for a specified rotation period, one age class can be harvested in each year."
- The authors emphasize their use of "marginal" fossil carbon displacement factor, describing the fossil emission reduction per additional unit of biomass used. This is the same interpretation of displacement factor used by other authors, though Pingoud *et al*. are correct in their emphasis on marginal change. Systemic changes may yield different results.
- The forest modeling includes single-species stands of Scots pine and Norway spruce, managed with varying rotation lengths and thinning intensities. Modeling was done with the MOTTI simulator, which uses individual-tree, distance-independent growth models.
- The biomass supply is broken down into sawlogs, pulpwood, and energy wood. Sawlogs are assumed to replace non-wood construction materials. Marginal changes in pulpwood production is assumed used for bioenergy. Energy wood, which includes logging and processing residues, is used to substitute either coal or natural gas.
- For each management scenario, two climate effects are calculated: 1) the steady-state carbon stocks in forest biomass and wood products, and 2) the substitution benefits of wood product use. Soil carbon stocks are not considered.
- Results varied by species and by management intensity, but in general lengthening the rotation and increasing the density resulted in higher carbon stocks in forests and in wood products, and also gives lower annual fossil emissions due to greater biomass substitution.
- The authors find that maximizing total annual biomass production does not necessarily give the highest substitution benefits. Rather, managing forests for high sawlog production results in more avoided fossil emissions.
- The study assumes various steady-state conditions, but does not analyze how to shift toward these conditions. The authors briefly discuss this issue and its implications.

47 Reid, H., Huq, S., Inkinen, A., MacGregor, J., Macqueen, D., Mayers, J., Murray, L. and Tipper, R. 2004. **Using wood products to mitigate climate change: A review of evidence and key issues for sustainable development.** International Institute for Environment and Development, London. 90 pg. http://www.iied.org/pubs/pdfs/10001IIED.pdf

- Conclusion: This report discusses the potential contributions of wood products to climate change mitigation efforts as well as to sustainable development as a whole. The role of forests in the global carbon cycle is described, and forest sector strategies for CO_2 emission reduction are outlined. The environmental, economic and social benefits of sustainable forest management are described, as are the challenges to its effective implementation.
- The authors are from the International Institute for Environment and Development, and the Edinburgh Centre for Carbon Management, in the UK.

- This is a multi-disciplinary analysis of the use of wood products for climate change mitigation. It includes an overview of the role of forests in the global carbon cycle, and discusses potential strategies for using forests for climate change mitigation. These include reducing deforestation to preserve existing carbon stocks in forests, increasing forest area to sequester additional carbon, and storing additional carbon in wood products. The authors review trends in wood markets, on global and European levels. They also discuss wood products in the context of broader concerns about sustainable development, and the role of sustainable forest management in terms of economic, social and environmental sustainability.
- The authors discuss barriers to more widespread use of wood instead of other materials, such as perceived issues with fire safety and durability, and the lack of knowledge and experience of architects and builders about wood engineering and construction.
- Chapter 4 is of particular interest to the present review. This chapter discusses the comparative GHG impacts of wood and non-wood materials. The authors briefly review six life cycle assessments of wood products, most of which were conducted in European countries.
- The authors present data on the CO_{2eq} emissions associated with a range of building materials, such as concrete, bricks, sawn lumber and particleboard, expressed per kg and per m^3 of material. They also present similar emission data on various packaging materials, such as cardboard, glass, plastics, steel and aluminum, expressed per kg of material. The wood-based materials are seen to have significantly lower GHG emission than the non-wood materials. Unfortunately, the authors do not relate the data to comparable functional units, so no results-oriented conclusions can be drawn from the data. Indeed, the authors fail to mention that data on GHG emission per unit mass or volume is insufficient to compare the relative impacts of different materials, because often different amounts of each material will be required to fulfill the same function.
- The authors state that each m^3 of wood substituted in place of other materials reduces CO_2 emissions by an average of 0.8 t CO_2. The article[3] from which this figure comes provides no supporting data, and cites no sources for the information.

48 Salazar, J. and 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. http://dx.doi.org/10.1016/j.jclepro.2009.06.006

- Conclusion: In a comparison of two houses, one conventionally built and one with increased use of wood-based components, the wood house has significantly lower life cycle carbon emissions. End-of-life energy recovery from wood materials further improves the performance of the wood house.
- The authors are from the Athena Sustainable Materials Institute, in Canada.
- Two houses are compared: a reference house using typical Canadian construction practices and materials, and a wood-intensive house using wood shakes, window frames, cladding, and cellulose insulation. The houses are assumed to be in Ottawa, and have a 100 year service life. The Athena Institute’s Impact Estimator (v4.0) and LCI data are used for the analysis.
- Carbon accounting includes three sub-systems: carbon flows associated with forest growth, industrial carbon flows from production and maintenance, and end-of-life carbon flows.

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[3] Dargnies-Peirce, C. 2003. Industry: Using wood to tackle climate change. *Enterprise Europe*, (11): 10-11. http://europa.eu.int/comm/enterprise/library/enterprise-europe/issue11/articles/en/enterprise07_en.htm

- The authors argue that due to natural forest disturbances such as fires and insects, harvesting of trees for use as wood products acts to preserve stored carbon that otherwise would have been released naturally to the atmosphere.
- The authors 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.
- At the end of the houses' service life, the wooden material is assumed to either be placed in a landfill with methane capture, or burned to replace coal and natural gas for marginal electricity production.
- The wood-intensive house used 25.1 tons of forest products, while the reference house used only 11.6 tons of forest products. 40% of the wood used in the wood-intensive house is replacement products used to maintain the house during its service life.
- Manufacturing the wood-intensive house used 52% fewer fossil fuels, and emitted 33% fewer greenhouse gases, than manufacturing the reference house.
- If the post-use materials are landfilled, the end-of-life emissions are greater for the wood-intensive house. If the wood materials are recovered and incinerated, the end-of-life emissions are lower for the wood-intensive building.
- Considering the total building life cycle, if the post-use materials are landfilled the reference house emits 72.0 tons of CO_{2eq} and the wood-intensive house emits 20.2 t CO_{2eq}. If post-use wood is recovered, the reference house emits 63.4 tons of CO_{2eq} and the wood-intensive house has a net avoided emission of 5.2 t CO_{2eq}.

49 Salazar, J. and 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. http://dx.doi.org/10.1080/02827580801906981

- Conclusion: A window frame made of aluminum-clad wood produces fewer GHG emissions than frames made of polyvinyl chloride (PVC) or fiberglass. The aluminum-clad wood frame also compares well in other non-climate impact categories.
- The authors are from the University of British Columbia, in Canada.
- The authors conduct a life cycle assessment comparing residential window frames made of aluminum-clad wood, polyvinyl chloride (PVC) and fiberglass frames. Site-specific data were gathered on material flows and energy inputs during the manufacturing of each window type. Sima Pro and IMPACT software were used for the analysis.
- The LCA results in the global warming impact category show that the aluminum-clad wood window frame produces 341 kg CO_{2eq}, the fiberglass frame produces 357 kg CO_{2eq}, and the PVC frame produces 456 kg CO_{2eq}.
- Carbon storage in the wood material is not considered in the LCA results, but is discussed by the authors. They note that 13 kg is stored during the service life of the window frame, some of which is stored indefinitely if the post-use product is landfilled. Other post-use material fates are not discussed.
- The aluminum-clad wood frame ranks better or equal than the PVC and fiberglass frames in most non-climate impact categories, including human health damage, ecosystem damage, and resource damage. The aluminum-clad wood frame has a higher level of aquatic toxicity, however, presumably due to aluminium production.

50 Sathre, R. 2007. **Life cycle energy and carbon implications of wood-based materials and construction.** Ph.D. Dissertation, Ecotechnology and Environmental Sciences, Mid Sweden University, Östersund. 102 pg. http://urn.kb.se/resolve?urn=urn:nbn:se:miun:diva-50

- Conclusion: In this dissertation, a methodology is developed to compare the life cycle energy use and carbon emission associated with wood and non-wood construction. Two case-study multi-storey apartment buildings are analyzed. Significantly less energy is used, and less CO_2 is emitted, over the life cycle of the wood materials. The most important single factor affecting the energy and carbon balances is the use of biomass by-products from the wood product chain as biofuel to replace fossil fuels. Carbon stock changes in forests and wood materials are less significant over the building life cycle and forest rotation period. In the long term, the active and sustainable management of forests, including their use as a source for wood products and biofuels, allows the greatest potential for reducing net CO_2 emission.
- The author is from Mid Sweden University in Östersund, Sweden.
- The author analyzes the mechanisms by which wood product substitution can affect energy and carbon balances. These include: the energy needed to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emission from e.g., cement manufacture; the use of wood by-products as biofuel to replace fossil fuels; and the physical storage of carbon in forests and wood materials.
- The author develops a methodological framework by integrating knowledge from the fields of forestry, industry, construction and energy. A life cycle perspective is employed encompassing the entire product chain from natural resource acquisition to material disposal or re-use. Analytical challenges that are addressed include the functional unit of comparison, the fossil reference system, land use issues of wood vs. non-wood materials, and the diverse phases of the product life cycle. The methodology is then applied to two multi-storey wood-frame buildings in Sweden and Finland, compared with two functionally equivalent buildings with reinforced concrete structural frames.
- The results show that less primary energy is needed to produce the wood-frame buildings than the concrete-frame buildings. CO_2 emission is significantly lower for the wood-frame buildings, due to reductions in both fossil fuel use and cement calcination process emission.
- The most important single factor affecting the energy and carbon balances is the use of biomass by-products from the wood product chain as biofuel to replace fossil fuels. Over the life cycle of the wood-frame buildings, the energy of biomass residues from forest operations, wood processing, construction and demolition is greater than the energy inputs to produce the materials in the buildings. Realisation of this benefit is facilitated by integrating and optimising the biomass and energy flows within the forestry, industrial, construction, energy, and waste management sectors.
- The author studies different forest management regimes in an integrated carbon analysis to quantify the carbon flows and stocks associated with tree biomass, soils, and forest products. Intensified forest management that produces greater quantities of biomass leads to net CO_2 emission benefits by augmenting the potential to substitute for fossil fuels and non-wood materials. The increased energy use and carbon emission required for the more intensive forest management, as well as the slight reduction in soil carbon accumulation due to greater removal of forest residues, are more than compensated for by the emission reduction due to product substitution.
- Carbon stock changes in forests and wood materials can be temporarily significant, but over the building life cycle and forest rotation period the stock change becomes insignificant. The author finds that in the long term, the active and sustainable management of forests, including their use as a source for wood products and biofuels, allows the greatest potential for reducing net CO_2 emission.

- The author also studies implementation issues related to the wider use of wood-based materials to reduce energy use and carbon emission. An analysis of the effects of energy and taxation costs on the economic competitiveness of materials shows that the cost of energy for material processing, as a percentage of the total cost of finished material, is lower for wood products than for other common non-wood building materials. Energy consumption and carbon taxation affect the cost of wood products less than other materials. The economic benefit of using biomass residues to substitute for fossil fuels also increases as tax rates increase. In general, higher taxation of fossil fuels and carbon emission increases the economic competitiveness of wood construction.
- An analysis of added value in forest product industries shows that greater economic value is added in the production of structural building materials than in other uses of forest biomass. Co-production of multiple wood-based products increases the total value that is added to the biomass produced on an area of forest land. The results show that production of wood-based building material is favoured economically by climate change mitigation policies, and creates high added value within forest product industries.

51 Scharai-Rad, M. and Welling, J. 2002. **Environmental and energy balances of wood products and substitutes.** Food and Agricultural Organization of the United Nations. 70 pg. http://www.fao.org/docrep/004/Y3609E/y3609e00.htm.

Summarized in: Frühwald, A., Welling, J. and Scharai-Rad, M. 2003. Comparison of wood products and major substitutes with respect to environmental and energy balances. Paper presented at seminar, Strategies for the Sound Use of Wood, 24-27 March, Poiana Brasov, Romania. 10 pg.

- Conclusion: In a series of life cycle assessments of buildings and building components made of wood and non-wood materials, production of the wood alternatives consistently used less energy and emitted less GHG than non-wood materials. The recovery of energy from demolition wood at the end of the product life cycle further improved the energy and GHG performance of the wood alternatives. Wood also generally performed better on other environmental impact indices (acidification, eutrophication and photochemical ozone creation).
- The authors are from the Federal Research Centre for Forestry and Forest Products, Germany.
- The authors compare the environmental impacts of several buildings and building components made of wood and non-wood materials. In each comparison, they analyze two cases: one restricted to the impacts resulting from the construction of the building or component, and another that takes into account the energy content of the wood-based materials at the end of their service life. The recovered energy in the demolition material is assumed to replace fossil fuel. The thermal performance of the buildings is assumed to be identical regardless of the construction material, so the energy used in the operation phase is disregarded. The method used to calculate GHG impacts appears to not explicitly consider the carbon dynamics in forests and wood products.
- The first comparison is between three single-family houses: one made of brick, one with a wood frame but containing substantial amounts of non-wood materials, and another built predominantly with wood materials. Production of the brick house uses 41.1 MWh of energy, and the two wood houses each use 34.25 MWh. Without considering the energy recovery in the demolition wood, the GWP of the brick, mixed content and wood dominant houses are 115.0, 94.9, and 96.3 t CO_{2eq}, respectively. When demolition wood is used to replace fossil fuels, the GWP of the three houses are 108.4, 79.3, and 53.0 t CO_{2eq}. The house with the highest wood content has the lowest GWP in a life cycle perspective, due to the relatively low emissions during construction and the high potential for substituting fossil fuels with the demolition wood.

- The second comparison is between two unspecified multi-storey buildings, one with a steel frame and one with a wood and steel frame. Production of the steel frame uses 17,000 GJ of energy. Production of the wood/steel frame uses 5,460 GJ, but 12,750 GJ of energy can be recovered from the demolition wood, resulting in a life cycle energy surplus of 7,290 GJ. Without considering the energy recovery in the demolition wood, the GWP of the steel and wood/steel frames are 3,410 and 1,096 t CO_{2eq}, respectively. When demolition wood is used to replace fossil fuels, the GWP of the frames are 3,410 and -1,463 t CO_{2eq}. The GWP of the wood/steel frame is negative because more fossil emissions can be avoided by recovery of energy from the demolition wood than are emitted during production of the frame.

- The third comparison is between three warehouses made of wood, steel and concrete. Life cycle energy use (including operation energy) is 5,330, 6,580, and 8,000 GJ for the wood, steel and concrete warehouses, respectively. 3,400 GJ of energy can be recovered from the demolition wood of the wood-framed building. Without considering the energy recovery in the demolition wood, the GWP of the wood, steel and concrete warehouses are 1,030, 1,320, and 1,600 t CO_{2eq}, respectively. When demolition wood is used to replace fossil fuels, the GWP of the concrete and steel buildings are unchanged, but the impact of the wood warehouse reduces to 829 t CO_{2eq}.

- The fourth comparison is between window frames made of wood, PVC and aluminum. The glass is identical in the three frame types, and is not included in the analysis. The energy used for production is 19.8, 20.8, and 26.6 GJ for the wood, PVC and aluminum frames, respectively. Over a quarter of the energy used to produce the wooden frame comes from renewable sources. Without considering the energy recovery in the demolition wood, the GWP of the frames are 906, 997 and 1,090 kg CO_{2eq}, respectively.

- The buildings and components made of wood, in addition to having lower energy use and GWP than the non-wood alternatives, also generally had lower impacts in the other categories (acidification, eutrophication and photochemical ozone creation). The authors conclude that wood is generally a more environmentally benign building material than common non-wood alternatives.

52 Schlamadinger, B. and Marland, G. 1996. **The role of forest and bioenergy strategies in the global carbon cycle.** Biomass and Bioenergy, 10(5-6): 275-300. http://dx.doi.org/10.1016/0961-9534(9)00113-1

- Conclusion: In a theoretical analysis of system-wide carbon flows associated with biomass production and use, the avoided carbon emissions due to fuel and material substitutions dominate over carbon storage in biomass and products in the long term. Carbon stocks eventually reach equilibrium, but substitution benefits are continuing and cumulative. The displacement factor, or avoided emissions per unit of wood use, is an important parameter in carbon mitigation efficiency of the biomass system.

- The authors are from Joanneum Research in Austria, and Oak Ridge National Laboratory in the USA.

- This study provides a strong theoretical foundation for understanding the carbon dynamics of wood product substitution. The authors describe modeling exercises that track carbon in the atmosphere, forest biomass, forest soils, wood products and fossil fuels. They create 16 land use scenarios, and run the scenarios over a 100-year period to determine the net effect on atmospheric carbon.

- The model uses numerical parameters to define the characteristics and interactions of the various carbon stocks and flows. The focus of the study is to clarify the dynamic relationships of carbon flows, and the authors acknowledge that the numerical value of some of the parameters may be inaccurate.

- The authors define a displacement factor for products as "the amount of fossil C not oxidized because wood products are used instead of products from other, more energy intensive materials like concrete and steel." For a base case and a high efficiency case, respectively, the authors assume displacement factors of 0.5 and 1.0 for long-lived products, and 0.25 and 0.5 for short-lived products. They defined another displacement factor for biofuels that directly substitute for of fossil fuels, with assumed values of 0.6 and 1.0 in the base case and a high efficiency case, respectively. They assume that energy is recovered from 15% and 30% of wood products at the end of their service life. The displacement factors used by the authors should be compared to those calculated in the present review and listed in Table 2 (page 107). Note, however, that some of the displacement factors in Table 2 include the benefits of post-use energy recovery, and also include avoided cement process emissions and other wider system benefits.
- The authors find that in all scenarios, over long time periods the carbon balance is dominated by the use of biomass to substitute fossil fuels and carbon-intensive products. The carbon pools in trees, soil, and wood products eventually reach equilibrium, and then provide no further sequestration over time.
- The efficiency with which wood product use results in reduced fossil emissions is a very important factor in the overall climate change mitigation performance of the scenarios. The authors say, "It may be that the energy displacement factor, over time, dominates the amount of carbon stored in the wood products and the C benefit of wood products will be very much larger that the C physically contained in the materials." The displacement factors listed in Table 2, with an average value of 2.1, suggest that this is the case.
- The initial condition of the land makes a significant difference to the net carbon benefits of the land use activities. Whether the land had been a primary or secondary forest, or had previously been cleared for agriculture, affects the pre-existing carbon stock in soil and biomass that may be affected by the land use. Eventually the carbon benefits of fuel and material substitution will outweigh the carbon stock changes, but this may take ~100 years.

53 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. http://dx.doi.org/10.1023/A:1022833227481

- Conclusion: This paper reviews earlier studies of wood substitution benefits, and calculates that converting from wood utility poles to steel poles in the US would cause an increased emission of 163 Tg CO_{2eq}. Of this amount, 100 Tg is due to the increased emission of producing steel poles instead of wooden poles, and 63 Tg is due to the release of carbon currently stored in wooden poles.
- The author is from Resources for the Future, Washington DC, USA.
- The paper begins with a review of several previous studies that examined the GHG impacts of using wood products.
- The author then describes in detail the study of Künniger and Richter (1995) (#32) on the GHG benefits of using wood instead of steel or concrete utility poles. He then uses these data in a case-study of utility poles in the USA. Based on an estimate of 2.9 million linear kilometers of utility pole lines in the US, and Künniger and Richter's (1995) figure of 34436 kg CO_{2eq} reduction in GHG emission if wood poles are used instead of steel poles, he calculates that US emissions would increase by 100 Tg of CO_{2eq} if all the poles were to be made of steel instead of wood.
- The author also calculates that the carbon stored in all the wooden utility poles in the US is equivalent to 63 Tg CO_2.

- The sum of these two figures is 163 Tg CO_{2eq}, which is about 2.8% of the annual US emission at the time of writing. Thus, the author states that "the conversion from wooden utility poles to steel would result in a small but significant increase in total US emissions."

54 Skog, K. and Nicholson, G. 1998. **Carbon cycling through wood products: The role of wood and paper products in carbon sequestration.** Forest Products Journal, 48(7/8): 75-83.

- Conclusion: This study estimates the use of wood and paper products in the US from 1910 to 2040, and analyzes the fate of the carbon contained in the products. Historical data from 1910 to mid-1960s show a decrease in forest product use, partly due to decreasing fuelwood use. After the mid-1960s it has increased, and is projected to continue increasing to 2040. Significant amounts of carbon are accumulating in landfills, and are expected to remain in long term sequestration. Burning of forest products for energy purposes (including byproducts and post-service-life products) is increasing, while emissions without energy recovery are expected to remain low.
- The authors are from US Forest Service Forest Products Laboratory and Maryland Department of Natural Resources, USA.
- This study tracks carbon in US forest products, from the removal of roundwood from forests, its manufacture into wood and paper products, the storage of C in products in use, and the sequestration in landfills or release to the atmosphere of C in post-use products.
- Historical data from the US Forest Service are used from 1910 to 1986. Projections through 2040 are based on models of the US forest sector, subdivided into various kinds of pulp, paper, lumber and panel products. Net imports to the US market are included, to track the total flows of carbon in forest products in the US.
- The service lives of the various products are assumed to follow a simple exponential decay pattern, expressed by the half-life (the time after which the quantity in service is reduced by half). The estimated half-life ranges from 1 year for some types of paper products, to 100 years for single-family houses built after 1980.
- The fate of landfilled forest products is modeled based on data from Micales and Skog (1997). This study suggests that lignin-containing forest products (e.g., solid wood, newsprint paper) have very limited decomposition in landfills. This results in a high level of long term C sequestration of wood products in landfills. Several other studies have reported somewhat higher levels of decomposition in landfills.
- The authors track the quantities of C released due to the burning of forest products and residues with energy recovery, and the C released due to decay or burning without energy recovery. Unfortunately the system boundaries chosen for the study are limited to the flows of C contained in the forest products. Thus, the overall GHG impact of burning products with energy recovery (including the potential for substituting for fossil fuels, thus reducing fossil C emissions) is not covered by the study.
- The results suggest that in the coming decades, the amount of C stored in forests will decrease due to maturation of some forests, and increased management intensity of other forests. The amount of C stored in products in use will decline slightly, due to the increasing proportion of wood used in paper products, which have a shorter service life than solid wood products. The amount of C sequestered in landfills, and burned for energy, is expected to steadily increase.
- The authors state that "the total drain from the atmosphere to the United States in 1990 was 24 percent of the 1990 U.S. carbon emissions level of 1,367 Tg." However, their

definition of “total drain” does not include emissions due to the combustion or decay of forest products. When this is included, the figure becomes 18% of US emissions in 1990.

55 Suzuki, M. Oka, T. and Okada, K. 1995. **The estimation of energy consumption and CO_2 emission due to housing construction in Japan.** Energy and Buildings, 22(2): 165-169. http://dx.doi.org/10.1016/0378-7788(95)00914-J

- Conclusion: In a comparison of buildings made with wood, reinforced concrete and steel, construction of the wood buildings was found to have substantially lower energy use and CO_2 emissions than the other buildings. However, due to methodological issues (non-equivalent functional unit) the quantitative results of the concrete buildings should not be directly compared with those of the wood and steel buildings.
- The authors are from the Technology Division of Shimizu Corporation and the Faculty of Engineering at Utunomiya University, in Japan.
- The authors used a top-down methodology employing input/output tables of the Japanese economy, broken down into about 400 industrial groups. Based on estimated construction costs for various types of buildings, a Leontief inverse matrix operation was used to estimate the total amount of goods and services that were used directly and indirectly for the construction.
- The buildings compared were two reinforced concrete multi-family apartment buildings, four wood-framed single-family houses, and two steel-framed single-family houses. The wood and steel buildings are all two-storey structures ranging in floor area from 119 to 155 m^2. The concrete buildings, however, are 20- and 12-storey structures with 10,339 and 5,425 m^2 floor area, respectively. Although the authors make their analysis based on a functional unit of 1 m^2 of floor area, the multi-storey concrete apartment buildings are structurally and functionally not equivalent to the two-storey single-family houses built with wood and steel. The results from the concrete building should therefore not be directly compared to those of the other buildings. This issue is not raised by the authors in the article.
- Material costs per m^2 of floor area are 130,000 to 155,000 Yen for the concrete buildings, 95,000 Yen for the steel buildings, and 70,000 Yen for the wooden buildings.
- Energy use for construction of the buildings, per m^2 of floor area, is 8 to 10 GJ for the concrete buildings, 4.5 GJ for the steel buildings, and 3 GJ for the wooden buildings. It is not made clear whether these figures include the feedstock energy value of the wood raw material, or wood processing residues used internally as biofuel. It appears, however, that only purchased energy inputs are included.
- CO_2 emission from construction of the buildings, per m^2 of floor area, is 850 kg CO_2 for the concrete buildings, 400 kg CO_2 for the steel buildings, and 250 kg CO_2 for the wooden buildings. The CO_2 emission calculations appear to include emissions from purchased energy inputs and from cement calcination. No consideration is given to carbon stock changes in materials or forests.
- The authors point out that this analysis only covers the construction of the buildings. They suggest that the analysis should be extended to cover the complete life cycle of the buildings, including the operation phase and considering the life span of the materials.

56 Taverna, R., Hofer, P., Werner, F., Kaufmann, E. and Thürig, E. 2007. **CO_2 effects of the Swiss forestry and timber industry.** In: Environmental Studies No. 0739, Federal Office for the Environment (BAFU), Bern. 102 pg. http://www.bafu.admin.ch/publikationen/publikation/00076/index.html?lang=en.

- See #65, Werner *et al*. (2010)

57 Taylor, J. and van Langenberg, K. 2003. **Review of the environmental impacts of wood compared with alternative products used in the production of furniture.** Project No. PN03.2103, Forest and Wood Products Research and Development Corporation, Australian Government. 16 pg. http://www.timber.org.au/resources/Review%20of%20the%20Environmental%20Impact%20of%20Wood%20Compared%20with%20Alternative%20Products%20Used%20in%20the%20Production%20of%20Furniture%20.pdf.

- Conclusion: In a review of over 20 studies of wood products compared to non-wood materials, the wood products were consistently found to have lower GHG impacts than the other materials. The wood products also generally had better performance in other environmental impact categories.
- The authors are from CSIRO Forestry and Forest Products, Australia.
- The authors review and summarize over 20 studies that compare the environmental performance of wood products to that of non-wood products. Although the focus of the study is the use of wood in furniture manufacture, the authors find few studies specifically comparing wood and non-wood furniture. Therefore, the authors review studies of television cabinets, flooring materials, window frames, building elements and complete buildings.
- In all cases, the performance of the wood products in terms of GHG impacts was better than that of the non-wood products to which they were compared.
- Wood materials also had relatively lower environmental impact than non-wood materials in other categories such as waste generation, toxicity, photochemical ozone, acidification and eutrophication.
- The authors observe that the wood content in furniture results in very low environmental impact, but the presence of other materials like finishes, adhesives, and metal or plastic trim, even in small quantities, can significantly increase the environmental impact of the furniture.

58 Upton, B., Miner, R. and Spinney, M. 2006. **Energy and greenhouse gas impacts of substituting wood products for non-wood alternatives in residential construction in the united states.** Technical Bulletin No. 925. National Council for Air and Stream Improvement. 42 pg. http://www.ncasi.org/Publications/Detail.aspx?id=2923

Summarized in: Upton, B., Miner, R., Spinney, M. and 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. http://dx.doi.org/10.1016/j.biombioe.2007.07.001

- Conclusion: In a national-scale analysis of housing construction in the US with wood frames instead of steel or concrete, building with wood reduces net GHG emission by 9.6 Mt CO_{2eq}/yr and reduces net energy use by 132 PJ/yr. Issues that affect the results include the time horizon of the study, and the fate of the forest land if it is not used for wood production.

- The authors are from the National Council for Air and Stream Improvement and the US Forest Service.
- This study analyzes the national-level energy and GHG effects of building houses with wood-based materials instead of non-wood materials in the US. The authors use data from CORRIM comparing a wood and steel house in Minneapolis, and a wood and concrete house in Atlanta (see #5). The authors expand these case studies of individual houses to a national scale, over a time period of 100 years. To do this, the authors develop models that link the CORRIM data on construction materials in the houses to "upstream" and "downstream" issues. Upstream, the authors consider forest growth dynamics and land use issues. Downstream, they consider disposal of the demolition materials and the resulting GHG emissions.
- The authors assume an annual production of 1.5 million houses each year (the current rate of US housing starts) for the next 100 years. They analyze the energy and GHG effects if the houses were built of concrete and steel framing materials instead of wood. The authors state that about 90% of current US single-family house construction uses wood framing, so in effect the study estimates the increased energy use and GHG emission if non-wood material were used instead.
- The authors track the carbon stock in wood materials, and the amounts of wood entering landfills, by assuming first-order decay with a half-life of 100 years. This half-life is perhaps longer than realistic, but is varied in a sensitivity analysis.
- If non-wood materials are used instead of wood, less forest land will be harvested for wood material production, and the authors consider various options for this "surplus forest." The base assumption is that 20% will be cleared for other purposes ("land use leakage"), and the remaining 80% will grow to maturity. Carbon accumulation in growing forests is estimated based on data specific to forests in the Pacific Northwest US (the source of wood products for the Minneapolis house) and the Southeast US (providing wood product for the Atlanta house). Appendix B of the report gives more details on the methods used to estimate carbon accumulation in forests.
- The authors assume all construction site waste and demolition waste is landfilled. The calculation of carbon sequestration and methane emission due to landfilled wood is modeled assuming that 43% will eventually decay along first-order kinetics. It is assumed that half of the landfill gas is methane, and that the proportion of methane that is captured and burned increases over time as more landfills are equipped with gas collection systems. Appendix A of the report details the methodology and assumptions made regarding landfill carbon dynamics.
- The results show that building with wood instead of steel or concrete provides energy and GHG benefits. Over a 100-year period, building 1.5 million houses annually with wood instead of steel framing reduces net GHG emissions by 636 Mt CO_{2eq}, reduces non-renewable energy use by 18.9 EJ, and reduces total energy use by 17.0 EJ. Over the same period, building with wood instead of concrete framing reduces net GHG emissions by 1,282 Mt CO_{2eq}, reduces non-renewable energy use by 9.7 EJ, and reduces total energy use by 9.5 EJ.
- Assuming half steel framing and half concrete framing, the difference between the wood and non-wood alternatives is 9.6 Mt CO_{2eq}/yr and 132 PJ/yr. This represents about 22% and 27% of the embodied energy and GHG emissions, respectively, of the US residential housing sector.
- Under the base assumptions, the landfilled materials provide a net GHG emission benefit (sequestration minus methane emission) of 190 Mt CO_{2eq} for the steel case-study building, and 58 Mt CO_{2eq} for the concrete case-study building, over a 100-year period. These benefits are likely to decrease over time, as more of the landfilled wood is degraded into CO_2 and methane.

- The assumptions about carbon accumulation in surplus forest have a very significant impact on the results. If the period of analysis is extended from 100 years to 250 years, the GHG benefits of the wood houses increases because the surplus forest reaches maturity and the rate of carbon accumulation decreases. This effect is more pronounced in the comparison against the steel house because of the greater difference in wood content between the wood and non-wood versions. Land-use leakage, the co-production of wood products, and the forest carbon density at saturation level are also important parameters.
- The authors analyze the effects of recovering the construction and demolition debris and using them to replace natural gas, instead of landfilling them. This has no significant effect on the net GHG emission, as the avoided natural gas emissions are balanced by the lack of net carbon sequestration in landfills. The authors point out that if the debris replaced oil or coal instead of natural gas, the avoided emissions would be higher and this would increase the net GHG emission benefits of wood construction. Regardless of the fossil fuel replaced, recovering and burning the residues increased the net energy benefits of wood construction by 13 to 24%.

59 Upton, B., Miner, R., Spinney, M. and 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.

- See #58, Upton *et al.*, 2006.

60 Upton, B., Miner, R. and Vice, K. 2007. **The greenhouse gas and carbon profile of the canadian forest products industry.** Report No. 07-09, National Council for Air and Stream Improvement. 27 pg. http://www.ncasi.org/Publications/Detail.aspx?id=3013

- Conclusion: This report quantifies and discusses the “carbon profile,” or net effect on atmospheric carbon levels, of the Canadian forest sector. The authors distinguish among GHG emissions, carbon sequestration, and avoided GHG emissions associated with the forest products industry. Between 1990 and 2005, it appears that the carbon profile has improved substantially.
- The authors are from the National Council for Air and Stream Improvement (USA).
- The authors provide estimates of the GHG emission, sequestration and avoided emissions in 1990 and in 2005, to help determine trends and opportunities for improvement. Although they provide quantitative data for each of the various factors making up the carbon profile, the authors acknowledge that the data cannot simply be summed up to provide a meaningful value for the overall carbon profile of the sector.
- Emissions from the forest products industry value chain come from four sources: fossil fuel used in industry facilities, fossil fuel used to produce electricity that the industry purchases, fossil fuel used to transport raw material and products, and methane emissions from landfilled forest products. Emission from fossil fuels used in industry facilities (including in secondary processing, which the authors assume use 10% of the fossil fuel and electricity of primary processing) totaled 17.3 Mt CO_{2eq} in 1990, and 10.8 CO_{2eq} in 2005. The largest share of this, and the source of the reduction from 1990 to 2005, is the fuel used in pulp and paper mills. Emissions from net electricity purchases, calculated using province-specific emission factors, increased from 7.7 Mt CO_{2eq} in 1990 to 11.8 Mt CO_{2eq} in 2005. Material transport caused emissions of 2 and 3 Mt CO_{2eq} in 1990 and 2005, respectively.

- The authors calculate landfill methane emissions based on a time series of forest product production, the rates of removal from service of various product types, the fraction of each product type that is landfilled, the degradable fraction of each product type, a linear degradation rate, and a fraction of generated methane that is captured and burned. The parameter values used by the authors are IPCC default values, or based on Canadian research. The authors estimate a landfill emission of 22.7 Mt CO_{2eq} in 1990 and 27.4 Mt CO_{2eq} in 2005, the bulk of which is from post-consumer products in municipal landfills, and a small amount from industry waste.
- Emissions of CO_2 from biomass combustion or decay is not included in the above calculations, but instead is covered in carbon stock change calculations. Decay of biomass into methane (instead of CO_2) is included due to the higher GWP of methane.
- Carbon sequestration takes into account carbon stock changes in forests, in wood products and in landfills. The authors discuss forest carbon stock changes, noting that between 1990 and 2005 the forest has been a carbon sink in most years, and has had net carbon emissions in only five years. The year-to-year variability is due primarily to natural disturbances (e.g., fires and insects), while the effects of harvesting and regrowth are smaller and more consistent.
- The authors track carbon stocks in wood products, using a method based on the IPCC production approach. Thus, they track carbon in products and emissions from products from the standpoint of the country where the wood was harvested (Canada), regardless of where the products are used and disposed. Product stock changes were estimated based on annual production since 1900, and product service life assuming linear decay rates. The authors estimate that carbon stock in products increased by 22.4 Mt CO_{2eq} in 1990, and 39.8 Mt CO_{2eq} in 2005.
- Carbon stock in landfills, estimated using the method described above, is seen to have increased by 36.8 Mt CO_{2eq} in 1990 and by 40.6 Mt CO_{2eq} in 2005. At present, carbon storage in landfills is greater than methane emissions from the same products. In the long term, however, part of the stored carbon will degrade into methane, resulting in a net emission. The authors recommend increasing the capture and burning of methane, and decreasing the flow of degradable material to landfills, to reduce the net GHG impact of landfilled wood products.
- The authors describe three mechanisms by which the forest products industry contributes to avoiding GHG emissions that otherwise would have occurred. These are: using combined heat and power (CHP) systems to reduce electricity demand from external generating plants (assuming forest industries satisfy 40% of their net electricity demand with CHP systems); recycling paper (leading to multiple effects, of which only avoided methane landfill emissions were quantified by the authors); and the use of forest products in place of more carbon-intensive non-wood products. These three mechanisms are estimated to have avoided the emission of 6.3 Mt, 17.3 Mt, and 3.7 Mt CO_{2eq}, respectively, in 2005.
- Although avoided emissions are undoubtedly an important part of the GHG profile of the forest product industries, quantification of the impacts are difficult and imprecise, particularly in terms of defining the baseline from which comparisons are made. Innovations and efficiency improvements are ongoing, not only in the forest industry but in other sectors as well.

61 Valsta, L. 2007. **Sequester or harvest: the optimal use of forests to mitigate climate change.** Report No. 46, Department of Forest Economics, University of Helsinki, Finland. 23 pg. http://www.mm.helsinki.fi/MMEKN/english/research/FECM/Report-46-Valsta.pdf

- Conclusion: The optimal use of forests for climate change mitigation depends on two factors: the GHG benefits obtained by using forest products, and the change in carbon storage in forest ecosystems. GHG benefits are higher when wood is used as a material (e.g., building construction) than when used as biofuel. The economic value of carbon storage depends heavily on the discount rate that is chosen. For typical parameter values applied to managed secondary forests (not old-growth forests), it is climatically advantageous to harvest the forests and use the wood in place of other materials.

- The author is from Department of Forest Economics, University of Helsinki, Finland.
- Based on an economic model that incorporates carbon sequestration benefits, costs of C emissions or avoided emissions, and forestry/timber economics. Solutions are found by numerical optimization, related to management decisions on a forest stand level.
- Underlying question: should more wood be harvested to substitute for other materials and fuels that are more GHG-intensive, or should less wood be harvested so that C storage in forests is increased? The author believes that the answer depends on the relative GHG benefits of using the wood materials, compared to the change in C storage in forests.
- The author assigns economic values to C emissions and storage subsidies (base price is 5.45 Euros per metric ton of C). Costs for forest operations and timber are representative values from Finland. Interest rates ranged from 0% to 5%.
- Tree species are Scots pine and Norway spruce. Pulpwood-sized logs are assumed to be used for bioenergy, sawtimber-sized logs are assumed to be used as construction material.
- The quantity of C emissions avoided by using wood for construction is based on a survey of other studies. A parameter defined as the amount of C emissions avoided per unit of C content in sawlogs was estimated based on these studies, with values ranging from one to three tons C avoided per ton C in sawlogs.
- The results show that the economically optimal management of forests depends on the values of carbon storage and emission reduction. The interest rate chosen has a very significant effect on the value of carbon storage. At higher interest rates (higher value of stored carbon), greater emission reduction per unit of wood is required to warrant harvesting. Using wood as biofuel does not result in sufficient emission reduction to make it worthwhile, at interest rates considered “reasonable” by the author. Using wood for construction material, on the other hand, generally results in emission reduction greater than the value of the C storage changes.
- The parameters used in this study apply to managed, secondary forests, in which harvesting over a regular rotation period does not cause great long term changes in C stock. The results of this study are not necessarily valid in primary, old-growth forest with large accumulated C reserves.

62 Werner, F. and Richter, K. 2007. **Wooden building products in comparative LCA: A literature review.** International Journal of Life Cycle Assessment, 12(7): 470-479. http://www.scientificjournals.com/sj/lca/Abstract/ArtikelId/8968

- Conclusion: In a review of previous life cycle assessments of wood products compared to non-wood materials, the wood products were found to have lower GHG impacts than the other materials. The wood products also generally had better performance in other environmental impact categories besides GHG emissions.
- The authors are from Environment and Development, and Swiss Federal Laboratory for Materials Testing and Research, in Switzerland.
- The authors review and summarize life cycle assessments conducted in the last 20 years that compare the environmental performance of wood products to that of non-wood products. Based on a preliminary review of over 40 assessments, they conduct a more in-depth assessment of 13 studies that are quantitative, transparent and with no obvious

methodological flaws. The studies analyzed a range of wood products including door and window frames, insulation materials, flooring materials, wall construction, railway sleepers, utility poles and complete buildings.

- In all cases but one, the performance of the wood products in terms of GHG impacts was “positive” or “very positive” in relation to the non-wood products to which they were compared. The one case in which wood material was found to have higher GHG impact than other materials was wood flooring, which was assumed to be landfilled after its service life, with high methane emissions.
- Wood materials also had generally favorable performance in other environmental impact categories. In particular, wood products had lower total energy use, lower non-renewable energy use, and lower quantities of solid waste.
- Preservative-treated wood products had relatively high toxicological and/or photosmog impact. Incineration of wood products, while providing a source of biofuel, can cause acidification and eutrophication impact.
- Composite wood products, while making more efficient use of roundwood raw materials, require a relatively higher use of fossil energy than solid wood products. The energy is needed for production of resins and additives, as well as for the processing of wood fibres and manufacture of the finished products.
- The authors observe that the results of comparative life cycle analyses can be very sensitive to allocation procedures used to model recycling or multi-output processes, and to assumptions related to end-of-life scenarios (e.g., landfilling or thermal energy recovery).

63 Werner, F., Taverna, R., Hofer, P. and 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. http://dx.doi.org/10.1051/forest:2005080

- Conclusion: In a scenario analysis of the GHG impacts of increased use of wood products in Switzerland, substitution of wood for non-wood products reduces net GHG emissions. A 30% increase in wood use leads to 0.60 Mt of avoided CO_2 emission per year due to reduced fossil fuel use for material production. An additional reduction of 0.36 Mt of CO_2 emission per year is achieved by using wood residues to substitute fossil fuel. The GHG benefit of increased carbon storage in products becomes less significant over time, as the carbon stock stabilizes while the substitution effects continue to provide cumulative GHG benefits.
- The authors are from Environment and Development, GEO Partner AG, and Swiss Federal Laboratories for Materials Testing and Research, in Switzerland.
- This study analyzes the GHG impacts of an increased use of wood products in Switzerland. The authors develop a scenario in which the use of wood increases by 29.7% between the years 2000 and 2030, and then remains at the elevated level through 2130. Breakdown of wood usage: 38% is used for “construction” work (structural elements, insulation, piles, etc.), 30% for “interior” work (furniture, flooring, wall paneling, etc.), and 32% is processing residues. The authors assume a service life of 80 years for construction wood and 25 years for interior wood. The processing residues, and the wood products at the end of their service life, are used as biofuel to replace fuel oil. Twelve different types of wood products are defined in the scenario, and they are assumed to substitute for non-wood products with the same function and service life.
- Data from LCA studies are used to determine the GHG flows associated with the wood products and the avoided non-wood products and fuels. GHG flows occurring within Switzerland are distinguished from those occurring in other countries, to analyze political

implications of the increased wood use. Changes in carbon stock in the wood products are also tracked over the study period.

- Results show that carbon stock in wood products initially rises as wood use increases, but as the products reach the end of their service life the increased carbon stock diminishes. Eventually (year 2110 in the scenario) equilibrium is reached in which wood quantities entering service equal wood quantities leaving service. The total stock of carbon in wood products will have increased, but no additional carbon will be entering the stock after that time.
- The effect of product substitution is calculated as the difference between the fossil emissions associated with the life cycle of wood products and the avoided fossil emissions associated with the non-wood products that are not used. In all cases except one (wood fibre insulation panel vs. mineral wool insulation), the substitution effect is beneficial, i.e., the life cycle fossil emissions of the wood product are lower than those of the non-wood product.
- Energy recovery from wood residues, both from processing and from post-use products, makes an important contribution to reducing net GHG emissions by replacing fossil fuel.
- During the initial decades of the scenario, the increasing carbon stock is the dominant factor affecting the GHG balance. Later, as carbon stock stabilizes and substitution effects (of both materials and fuels) continue to accumulate, the effect of carbon storage in products becomes less significant. In the long term, the substitution effects continue to provide cumulative GHG benefits, while the carbon stock change does not.
- After the system reaches equilibrium in 2110, the material substitution effect of the wood products provides 0.60 Mt of avoided CO_2 emission per year, and the fossil fuel substitution effect of the wood residues provides 0.36 Mt of avoided CO_2 emission per year. The carbon stock in wood products remains stable at a level of 30 Mt CO_2 greater than in 2000.
- Most of the CO_2 emission reduction occurs within Switzerland. Much of the “construction” wood substitutes for heavy, nationally-produced materials such as concrete and brick, resulting in decreased emissions in Switzerland. A greater share of the “interior” wood substitutes for e.g., steel products manufactured outside of Switzerland, leading to decreased emissions in other countries. Some product substitutions result in increased emissions within Switzerland, but decreased net (global) emissions.

64 Werner, F., Taverna, R., Hofer, P. and Richter, K. 2006. **Greenhouse gas dynamics of an increased use of wood in buildings in Switzerland.** Climatic Change, 74(1-3): 319-347. http://dx.doi.org/10.1007/s10584-006-0427-2

- See #63, Werner *et al.,* (2005)

65 Werner, F., Taverna, R., Hofer, P., Thürig, E. and Kaufmann, E. 2010. **National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment.** Environmental Science and Policy, 13(1): 72-85. http://dx.doi.org/10.1016/j.envsci.2009.10.004

- Conclusion: The greatest long-term reduction in GHG emission occurs when forests are harvested at their maximum sustainable level, the wood is used for long-lived products, and post-use wood is used for energy generation. Other management regimes resulted in greater short-term emission reductions. 20-30% of the emission reduction occurs outside of the national border.

- The authors are from Werner Environment & Development, GEO Partner AG, and Swiss Federal Research Institute WSL, in Switzerland.
- The authors integrate three models of the Swiss forest carbon pools, the Swiss forest products industry, and wood substitution effects. The analysis covers a 100-year time horizon.
- Five scenarios are developed of forest management and wood use: 1) the forest is managed for maximum production, harvest is at a maximum sustainable level, and wood is prioritized for use as construction material; 2) as scenario 1, but all the harvested wood is used for bioenergy; 3) as scenario 1, but carbon stock increase in the forest is limited to the amount that Switzerland can account for in the Kyoto Protocol; 4) business-as-usual, with a continuation of current forest management practices; 5) the forest is managed to maximize forest carbon stock, and harvest levels are reduced.
- Harvested wood is assumed to be used for a variety of construction applications in place of non-wood materials, as guided by a survey of Swiss architects, engineers and building owners. The GHG emissions from using the wood and non-wood materials are determined by comparative life cycle assessments. The substitution benefits are the same as those assumed by Werner *et al*., (2006). Wood used for energy purposes is assumed to replace oil and natural gas.
- The results show that over the long-term, scenario 1 (maximum forest production, maximum sustainable harvest, wood used for construction) gives the lowest net carbon emission. CO_2 emission is reduced by about 5 million metric tons CO_2 annually, or about 9% of current Swiss annual emissions.
- In the short-term of the first 20 years, scenario 5 (maximum forest carbon stock, reduced harvest) gives the lowest net annual carbon emission. After that time, however, emissions increase for this scenario, and after 65 years the net annual emission is greater than at the beginning of the study period.
- Scenario 2 (maximum forest production and harvest, wood used for energy) consistently gives greater annual carbon emissions than if the wood is used for construction (scenario 1). Scenario 4 (business-as-usual) gives fairly low emissions in the short term, but high emission in the medium to long term, suggesting that the Swiss forestry sector should shift to increased harvesting levels.
- The relative performance of the five scenarios follows the same patterns when analyzed in terms of global emission, Swiss emission, and non-Swiss emissions. About 20-30% of the global GHG emission reduction occurs outside of the Swiss borders, depending on the scenario.
- The authors assume constant imports and exports of wood and wood products in all the scenarios over the entire study period. They acknowledge that this assumption is unrealistic, for example in scenario 5 (maximum forest carbon stock, reduced harvest) where wood imports would likely increase to compensate for reduced Swiss production, leading to carbon effects in forests outside of Switzerland.

66 Wilson, J.B. 2006. **Using wood products to reduce global warming. Chapter 7 in: Forests, Carbon and Climate Change: A Synthesis of Science Findings.** Oregon Forest Resources Institute. http://www.oregonforests.org/assets/uploads/for_carbon_fullrpt.pdf

- Conclusion: Using wood products from sustainably managed forests is a practical and significant measure to help mitigate climate change. Policy instruments could promote the use of wood products to reduce net GHG emissions.

- The author is from Oregon State University, in the USA.
- This is a general overview of the climate advantage of using wood products, based on results of the CORRIM research project. The author discusses the interactions between forest growth, carbon storage in trees and wood products, and substitution of fossil fuels and materials.
- The author introduces the issue of climate change, and discusses the role of forests and forest products in the global carbon cycle. Three mechanisms are described through which wood product use reduces net GHG emissions: storage of carbon in trees and wood products, reduced fossil carbon emissions from using wood material instead of more GHG-intensive material, and using forest biomass for energy in place of fossil fuels.
- The author describes the CORRIM research project, and summarizes the project's main conclusions. The impact of different forest management practices is discussed, including the "no-action" management option. Carbon storage in forest biomass over time is compared to carbon storage in wood products and avoided fossil emissions due to material and fuel substitution.
- Considering only the carbon stocks in living biomass, the no-action option seems the most climate-friendly alternative. However, when other carbon stocks and flows are considered, more intensive forest management and wood product use results in lower net GHG emissions to the atmosphere.
- The author examines energy sources used in the forest products industries, and finds that most production energy comes from biomass residues. This renewable fuel contributes to the low net GHG emissions from wood products.
- The author discusses ways to increase wood product use as a means to mitigate climate change. These ways include building standards that encourage wood product use, implementing forest management practices that satisfy diverse objectives including climate change mitigation, placing a cost on carbon emissions which would make wood products relatively more competitive than non-wood materials, and implementing outreach education among architects, engineers, policymakers and the public.

Methodological Issues in GHG Analysis of Wood Substitution

Introduction

Although sophisticated tools for the analysis of environmental impacts of many products and services have been developed over the last several decades, there are additional challenges in analysing forest products. Reasons for the complexity of environmental analysis of forest products include the long time frame involved, including the time for forest growth and the long lifespan of some wooden products; the range of useful products that are obtained at different points in time, including forest thinnings during the time of forest growth, primary products and co-products at the time of forest harvest, and combustible residues at the end of the product lifespan; the broad array of joint products that can be obtained from a tree (e.g. saw, veneer, and pulp logs) and a stand (e.g. different uses from different species in a mixed forest stand); and the unique relationship between forest development and environmental services (Perez-Garcia *et al*. 2005).

In recent years, methodological approaches have been developed by various authors to explore the climate implications of wood substitution. The present review of these previous studies of wood substitution shows that two issues of crucial importance are the definition of a functional unit of comparison, and the establishment of effective and workable system boundaries in terms of activity, time and place. Here, drawing on material from Gustavsson and Sathre (2010), we discuss these issues and suggest appropriate methodological approaches to analyse the GHG implications of substituting wood in place of non-wood materials. Defining the functional unit and system boundaries is a necessary part of analyzing carbon impacts. A functional unit is the basis on which different objects or services can be compared. System boundaries delineate what is included in the analysis, and what is disregarded. System boundaries can be identified in terms of procedural, temporal, or spatial characteristics. For clarity we discuss these boundaries separately although they are not truly independent: an activity always has spatial and temporal boundaries; and without an activity, spatial and temporal boundaries have no significance.

Functional Unit

A comparative analysis of wood-based materials relative to non-wood materials requires the definition of a reference entity or "functional unit" to allow objective comparison of the materials. A functional unit is a measure of the required properties of the studied system, providing a reference to which input and output flows can be related. These inputs and outputs, which vary between the different products compared, are the reference flows which determine the environmental impacts. The reference flows are the specific outcomes of fulfilling the abstract functional unit in different ways (Weidema 2004). Energy and CO_2 analysis of wood substitution in construction can be compared on a variety of functional units: material mass or volume, building component, complete building, or services provided by the built environment. The functional unit applies to the buildings and materials, not to the energy use or the CO_2 emissions which are the result of the functional unit being fulfilled.

A commonly used unit by which impacts are calculated is a unit mass of individual materials. For example, industrial process analyses commonly determine the primary energy required to manufacture a kg or tonne of material. This information can be useful input for a more elaborate analysis, but by itself is incomplete because the function of different materials cannot be directly compared. One tonne of lumber, for example, does not fulfil the same function as one tonne of steel. Similar analysis on the basis of unit volume of material suffers the same shortcoming. A more useful functional unit is to compare performance on the basis of the function provided by building components. That is, building components that provide the same function (e.g. structural support, or wall sheathing), made of either wood-based or non-wood materials, can be compared (see e.g. Jönsson *et al*. 1997, Knight *et al.* 2005, Lippke and Edmonds 2006).

Nevertheless, a particular material may fulfil more than one function (e.g. structural support and thermal insulation), and a given building function may be fulfilled by a combination of materials. Changing one material may impact on other functions in various ways, for example sound transmission, fire protection, and the overall weight of the building which in turn affects the required foundation design. Thus, a more comprehensive analysis is at the building level (Kotaji *et al*. 2003), alternately using wood-based or non-wood materials. This can be based on a generic hypothetical building (Björklund and Tillman 1997), or a case study of completed buildings (Gustavsson, Pingoud *et al*. 2006; Lippke *et al*. 2004). The functional unit can be defined so that all the options have the same impacts during the operation phase, potentially simplifying the analysis.

If possible, the functional unit should be selected to avoid allocation. The choice of allocation procedure can have a significant effect on the results of a comparative analysis of wood and non-wood products (Jungmeier *et al.* 2002). Allocation is the process of attributing impacts or benefits to a particular part of a process that results in multiple outputs. This is particularly important for wood materials, because multiple co-products are produced from the same raw material, and wood products themselves can be used as biofuel at the end of their service life as a material product. Allocation is a subjective procedure, and depends in part on the perspectives and values of the analyst (Werner *et al*. 2007). However, allocation can often be avoided, e.g. by system expansion by adding additional functions to the functional unit so the systems compared have identical functions (Gustavsson and Karlsson 2006). For example, the secondary function of wood as an energy source can be compared to an alternative of providing the same energy with fossil fuels.

To facilitate comparison among different case studies, performance can be measured on the basis of the services provided by the building, rather than the building itself. For example, if the primary service provided by a building is protection against the climatic elements, comparison can be made on the basis of m^2 or m^3 of climate-controlled floor area or interior space. This can allow comparison between buildings of different size, although it may be difficult to distinguish between differences due to the scale effect of the buildings (e.g. inherent differences between single family and multi-family buildings, or single storey and multi-storey buildings) and the differences due to the building material choice.

Building codes can be used as a measure of function of a building, thus different buildings that each fulfil building codes for e.g., thermal efficiency or fire resistance, might be considered to be functionally equivalent in this regard. However, building codes are minimum standards that must be reached, and a building that performs significantly better than the code requirements may erroneously be considered equivalent to a building that simply meets the code. Therefore, caution should be taken when building codes are used as a measure of building function.

When analysing at the level of entire buildings, it should be recognised that a structural frame of a certain material does not imply that the entire building is constructed of that material. The objective of material substitution is therefore not to completely replace one material with another, but to favour the use of one material over another in cases where either material could practically be used. As some wood is generally used in most buildings, the focus of analysis is on the amount of additional wood that is used, and the resulting decrease in non-wood materials that are required. The functional unit is always described as a demand side variable, i.e. the building or product used. However, land use issues and sustainability concepts involving substitution may also be revealed from a supply side perspective such as the unit of forest that produces such functional units.

System Boundaries: Activities

There exists a range of mechanisms by which wood product substitution affects GHG emissions, and system boundaries should be established to ensure that the significant effects of these mechanisms are included in the analysis. Boundaries should be established broadly enough to capture the significant impacts of interest, but not so broad as to make the analysis too unwieldy.

Procedural system boundaries define which physical activities or processes are considered in the analysis. These can include, for example, production of the materials, operation of the building, recovery and use of co-products, and post-use material management. Supply of energy has a strong impact on primary energy use and net CO_2 balance, and is discussed in depth in a separate section.

Production Phase

The first stage of a building material life cycle is the acquisition of materials. Raw materials are extracted from their natural state (e.g. by mining of minerals or harvesting of forests) or are cultivated (e.g. timber production in managed forests). The materials may then go through one or several stages of processing and re-processing. Processing operations may involve resizing, separation of different components, combining with other materials, and changing of chemical structure. Primary and secondary processing may occur at the same location, or may require transport from one processing facility to another. The burdens of building the processing infrastructure that produce the products are usually excluded from life cycle studies, under the assumption of a long life span that allocates these burdens over so many products so as to have a negligible impact.

Processing Energy

Energy is required to manufacture both wood products and non-wood products. A “cradle to gate” analysis of material production includes the acquisition of raw materials, transport, and processing into usable products. The type of end use energy varies, and could include electricity, biofuels, and various types of fossil fuels. Primary energy required to provide the different types of end use energy, and the resulting CO_2 emissions, can be determined through consideration of fuel cycle, conversion, and distribution losses.

Different physical processes can be used to produce the same material, each process with unique requirements and effects on the environment. The efficiency of industrial technologies has generally improved over time resulting in differences in energy requirements and emissions between materials processed by state-of-the-art technologies and those made in older factories. Variation is also seen geographically, as technological innovations diffuse across countries and regions. Data on industrial energy use can also vary depending on the methodology used to obtain the data. System boundaries of an energy analysis can range from a restrictive analysis of direct energy and material flows of a particular process, to an expansive analysis including energy and material flows of entire industrial chains and society as a whole. Data may be direct measurements of a particular machine or factory, or may be aggregated for an entire industrial sector. Figure 1 shows the primary energy used for production of materials for wood- and concrete-framed versions of a building, using specific energy use data from three different European process analyses. These results suggest that in spite of absolute differences between the analyses (due to varying system boundaries, regional differences, etc.), the relative energy use of wood vs. non-wood materials is more consistent (Gustavsson and Sathre 2004).

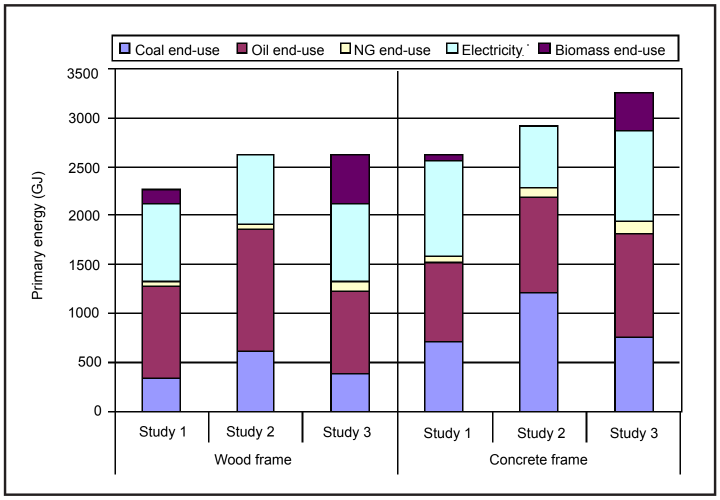

Figure 1. Primary energy used for production of materials for wood- and concrete-framed versions of a building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell *et al*. (1994) and Study 3 is Björklund and Tillman (1997). (Adapted from Gustavsson and Sathre 2004).

Raw Material Supply

For those materials extracted directly from natural deposits, for example mineral ores, an appropriate system boundary for the calculation of energy and carbon balances begins at the point of extraction. For biological materials that are cultivated, for example wood from sustainably managed forests, the analysis includes the technological (i.e. human directed) energy used for biomass production. This includes the fossil fuels used for the management of forest land and for the transport and processing of wood materials. Gross solar energy intercepted by the plants for photosynthesis and growth is generally not included in the energy balance (IFIAS 1974), unless the specific objectives of the analysis requires it. Carbon balances of biological materials include the carbon fluxes that occur during the life cycle of the plants.

There is an inherent variability in the utility of forest biomass, thus the different types of biomass (e.g. sawlogs, pulpwood, forest residues) are not completely comparable or substitutable. For example, any biomass can be burned to produce heat, but not all biomass can be made into structural lumber. Sawlogs can be used for a full range of processes including lumber production, pulp manufacture, and heating, but the uses of forest residues are more limited. Similarly, the characteristics of wood (durability, dimensional stability, bending properties, grain structure, colour etc.) determine the range of appropriate uses, e.g. for building construction, furniture manufacturing, pulp and paper. Thus, in an analysis involving forest production, it is important to distinguish between various types of forest biomass.

Cement Process Reactions

Manufacture of cement-based products result in industrial process carbon emissions. CO_2 is released during the production of Portland cement due to calcination reaction, when calcium carbonate is heated and broken down into calcium oxide and CO_2. Cement production is the largest source of non-energy-related industrial emission of CO_2. Approximately 0.5 tonnes of CO_2 is released for each metric ton of cement produced. While calcination reaction emissions are well quantified, there is much uncertainty regarding the net effect of cement process emissions, due to subsequent CO_2 uptake by carbonation reactions (Gajda and Miller 2000). In this slow reaction that occurs over the life cycle of cement products, calcium hydroxide in the hydrated cement reacts with atmospheric CO_2 to form calcium carbonate and water. The extent of carbonation depends on many factors including surface area, surface coatings, cement composition, temperature, and humidity (Dodoo *et al*. 2009). Gajda (2001) estimated that 8% of the initial calcination emission is re-absorbed by carbonation over a 100-year life span, but did not consider the post-use phase of concrete products. Demolition and crushing of concrete increases its specific surface area and hence increases the carbonation uptake. Pade and Guimaraes (2007) estimated that between 33 and 57% of the CO_2 released by calcination is re-absorbed by carbonation, assuming a service life of 70 years after which the concrete is crushed and then exposed to air for 30 years. Dodoo *et al*. (2009) estimated that about one-third of the calcination emission is reabsorbed by carbonation uptake after a 100 year life span followed by crushing and exposure for 4 months, and about two-thirds is reabsorbed if the crushed concrete is exposed for 30 years. Thus there is substantial uncertainty about the net life cycle carbon emissions of a concrete product, depending in part on the post-use management of the material. Nevertheless, as carbonation uptake is less than calcination emission, net process reaction emissions can be a significant part of the GHG emissions of cement products, and should be included in a comparative analysis of wood and concrete structures.

Operation Phase

Activities in the operation phase of a building include maintenance tasks such as cleaning, painting and periodic component replacements, plus energy consumption for heating, cooling, ventilation, etc. Maintenance and replacement activities can have a significant effect on life cycle impacts and can vary substantially as a function of material; hence, they are included in LCA studies. Energy consumption is typically the primary impact of interest during the operation phase; in fact, the operation phase generally contributes the greatest share of life cycle energy use and CO_2 emissions of a building. Operating energy consumption is typically not included in comparative LCA studies where the emphasis is on the energy and carbon balances of building materials, because operating energy is deemed equivalent between the buildings and can therefore be ignored. This assumption is rationalized several ways. First, in a comparison of functionally-equivalent buildings, by definition (theoretically) the buildings have equivalent energy performance. This reasoning is inherent in many of the studies reviewed in the present paper. In actual practice, buildings that are equivalent in basic dimensions, level of insulation, orientation, usage and so forth may not actually have equivalent energy performance in spite of being otherwise functionally equivalent. However, several studies indicate that operating energy differences as related to structural material choices are minimal. Adalberth (2000) compared apartment buildings constructed with a wood frame and a concrete frame, and calculated the difference in operation energy between them to be less than 1%. Cole and Kernan (1996) found the difference in operating energy between wood and concrete framed office buildings in Canada to be negligible, and Lippke *et al*. (2004) compared wood houses with steel and concrete houses having identical thermal properties, and found no difference in operation energy. A side-by-side study of actual energy use of two equivalent homes, one in steel and one in wood, insulated with the exact same materials found energy performance to be within about 10% of each other (NAHB 2002). In such cases, adding the operational energy use to the life-cycle GHG assessment would increase the total primary energy use for both the wood and non-wood alternative, but the difference between them would remain the same. In cases where a wood and non-wood comparative study involves different energy performance between the buildings, then operating energy should be included in the life cycle analysis as in John *et al*. (2009).

Major efforts have been made to reduce the energy used for building operation, e.g. by improved insulation, reduced leakage through the house envelope and by heat recovery from ventilation air. Such measures result in lower space heating demand, but increased material use and hence increased energy demands for production and construction. Gustavsson and Joelsson (2008) conducted an integrated analysis of the linkage between construction energy input and operational energy input. This type of analysis permits the optimisation of primary energy use over the entire building life cycle. Connections, trade-offs and synergies between different phases of the life cycle need to be identified to allow an optimisation of building construction and operation practices to reduce environmental impacts. In analyses of cost-effectiveness, the full life cycle building costs including external costs should be considered.

Co-products

Optimized biomass flows over the life cycle of a wood-based building material are shown schematically in Figure 2. In addition to the principal flows of roundwood and finished wood materials, there are numerous co-product flows. Co-products are materials or products of some value that are produced simultaneously with the main product. The harvesting of trees, and their processing into wood products, generates considerable biomass residues that can be used for other purposes. Residues are generated during silviculture, harvesting, primary processing when logs are milled into lumber, and in secondary processing for products such as doors, windows and glue-laminated beams. Such residues are used as biofuel, redirected to non-wood product streams such as pulp and paper, or used as a raw material for particleboard and other composite wood products.

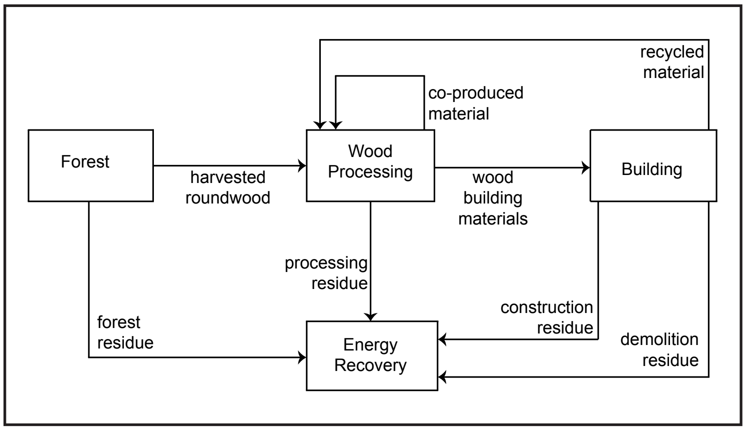

Figure 2. Schematic diagram of optimised forest biomass flows over the life cycle of a wood-based building material. Other co-produced materials (e.g. pulp chips) are not shown.

Re-use or reprocessing of wood materials at the end of the building life cycle can have significant effects on the energy and carbon balances of the material (Sathre and Gustavsson 2006). Such optimisation of end-of-life product recovery and recycling systems may become increasingly important in the future, to gain additional value from the wood as a material, before it is burned to recover its feedstock energy. In such a future scenario, the "design for disassembly" of buildings would become more prevalent to facilitate the removal of wood products with minimal damage, to maintain their potential for further re-use as a material (Kibert 2003).

Co-products of non-wood industrial processes, including fossil fuel fly ash and blast furnace slag, can be used as cement binders. Construction cement made of a blend of clinker and other additives is becoming more commonly used (Gardner, 2004). When cement is made with a blend of clinker and co-products of other industrial processes, total energy use is reduced because less clinker must be produced. CO_2 emissions are reduced in two ways: less fossil energy is needed for the production of the lower quantity of clinker, and lower clinker production means less CO_2 emissions from the chemical reaction of limestone calcination. Another useful co-product is gypsum, which can be obtained from coal flue gas desulfurization.

Post-use Material Management

An analysis that covers the entire life cycle of a material must consider the fate of the material at the end of its service life. The final stage in the life cycle of a building is the demolition or disassembly of the building followed by the reuse, recycling or disposal of the materials. The energy used directly for demolition of buildings is generally small (1-3%) in relation to the energy used for material production and building assembly (Cole and Kernan 1996). The percentage of demolition materials that is recoverable is variable, and depends on the practical limitations linked to the building design and whether material recovery is facilitated. Also, systematic recovery of demolition wood is not yet practiced in some areas, and demolition wood is instead landfilled. Methods for accounting the climate effects of recycling materials are still at an early stage of development, particularly in the context of potential policy instruments for climate change mitigation.

Additional use of recovered wood material, such as reusing as lumber, reprocessing as particleboard, or pulping to form paper products, can improve the environmental performance of the material. Sathre and Gustavsson (2006) compared energy and carbon balances of products made of recovered wood to the balances of products obtained from virgin wood fibre or from non-wood material. They found that several mechanisms affect the energy and carbon balances of recovery wood, including direct effects due to different properties and logistics of virgin and recovered materials, substitution effects due to the reduced demand for non-wood materials when wood is reused, and land use effects due to alternative possible land uses when less timber harvest is needed because of wood recovery. They concluded that land use effects, e.g. the potential for carbon sequestration or forest biofuel production on the land no longer needed for timber production, have the greatest impact on energy and carbon balances. Substitution effects are next most important, while direct effects are relatively minor.

In cases where material reuse of recovered wood is not practical, recovery of energy by burning the wood is a resource-efficient post-use option. The use of recovered demolition wood as a biofuel directly affects the life cycle energy balance of the material. The use of the biofuel to replace fossil fuels, thus avoiding fossil carbon emissions, also affects the carbon balance. Methodological issues regarding the use of biofuels to replace fossil fuels are discussed further below.

Several studies have considered landfilling as the most suitable post-use management option for wood products (e.g. Upton *et al*. 2008, John *et al*. 2009). Carbon dynamics in landfills are quite variable, and can have a significant impact on the GHG balance of wood products. A fraction of the carbon in landfilled wood products will remain in semi-permanent storage, providing climate benefits. Another fraction may decompose into methane, which has much higher global warming potential 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 some climate benefit due to partial sequestration in landfills and partial production of methane biofuel, or severe climate impact due to emission of methane to the atmosphere. There is a lack of consistency in the methods and assumptions used to track carbon during the life cycle of wood products (Franklin Associates 2004). Particularly in regards to carbon sequestration and methane generation in landfills, a wide variety of methods and assumptions have been used in previous studies, leading to different and potentially contradictory conclusions.

The energy and climate performance of non-wood materials can also be significantly affected by post-use management. Production of steel products from recycled steel scrap requires less primary energy, and emits less CO_2, than production of steel from ore. Post-use management of concrete can also lead to reduced net CO_2 emissions, by promoting increased carbonation uptake of CO_2 by e.g., crushing the concrete and leaving it exposed to air. Nevertheless, wood material has relatively more opportunity to improve its energetic and climatic performance, due to its dual role of both material and fuel (Dodoo *et al*. 2009).

Energy Supply System

Fossil Fuel Use

During the life cycle of building materials, fossil fuels are used for extracting, processing, and transporting various raw, finished and residual materials. In a bottom-up analysis, calculation of total fossil fuel use begins with data on material quantities, and specific end-use energy for various production processes broken down by energy carrier. Based on this total end-use energy, total primary energy use can be calculated, taking into account “upstream” energy used over the entire fuel cycle, including extraction, transport, processing, conversion and distribution of the energy carriers (IFIAS 1974).

The use of fossil fuels produces CO_2 emissions in quantities that depend on the carbon intensity and fuel-cycle characteristics of the fuel. Specific CO_2 emission values are applied to end-use quantities of fossil fuels to give total emissions. To ensure accurate reporting, specific emission values must include emissions occurring over the entire fuel cycle, including the end-use combustion of the fuels as well as from fuel extraction, conversion and distribution (Gustavsson, Pingoud *et al*. 2006). Nevertheless, uncertainties arise in accounting for fossil fuel emissions, due to methodological differences, heterogeneity of fuels, and imprecision in measuring (Marland 2008).

In cases where the type of fossil fuel is known, e.g. end-use fuels used for material production in well documented industrial processes, the CO_2 intensity of that fuel is used in carbon balance calculations. In cases where there is some uncertainty as to the appropriate choice of fossil fuel, e.g. the fossil fuel that is used to produce marginal electricity or that is replaced by biomass residues, a “reference fossil fuel” can be employed to determine the significance of the carbon intensity of the fossil fuel that may be used (Sathre 2007). Coal and fossil gas are two reasonable reference fossil fuels, representing the high and low ends, respectively, of the range of carbon intensity (kg C emitted per GJ heat energy released) of fossil fuels, thus indicating the range of uncertainty introduced by the fossil fuel used.

Electricity Supply

The primary energy use and CO_2 emissions during a material life cycle are affected by the supply system used to provide electrical energy for the various processes. Various types of electrical energy production systems exist, with significant variations in associated primary energy use and GHG emissions. Values for average or marginal primary energy efficiency and CO_2 emissions from electricity production could be used in a substitution analysis. However, average data would inadequately capture the effect of changes to the system brought about by an increased use of wood material. This is because changes in electricity supply do not occur at the average level, but at the marginal level (Hawkes 2010). An electricity grid is generally powered by a variety of sources of differing capacities, and some of these sources are brought on-line and off-line depending on changes in demand over time scales of hours, weeks and years; these are defined as marginal sources. A decrease in electricity use, for example through reduced energy use in material processing industries, will cause a decrease in production of electricity from marginal sources. Likewise, an increase in electricity supply, for example from increased use of biomass-fired combined heat and power plants using residues from the forest products industry, will also decrease the existing marginal electricity production. When analysing incremental changes in material use, it is thus appropriate to use data on marginal electricity production that will be influenced by material substitution, rather than data on average electricity production.

Depending on the magnitude of the material substitution that occurs, i.e. whether the substitution occurs on the level of an individual building construction or a society-wide transition toward a bio-based economy, an analysis of the dynamics of the electricity supply system might be needed to understand marginal changes that may occur at differing scales of substitution. Furthermore, electrical supply systems continue to evolve over time. In the years and decades to come, the marginal electricity production will be affected by the evolution and development of the energy system as a whole (Sjödin and Grönkvist 2004). New investments in electricity production will be largely determined by relative costs and policy incentives. Existing coal-fired condensing plants, which are currently the dominant marginal electricity production method in many regions, will eventually be replaced. The electricity plants that are currently being constructed will likely be used until 2040 or longer. Decarbonisation and CO_2 sequestration in large-scale, fossil fuel-fired plants may become commercialised over this time period, driven by the need for GHG emissions reduction. The production capacity of biomass, wind power and other renewable sources is likely to increase in the future. The identification of marginal electricity production depends on numerous factors including the time frame of analysis, the future development of technology, the need for and incentives to reduce carbon emissions, and the development of alternative sources such as nuclear and renewables.

Replacement Of Fossil Fuel By Biomass Residues

Biomass residues from the wood products chain can be used as biofuel to replace fossil fuels, thus affecting the energy and CO_2 balances. The net carbon emissions reduction of fossil fuels substitution should be based on the full fuel-cycle emissions of the avoided fossil fuel, the difference in energy conversion efficiency between the fossil fuel and the biofuel, and take into account the emission from fossil fuels used for recovery and transport of the biofuel. The actual combustion emissions of biofuel obtained from sustainably managed forests is generally assumed to be balanced by carbon uptake by re-growing trees. Important methodological issues when comparing fossil- and bioenergy-based systems are the type of fossil system to be replaced, and the type of bioenergy system used to replace it (Schlamadinger *et al*. 1997). Because the fossil fuel that will be replaced by biofuel use may not be known with certainty, it is worthwhile to conduct the analysis with more than one reference fossil fuel to determine the significance of this uncertainty.

The carbon balance effect of fossil fuel substitution will depend on the extent of biomass residue recovery. Recovery and utilisation of forest residue is becoming more common in some regions. In particular, residue from clear-cut areas is increasingly recovered, with efficient logistical systems to collect and transport the residue currently being developed (Eriksson and Gustavsson 2010). Recovery of forest thinning residue is less common, due to its dispersed nature making efficient and economic collection more problematic. Recovery of stumps is a potentially significant source of biofuel. The use of wood processing residue as biofuel is quite widespread, often within the processing facility itself. The recovery of wood-based construction and demolition waste for use as biofuel is becoming more widespread, with source separation of different types of wastes occurring on many work sites. Utilisation of wood-based waste has a significant impact on the energy balance of wood construction. Recovered wood that is contaminated with paint or preservative treatment can often be incinerated under suitable combustion conditions with flue gas cleaning and ash disposal. Various regulatory and economic factors affect the amount of wood that is recovered from building construction and demolition sites. Greater reuse and recycling of materials is possible, particularly if more attention is paid during building design and construction to facilitate disassembly (Kibert 2003).

Biofuel is generally assumed to replace fossil fuel that otherwise would have been used. However, in economies where energy and/or material use is supply-limited, the availability of an additional unit of biofuel may not lead to a unit reduction in fossil fuel use, due to equilibrating effects in the wider economy. In this case, an additional unit of biomass fuel or material may not displace the use of fossil fuel or non-wood material, but instead be used in addition to it. This “leakage” results in the actual climate benefit of using wood products being somewhat lower than the potential benefits, but will increase the services delivered to society.

System Boundaries: Temporal

GHG stocks and flows associated with forestry and wood substitution exhibit a variety of temporal patterns (Figure 3). Cyclical patterns repeatedly accumulate and release carbon stocks in a predictable pattern, such as a forest rotation cycle. Step changes involve a discrete increase or decrease in carbon stock in a given pool, for example during the life span of a wood product. Cumulative changes are non-reversible flows that accumulate over time, such as avoided fossil emissions due to biomass substitution. Asymptotic changes are rapid at first and become slower over time, for example an increase or decrease in soil carbon stock. Different forest management actions and wood product uses will result in different combinations of GHG emissions and uptakes over time. This heterogeneity over time complicates the comparison of the effectiveness of different GHG mitigation options.

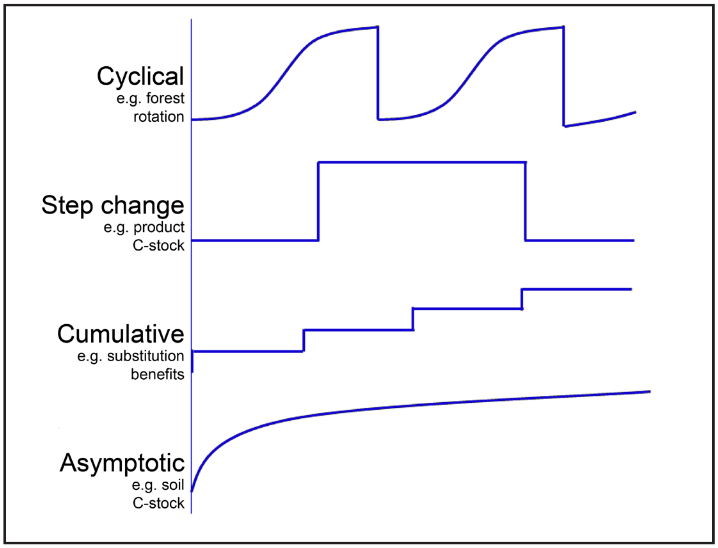

Figure 3. Examples of temporal patterns of GHG stocks and flows associated with forestry and wood substitution.

Most substitution analyses to date have used a GHG balance approach, where all emissions and uptakes that occur during the study time horizon are simply summed up, regardless of when they occur. Non-CO_2 GHG emissions (e.g. CH_4, N_2O) are converted to "CO_2 equivalents" based on the Global Warming Potential (GWP) of the gases, which express the relative climate impact of the gases compared to an equal mass of CO_2. A system with lower net carbon equivalent emissions at the end of the time period is considered to be more climate-friendly than a system with higher net emissions. This approach, however, does not fully take into account the atmospheric dynamics of the GHGs. The temporal pattern of GHG emissions and uptakes can affect the resulting radiative forcing, and hence the climate impact, depending on the time horizon under consideration. Radiative forcing is a measure of the GHG-induced imbalance between incoming and outgoing radiation in the earth system. GHGs allow shortwave light radiation to enter the earth's atmosphere but restrict the exit of longwave heat radiation, resulting in an accumulation of energy that leads to global warming. Cumulative radiative forcing can be considered as a proxy for surface temperature change and hence disruption to physical, ecological and social systems. GHGs do not remain in the atmosphere indefinitely, but are slowly removed through natural processes, thus over an infinite time horizon a unit of GHG will cause a given amount of radiative forcing regardless of when it is emitted. However, many policy objectives cover a finite time horizon, for example reducing climate change impacts during the next 20 or 100 years, thus the effectiveness of a mitigation activity will depend not only on how much GHG is emitted, but also on when it is emitted. The climate significance of emission timing is receiving increasing attention in analyses of the mitigation effectiveness of biofuels (e.g. Holmgren *et al*. 2007, O'Hare *et al*. 2009), but has heretofore not been addressed in material substitution analyses.

Important temporal aspects of wood substitution include the dynamics of forest growth including regeneration and carbon saturation, the duration of carbon storage in products, the temporal pattern of fossil fuel use, the availability of residue biofuels at different times, and the time dynamics of cement process reactions. The available data are generally based on current practices and technology, although the full time scope of wood substitution extends both back in time (e.g. when currently mature forests were established) and forward in time (e.g. to the end-of-life of wood products). It may be appropriate to make assumptions about previous practices or forecasts of future technologies, though such projections must be made transparently.

Forest Growth

Consideration of forest dynamics is an essential part of an analysis of energy and carbon balances of wood products. The life cycle of a wood product begins with the germination of the tree seed, and continues through the growth and harvest of the tree and the manufacture and use of the resulting product. The carbon flux is time-dependent, as the plants grow and accumulate carbon in their tissues, and affects soil carbon content due to the root development and detritus-fall of the plants. This requires an analytical approach that captures the time dynamics of the plant growth, with explicit consideration of temporal scope of the analysis (Schlamadinger *et al*. 1997). Material inputs to the system include CO_2, water and nutrients, while the wood is an internal flow within the system boundary (Yaro 1997). The accumulated carbon stock is tracked through the life of the tree, and through the life cycle of the wood product, until the carbon is eventually released again to the atmosphere through combustion or decay. Energy flows begin with the accumulation of solar energy in tree biomass, through to its eventual release when the biomass is burned or decomposes.

Forest carbon flows have different dynamics when analyzed at the tree or stand level, or at the landscape level. When a tree or stand is harvested, the carbon in living biomass is transferred into other carbon pools such as wood products and forest floor litter. The carbon in these pools can then be tracked over time, while the carbon stock in living biomass re-accumulates as the forest regrows. Depending on biogeographical factors, the rotation period of forest stands ranges from decades to over a century. Following harvest of the forest stand, assuming no change in land use, the regeneration of the trees initiates another cycle of carbon accumulation in living biomass. At the landscape level, the dynamic patterns of the individual trees or stands are averaged over time as carbon flows into and out of various carbon pools associated with trees at differing stages of development. Thus, at the landscape level the total carbon stock in living biomass tends to remain fairly stable over time, as the harvest of some trees during a given time period is compensated by other trees growing during the same period. If forests are managed appropriately, the average carbon stock in forest biomass can increase over time (Pingoud *et al*. 2010). Simultaneously, the flow of harvested biomass out of the forest results in continually increasing carbon benefits due to fuel and material substitution.

If instead the trees are not harvested, the forest biomass would eventually reach a dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration in living trees and decay of dead trees, but without the biomass flows available for substitution. Carbon storage in forest soils changes at a slower rate, thus buffering the changes in total forest ecosystem carbon stock (Eriksson *et al*. 2007).

Product Duration

A part of the carbon that is taken from the atmosphere during the growth of a forest stand remains sequestered during the service life of a wood product. About 50% of the dry weight of wood is carbon. The longer a particular wood fibre is used or reused as a material, the longer those particular carbon atoms will remain out of the atmosphere. Eventually, however, and in the absence of long-term sequestration in e.g. landfills, all the carbon will be emitted through combustion or decomposition. As part of a dynamic biogeochemical cycle, carbon storage in wood products is an inherently transient phenomenon, though some long-lived wood products may store carbon for centuries.

Over the life cycle of a building, there is no change in carbon stock in the building itself. Before the building is built it contains no carbon stock, and after the building is demolished it contains no carbon stock. Combustion of wood-based demolition material ensures that 100% of the carbon stock is oxidised and re-enters the atmosphere as CO_2. If the demolition material is used as biofuel to replace coal, the avoided fossil carbon emissions are roughly equivalent to the carbon stored in the wood material during the building lifespan (Gustavsson, Pingoud *et al*. 2006). If the material is landfilled, there may be a fraction of carbon remaining in semi-permanent storage, with the remainder emitted as CO_2 or methane.

On a larger scale, a carbon sequestration effect occurs if the total stock of wood products is increasing. This could occur as a result of general economic growth, whereby more products of all kinds are produced and possessed, or through a societal transition from non-wood to wood-based products. If the total stock of carbon in wood products is increasing, carbon storage in products contributes to reducing atmospheric CO_2 concentration. The carbon stock in wood products would increase if a change were made from non-wood to wood-based construction. This would occur if non-wood buildings, representing the baseline, are replaced by wood-framed ones, which after demolition are always replaced by new wood-framed buildings with a similar carbon stock. This would result in a step change in carbon stock compared to the baseline, at the point in time when the non-wood material is replaced by wood. The permanence of the carbon stock in buildings depends on the difference between the amount of wood added to new construction and the amount of wood removed from demolished buildings (Lippke *et al*. 2010). The stock of wood products will stabilise if the rate of wood entering the wood products reservoir is equal to the rate at which used wood is oxidised and releases its stored carbon to the atmosphere. At this point, the storage of carbon in wood products has no net effect on the atmospheric CO_2 concentration. This is in contrast to the substitution effect that occurs each time a new wood product is used instead of a non-wood product, which results in permanent and cumulative avoidance of carbon emissions.

Fossil Fuel Use

Fossil fuels are used at different times over the life cycle of a building, as discussed above. Fuels are used to extract, process and transport materials used to construct the building. Fuels are used to operate the building, and are later used to dismantle the building. The use of these fossil fuels results in carbon emissions occurring at different times throughout the life cycle of the material.

Biomass Residue Availability

Over the life cycle of a wood-based material, biomass residues will become available at different times. Thinning residues may be generated at different times during the growth phase of the forest. Later, forest residues are created when the forest stand is harvested, processing residues are available when the roundwood is transformed into wood products, and construction site residues are left when the building is assembled. Later still, demolition residues are produced at the end of the building life cycle. The use of these residues to replace fossil fuel results in reduced fossil carbon emissions at different times in the life cycle of the material. The time dynamics of forest residue oxidation vary. Forest residues left to decompose naturally in the forest slowly release CO_2 into the atmosphere over a time scale of decades, while residues removed from the forest and used as biofuel release CO_2 when burned. This can result in varied radiative forcing, the significance of which depends on the time horizon under consideration (Holmgren *et al*. 2007). This effect is more pronounced for slower-decaying biomass such as stumps.

Cement Process Reactions

As discussed, chemical reactions affecting the net carbon balance occur at differing rates throughout the life cycle of cement-based materials. CO_2 emissions occur due to calcination at the time the cement is manufactured, and CO_2 uptake occurs due to carbonation throughout the life cycle of the cement product. The rate of CO_2 absorption by carbonation can increase significantly if the concrete is crushed and exposed to the air at the end of its service life. Roughly one-third to two-thirds of the initial calcination emission will eventually be taken up by carbonation reaction, depending on exposure duration and conditions during and after the product lifespan (Dodoo *et al*. 2009).

System Boundaries: Spatial

Land Use Modelling Approaches

Careful definition of spatial boundaries, and the general consideration of how land is used, are important issues when comparing wood and non-wood materials. The use of wood-based materials instead of non-wood materials uses greater quantities of biomass, requiring the use of more land area or intensified forest management (Börjesson and Gustavsson 2000). A fundamental difference between biomaterials and mineral materials is the regenerative ability of land, subject to appropriate management, to continue to produce the biomaterials during successive rotation periods in perpetuity, via biological processes. Although some materials like metals can be recycled successively, and all materials are naturally recycled over geological time spans, only biomaterials can be indefinitely regenerated on a time scale of use to society. This regeneration is driven by the energy of the sun through the process of photosynthesis, which accumulates the flow resource of solar energy into the replenishable fund resource of plant biomass (Swan 1998). Land area for the capture of solar radiation is essential to this process, thus a consideration of the use of land and its productive capacity is an essential element of a comparative analysis of wood material use.

A major challenge when comparing wood materials with non-wood materials is to compare the differences in land use needs between the two materials. Sathre (2007) explored four different analytical approaches to treat this issue. The first was to assume that an equal area of land is available to both the wood-based and non-wood-based product, and analyse the carbon balance impacts of various usage options for any land not used for material production. Assumptions on alternative land use may be based on a plausible market response, considering supply and demand for forest biomass and forest-related environmental services over different time scales. For example, a reduction in demand for timber may result in a decreased harvest, leading to an increase in forest carbon stock, or alternatively the trees may be harvested and used for the next lower-valued product.

The second approach was to model the biomass production from a unit area of land under different management options, and analyse the carbon balance impacts of using the produced biomass for various purposes. A third approach was to increase the intensity of use of the biomass resources through material cascading, or multiple reuse of wood fibre in applications that require successively lower quality of material, in effect gaining more functional service from the output of a given land area, or alternatively getting the same function from a smaller land area.

A fourth approach was to assume that the incremental wood material is produced though more intensive use of forest land, or from land that had not been previously used for wood production. The annual harvest of some forest land is much lower than the annual potential harvest. For example, wood harvested in Europe in the mid 1990s was about 60% of the net growth increment of European forests, leaving an unused increment of about 300 Mm^3/yr (UNECE/FAO 2000). Continuation of these harvesting levels would change the age class structure towards older age classes and the growth increment would decline in the long run. If harvesting levels are increased, age class structure would change towards younger age classes and growth increment would increase, further increasing the substitution potential.

Forest Management Intensity

Forest management produces a multiplicative effect whereby energy inputs used for forest management are leveraged into a greater energetic output in terms of biomass harvest. A continuum of forest management intensities is possible, from an intense regime to the non-management and non-use of forests. At least three effects on carbon balance can be distinguished if a forest is not managed. First, the forest biomass would continue growing until the stand is mature. At this point a dynamic balance would be reached, where natural mortality equals growth and the long-term average carbon stock remains near-constant. Second, the soil carbon stock would behave in a similar way, i.e. continue to grow at a successively lower rate until a near steady-state situation is reached (Lal 2005). Third, no forest products would be produced and other, more carbon-intensive, materials and fuels would be used instead, resulting in increased net CO_2 emissions.

The carbon stocks of forest biomass and soil are affected by forest management regimes, including rotation length, thinning, fertilisation, and harvest (Eriksson *et al*. 2007). Intensification of forest management would increase the growth increment and the substitution potential. Transition to a management regime involving a longer or shorter rotation length would result in a temporary decrease or increase, respectively, in the harvest levels, as individual stands are harvested later or earlier than they otherwise would have been harvested.

A fundamental basis of wood substitution studies is that the forest land must be managed sustainably, in such a way that the land use can be continued indefinitely. Essential elements of sustainable land use include the maintenance of levels of soil nutrients and organic matter, the efficient use of available water supplies, and the protection of natural biotic diversity (Reijnders 2006).

Scale Issues

Wood substitution can be analysed on different levels: micro-level studies, focusing on individual products, processes or decision-making entities; meso-level studies, focusing on certain industries or sectors of the economy; and macro-level studies, focusing on macroeconomic and landscape implications of wood substitution (Gustavsson, Madlener *et al*. 2006). Studies at each level have their own advantages and limitations. Results from studies at different levels can complement each other, thus providing a richer picture of the complex issue of wood substitution than studies using a single approach only.

Several authors have analyzed wood substitution at the national or regional level. Pingoud and Perälä (2000) analysed the potential for wood substitution in the Finnish construction sector. The authors compared the total amount of new building construction to a scenario in which the same buildings were built in a way that maximized wood use, finding that the use of wood-based products could increase by almost 70%. Kram *et al*. (2001) analysed the climate impact of using an additional 50 million t of wood products per year to substitute for non-wood materials in OECD-Europe. They estimated that annual GHG emissions would be reduced by 50 million tCO_2, based on a displacement factor of 1 tCO_2 per t wood. An additional temporary carbon sequestration in wood products of 75 million tCO_{2eq} per year would occur. The estimated cost for this substitution ranged from negative cost (i.e. economic benefit) up to 1000 Euros per tCO_2. Werner *et al*. (2005) analyzed the GHG impacts of increased use of wood products at a national level in Switzerland. The authors developed a scenario of a 30% increase in wood use through 2130. Twelve different types of wood products were assumed to substitute in place of non-wood products with the same function and service life. The processing residues, and the wood products at the end of their service life, were used as biofuel to replace fuel oil. Upton *et al*. (2008) conducted a national-scale analysis of housing construction in the US. Beginning with substitution data of individual case study houses built with wood frames instead of steel or concrete, the authors expand the analysis to 1.5 million houses each year for the next 100 years. They linked the case study data on construction materials in the houses to “upstream” issues like forest growth dynamics and land use issues, and “downstream” issues like disposal of the demolition materials.

As the analysis is scaled up from the micro to macro level, a different set of issues is involved. The aggregate use of forest land will depend on the competing demands for the various products and services that the forest can provide, and the alternative materials available. This will differ between a marginal change in product use (i.e. the consideration of a single product substitution) and a structural change in society’s production and consumption patterns. On a macro-level, methods are needed to determine the aggregate impact of large-scale changes in forest biomass supply or demand, not only for building materials, but also for fuel, paper, carbon storage and ecological services.

An analysis that integrates the dynamics of forest processes and economic markets is needed to identify interdependencies. For instance, increased carbon sequestration in forest biomass reduces the quantities of biomass available for energy and material substitution. Other interdependencies are transmitted by the price mechanism such that increased use of wooden construction material will tend to increase timber prices, resulting in more intensive forest management. The long time scales further complicate comparisons of strategies; whereas wood fuel can substitute for fossil fuel today, the use of wood in construction will affect energy use in different sectors immediately and fossil fuel substitution when the building is eventually demolished in the future.

Carbon dynamics differ substantially as the scale increases from the forest stand level to the landscape level. At the landscape level, the total carbon balance at any time is the aggregate of the balances of a multitude of stands, each at a different stage of its rotation. The maximum carbon stock at the landscape level is thus lower than the maximum at the stand level, because not all the individual stands will hold the maximum stock at the same time (Kurz *et al*. 1998). A substitution analysis on the micro-level can analyse wood flows in terms of their relation with the production of an individual stand, while a macro-level analysis must consider flows on the landscape level.

Larger-scale analysis may seek to understand the spatial distribution of the GHG benefits of material substitution. The forest growth, wood processing, material use, and waste disposal may occur at different sites, and possibly different countries (Werner *et al*. 2010). The international trade in wood-based products and fuels is increasing, and there is a large potential for exporting prefabricated wooden buildings, or lumber to be used for wood construction, from forest-rich countries to other regions that predominately use brick or concrete construction. This process would be encouraged by the wider establishment of economic policy instruments for climate change mitigation, e.g. taxation of carbon emissions and fossil fuel use, which economically favour less carbon-intensive materials such as wood (Sathre and Gustavsson 2007). By exporting biomass to be used in applications that result in high CO_2 emissions reductions per unit of biomass, the total emissions reduction from the available supply of biomass could by increased. For example, the total number of new buildings built per year in Nordic countries and Canada is small in relation to the total quantities of biomass potentially available in the regions. If the export potential was ignored, the additional biomass would then be used for other applications with lower efficiency of emission reduction, or would be left in the forest. However, if additional biomass were exported and used instead of non-wood building materials in other countries, the higher emission reduction per unit of biomass could be gained by a larger share of the biomass, thus resulting in a greater overall emission reduction globally.

The complexity of wood product substitution across national borders is illustrated by Werner *et al*. (2005, 2010). In analyses of increased wood use in Switzerland, they found that much of the wood substitutes in place of heavy, nationally-produced materials such as concrete and brick, resulting in decreased emissions in Switzerland. However, wood also substitutes in place of e.g. steel products manufactured outside of Switzerland, leading to decreased emissions in other countries. Some product substitutions resulted in increased emissions within Switzerland, but decreased net global emissions.

Substitution Validity

Taking a greenhouse gas “credit” for wood substitution is only valid if the application of wood is verifiably a substitution for another material. There is no additional GHG benefit in the continued use of wood products for applications where they are typically already used. This is analogous to the notion of additionality as used in carbon markets, whereby carbon credits are only available to GHG mitigation activities that would not have happened anyway in the absence of the credit. The reasoning here is to avoid providing economic rewards for business-as-usual but instead restricting the incentives to activities with a clear GHG benefit over business-as-usual.

The application of wood substitution displacement factors in policy development, carbon markets and wood industry promotion needs careful consideration of methods for indicating validity of the substitution. This is an area requiring further research. Determination of additionality could be made through top down or bottom up approaches. A top down approach could, for example, use national or sectoral goals or quotas to be achieved; if the quota has not yet been reached, all appropriate uses of wood would be considered as additional. A bottom up approach, on the other hand, would involve case-by-case evaluation of additionality, based on the particular project and its non-wood alternative.

For top down evaluation, a key issue would be determining a benchmark that defines “business-as-usual.” This may be a function of market share (perhaps with various conditional or contextual boundaries such as material availability, regional issues, etc.). For example, if 20% of single family homes in a region are currently built in wood, then wood is perhaps not viewed as standard practice and therefore eligible for a displacement credit. If the market share increases to some threshold, the use of wood would be considered “normal” and would not be considered as material substitution. A method would be needed for determining market share thresholds that indicate if the use of wood would likely have proceeded anyway and is therefore not considered an act of substitution. A potential complication is that the baseline of material use is dynamic. Relative shares of different materials are not constant; they have shifted in the past, and will continue to shift in the future even without policy measures.

For bottom up evaluation, the process used to determine additionality within the Clean Development Mechanism (CDM) could provide guidance for evaluating the validity of wood substitution. Within the CDM, realistic and credible alternatives to the proposed project are first defined (UNFCCC 2008). This is analogous to preparing alternative building designs using wood and non-wood materials. An investment analysis is then conducted to determine whether alternatives to the project would be more economically attractive than the proposed project; if so, the project can be considered as additional, as it is unlikely to be implemented without CDM credits. If necessary, a barrier analysis is also conducted to determine whether there are realistic and credible barriers that would prevent the implementation of the proposed project activity from being carried out without CDM credits. This criterion may be particularly relevant to wood substitution issues, because various non-economic obstacles exist to the wider use of wood in construction (Mahapatra and Gustavsson 2008).

To transparently quantify the approximate substitution benefits, a standardized software with a regionally-specific database could be used to analyze the GHG balance of wood and non-wood versions of a proposed building. The emission difference between the buildings would determine the credit applied to the substitution action. To gain credit, the applicant would need to prepare plans and materials list for both versions, which would help to prove additionality by showing that the non-wood version is feasible.

This discussion of validity does not apply in cases where a displacement factor is being used in scenario analysis for alternative paths from current practice, for example, an assessment of the GHG penalty should forest products operations be ceased and alternative materials sourced for replacement products. Similarly, a displacement factor can be applied in estimating the GHG penalty if wood should be used less often in a typically application, for example, if wood housing in North America lost market share to alternate materials.

Conclusions

Analysis of the energy and carbon balances of wood substitution is a complex issue. In this section we have discussed some important methodological issues of such an analysis, focusing on the definition of a functional unit of comparison and the establishment of effective and workable system boundaries in terms of activity, time and space.

The functional unit can be defined at the level of building component, complete building, or services provided by the built environment. Energy use or GHG emissions per unit of mass or volume of material can be an important input for a more comprehensive analysis, but by itself is inadequate because equal masses or volumes of different materials do not fulfil the same function. Analysis at the level of a complete building or building service is needed.

A comparative analysis is delimited by system boundaries. Activity-based boundaries include life cycle processes such as material production, product operation, and post-use material management. Differing production efficiencies and fuel types can result in different primary energy use and GHG emissions for identical materials. Process reactions can be a significant CO_2 emissions source for cement-based products. If the products compared are functionally equivalent in the operation phase and the impacts occurring during the operation phase are equal, this phase may be dropped from the analysis without affecting the comparative results. Post-use management options including reuse, recycling or energy recovery can significantly affect energy and carbon balances.

Numerous co-products are associated with the life cycle of wood products, and their analytical treatment can bring significant variability to the results. The use of wood co-products as biofuel can be analytically treated through system expansion, and compared to an alternative of providing the same energy with fossil fuels. The production of electricity used for material processing is another important energy-related issue, and using marginal production data may be more appropriate than average production.

Temporal system boundaries include such aspects of the wood life cycle as the dynamics of forest growth including regeneration and saturation, the availability of residue biofuels at different times, and the duration of carbon storage in products. If a forest stand is not harvested it will eventually reach a dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration in living trees and decay of dead trees. Carbon storage in wood products may be temporarily significant during the life span of the products, but will be partially or fully released again to the atmosphere at the end of the life cycle. Carbon sequestration occurs only if the total stock of wood products is increasing. Other temporal boundary issues include fossil fuels used at different times during the life cycle, and cement process reactions that occur throughout the life cycle of concrete products. The timing of GHG emissions and uptakes can significantly affect the cumulative radiative forcing, and hence the climate impact, over a given time horizon.

The establishment of spatial boundaries can be problematic, because use of wood-based materials instead of non-wood materials requires the use of more land area to grow the biomass. There are several possible methodological approaches to meet this challenge, including the intensification of land use to increase the time rate of biomass production, and the assumption that an equal area of land is available to both the wood-based and non-wood-based product followed by analysis of carbon balance impacts of various usage options for any land not used for material production. Finally, scaling up the analysis from the micro-level to the macro-level of national, regional or global scale is important to understand the wider implications of wood substitution. The total CO_2 emissions reduction from the available supply of biomass could be increased by exporting biomass to be used in applications that result in high CO_2 emissions reductions per unit of biomass.

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Meta-analysis of Displacement Factors of Wood Product Use

Introduction

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.

We determined that 21 studies in this review contain sufficient information to calculate the displacement factor of at least one wood product substituted in place of a non-wood product (Sathre and O'Connor 2010). 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*., 1995).

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.

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

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 t of wood product, or per m^3 of wood product, or per m^3 of roundwood, or per hectare of forest land. 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 below.

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

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

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_{2eq}. 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).

Results

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.

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.

Reference	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	3.57	15.0
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)	2.8	2.8	6.6
	Wood vs. steel (Minneapolis)	-0.01	0.4	2.2
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	14.0

... continued on next page

Table 2 cont'd.

Reference	Application	Estimates		
		Low	Middle	High
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.*, 2006	Single family house			
	Wood vs. concrete (Atlanta)	2.8	2.8	6.6
	Wood vs. steel (Minneapolis)	-0.01	0.4	2.2
Valsta, 2007	Literature survey	1.00	2.00	3.00
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).

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 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, and the use of this biofuel can reduce net GHG emissions by substituting in place of fossil fuels. 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).

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

			Recovered biomass type				
Reference	**Application**	**DF**	**Processing residues**	**Harvest slash**	**Stumps**	**Post-use wood product**	**Fossil fuel replaced**
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 (Swe)	4.0	X	X		X	natural gas
		5.6	X	X		X	coal
	Apartment building (Fin)	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).

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 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 versus 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 have 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.

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 CH2 pt 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**	

As discussed above, 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 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. See the section of this report on Methodological Issues for further discussion on applicability (validity) of displacement.

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 forest land, 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.

Application

In this study we present an average wood substitution GHG displacement factor based on data from a collection of studies with wide differences in approach and in wood product applications. This average displacement factor may be useful in roughly estimating the GHG impact of various scenarios such as successful wood market growth initiatives, however it should be applied with caution based on caveats and uncertainties as discussed throughout this report. It may be most meaningful if applied on a macro scale, for example to estimate the GHG benefit of a national increase in wood construction in general. If applied at the scale of a single building, it may yield a substantial over or under-estimate of the GHG impact.

Application of the displacement factor requires careful consideration of the units used in the calculation. We express the displacement factor in metric tons of carbon emissions reduction per metric tons of wood carbon. This unit cannot typically be applied to a building application without conversion calculations. Our average displacement factor of 2.1 can be expressed in other units more familiar or appropriate for the application at hand. For example, our average factor corresponds to 3.9 metric tons of carbon dioxide equivalent emission reduction per metric ton of oven-dry wood. Note this number must be reduced for wood at different moisture contents. An average equilibrium moisture content of wood in construction service is 15%, with an adjusted displacement factor of 3.4 metric tons of CO_{2eq} emission reduction per metric ton of wood in service. The displacement factor can also be expressed as GHG reduction per unit volume of wood, however this is dependent on wood density. A global average of oven-dry density for all wood species is perhaps around 500 kg/m^3. Using this density, the displacement factor can be expressed as 1.9 t CO_{2eq} emission reduction per m^3 of wood product. For a construction application that is likely using softwood, the displacement factor would be lower to reflect species densities that are probably in the range of 350 to 450 kg/m^3. For example, a density of 420 kg/m^3 yields a displacement factor of 1.6 t CO_{2eq} emission reduction per m^3 of wood product.

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 3.9 t CO_{2eq} emission reduction per oven-dry t of wood product, or roughly 1.9 t CO_{2eq} emission reduction per m^3 of wood product assuming a dry wood density of 500 kg/m^3.

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 forest land for the continuing production and efficient use of wood products.

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